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Application of Thermal Imagery and Aerial Photography to Hydrologic Studies of Karst Terrane in Missouri

Geological Survey, Rolla, Mo Water Resources Div

APPLICATION OF THERMAL IMAGERY AND AERIAL PHOTOGRAPHY TO HYDROLOGIC STUDIES OF KARST TERRANE IN MISSOURI

U.S. GEOLOGICAL SURVEY

Water-Resources Investigations 77-16

Prepared in cooperation with

Missouri Department of Natural Resources,

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16. Abstracts Planning waste-disposal facilities and impoundments is complicated by karst carbonate terrane in the Ozarks. Thermal imagery (8-13 micrometer wavelength) and color infrared photography aid in identifying losing streams, sinkholes and hydrologic conditions encouraging collapse. Imagery and photography were acquired in Greene and Reynolds Counties, Mo., in March 1972 and June 1973. Differences in thermal levels correlating with losing and gaining reaches of Logan Creek valley, Reynolds County, were not visually apparent in predawn March imagery but statistical analysis of predawn magnetic-tape data indicated greater variance in emitted energy from the losing reach than from the gaining reach.

In June, the gaining reach of Logan Creek was darker (cooler) on thermal imagery than the lighter (warmer) losing reach at postsunset and predawn. Overflights between May and June 1973, using a radiometer strengthened the visual interpretation of the imagery. Spring and autumn are poor times to collect thermal data for this purpose while midday in late summer may be a very good time.

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CONVERSION FACTORS

For readers who prefer metric untis to English units, conversion factors are listed below:

Multiply English unit	By	To obtain metric unit
acres	0.4047	hectares (ha)
feet (ft)	.3048	meters (m)
cubic feet per second (ft^3/s)	.02832	cubic meters per second (m^3/s)
inches (in)	25.4	millimeters (mm)
miles (mi)	1.609	kilometers (km)
square miles (mi^2)	2.590	square kilometers (km^2)

(To convert temperature in °C to °F, multiply by 1.8 and add 32.)

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ABSTRACT

Aerial thermal radiometric measurements, thermal imagery, and aerial photography were used in the Missouri Ozarks to distinguish gaining and losing streams and gross differences in drainage characteristics between basins. The imagery was acquired on March 7-9, 1972 and June 20-22, 1973, in predawn, midday, and postsunset hours.

Tonal contrasts in the postsunset and predawn June imagery appear to be indicative of a thermal difference between gaining and losing reaches of Logan Creek on the Salem Plateau and Terrell Creek on the Springfield Plateau. The losing reaches of the valleys were warmer than the gaining reaches in both postsunset and predawn hours. Ground and airborne radiometric (radiant temperature) measurements obtained in the months before and after the June flight support this interpretation of the June imagery.

Tonal contrasts were not obvious in the March imagery. Airborne radiometric measurements showed that the periods from March to May and October to November were transitional between the winter and summer thermal regimes, probably accounting for inconclusive differences in the March imagery. However, statistical analysis of predawn March imagery showed that variance in the emitted energy from the losing reach of the valley was significantly greater than that from the gaining reach.

Tonal contrasts between gaining and losing watersheds were more evident on imagery of the Salem Plateau than the Springfield Plateau. Imagery contrasts are subdued on the Springfield Plateau owing to lower topographic relief, more uniformity of agricultural land use, and the general similarity of soil material. Bedrock is a uniform massive limestone. Surface-water losses from streams occur as discrete flow into small solution cavities rather than as diffuse seepage into the alluvial and residual deposits of the Salem Plateau.

Structural features, particularly joints and sinkholes, could be more readily identified on imagery of the Springfield Plateau than the Salem Plateau due to the uniformity of the land. Features such as joints that affect surface drainage were enhanced on the imagery. Imagery obtained in March when vegetation was dormant was more useful than the June imagery for identification of structural features and sinkholes whereas that obtained in June was more useful for discriminating gaining and losing reaches of stream valleys. Sinkholes that are poorly defined on thermal imagery are often well defined on color infrared photographs obtained in the growing season owing to luxuriant vegetation.

INTRODUCTION

Problem

Aquifer contamination is an ever-present problem in the carbonate-rock terrane of the southern Missouri Ozarks. Effluents discharged into a losing reach of a stream may flow into and contaminate aquifers. Thus, serious water pollution can result from the location of waste-disposal facilities at the upstream end of a losing reach, leakage from an impoundment of contaminated surface water, collapse of an impoundment, or from accidental spills (Aley and others, 1972).

A losing stream is one in which surface flow may diminish or cease in a downstream direction. An interrupted stream is one that has alternating reaches with gains and losses in surface flow. The losing streams studied in this project lose surface flow into carbonate bedrock. Conversely, gaining streams receive ground-water discharge from the bedrock and overlying sediments.

A guideline established by the State of Missouri defines a losing stream as one that loses 30 percent or more of its flow at the 7-day Q_{10} low-flow discharge. The 7-day Q_{10} flow is the average minimum discharge for 7 consecutive days which will occur on an average of once in 10 years.

When the known information on losing streams is balanced against the vastness of the Ozarks and myriad of basins, small and large, the problem of identifying at least a majority of the losing streams by field examination alone exceeds reasonable manpower capabilities. Although many losing streams have been identified in site-by-site evaluation, a means is needed to define logically and rapidly the hydrologic features of watersheds and relate them to the structural framework on a regional basis rather than by site-by-site evaluation. Thermal imagery should be useful in this endeavor.

Purpose

The study was undertaken to evaluate the use of thermal imagery and photography as practical tools in the identification of gaining and losing streams for engineering geologic investigations. The basic premise is that alluvial valleys of gaining and losing streams differ in thermal-radiation characteristics. If differences in thermal-radiation levels between known gaining and losing streams can be measured and interpreted, other gaining and losing streams may be located from remotely-sensed data with little additional data on ground-water levels and streamflow.

Acknowledgments

Acquisition and analysis of airborne data generally require the assistance of many persons and agencies. The task of positioning flight lines at night and providing measured data at selected points as a basis for image interpretation is obviously important. The Sheriff's Department, Reynolds County; Missouri State Highway Patrol; the Missouri Conservation Commission; and the National Park Service assisted in flight-line orientation on Logan Creek. City of Springfield personnel, under the supervision of Mr. Harry Criswell, provided flight-line location assistance for Springfield Plateau studies. Mr. George Brancato, meteorologist-in-charge, and his staff, St. Louis National Weather Service, assisted in scheduling the missions.

Messrs. Richard Blythe and Robert Dye, Bendix Aerospace staff scientists, assisted in flight-line layout and mission planning, and made a statistical analysis of thermal imagery data. We are also indebted to Messrs. Bill Haeske, technician, and Harry Niendorf and Bill Kellogg, pilots of Bendix Aerospace.

The project began in 1970 in cooperation with the Department of Natural Resources, Division of Geology and Land Survey (formerly Missouri Geological Survey and Water Resources) when Dr. W. C. Hayes was the State Geologist. The project was completed under Dr. W. B. Howe, Director and State Geologist.

Location

Several areas on the Springfield Plateau in southwestern Missouri were selected for study (table 1 and figs. 1 and 2). The James and Sac Rivers and Pond, South, Terrell, and Wilson Creeks are located here. The rivers are perennial gaining streams and the creeks have gaining and losing reaches. The area A in figure 2 was included in the project because it has waste-disposal problems in a rapidly developing area with a wide distribution of sinkholes and many losing streams. Also, comparison

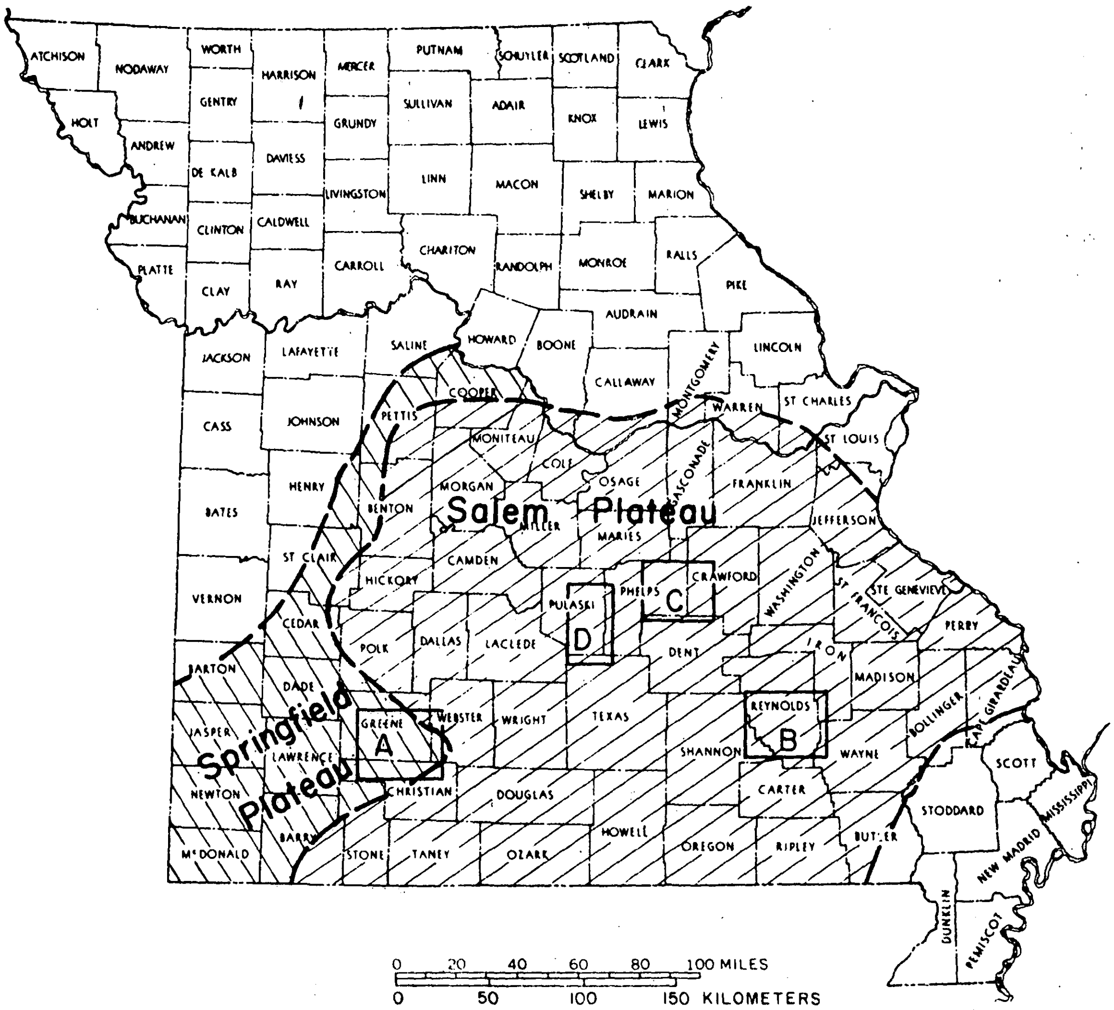


FIGURE 1.--MAP OF MISSOURI SHOWING SPRINGFIELD AND SALEM PLATEAUS AND THE AREAS OF THERMAL RADIATION STUDIES.

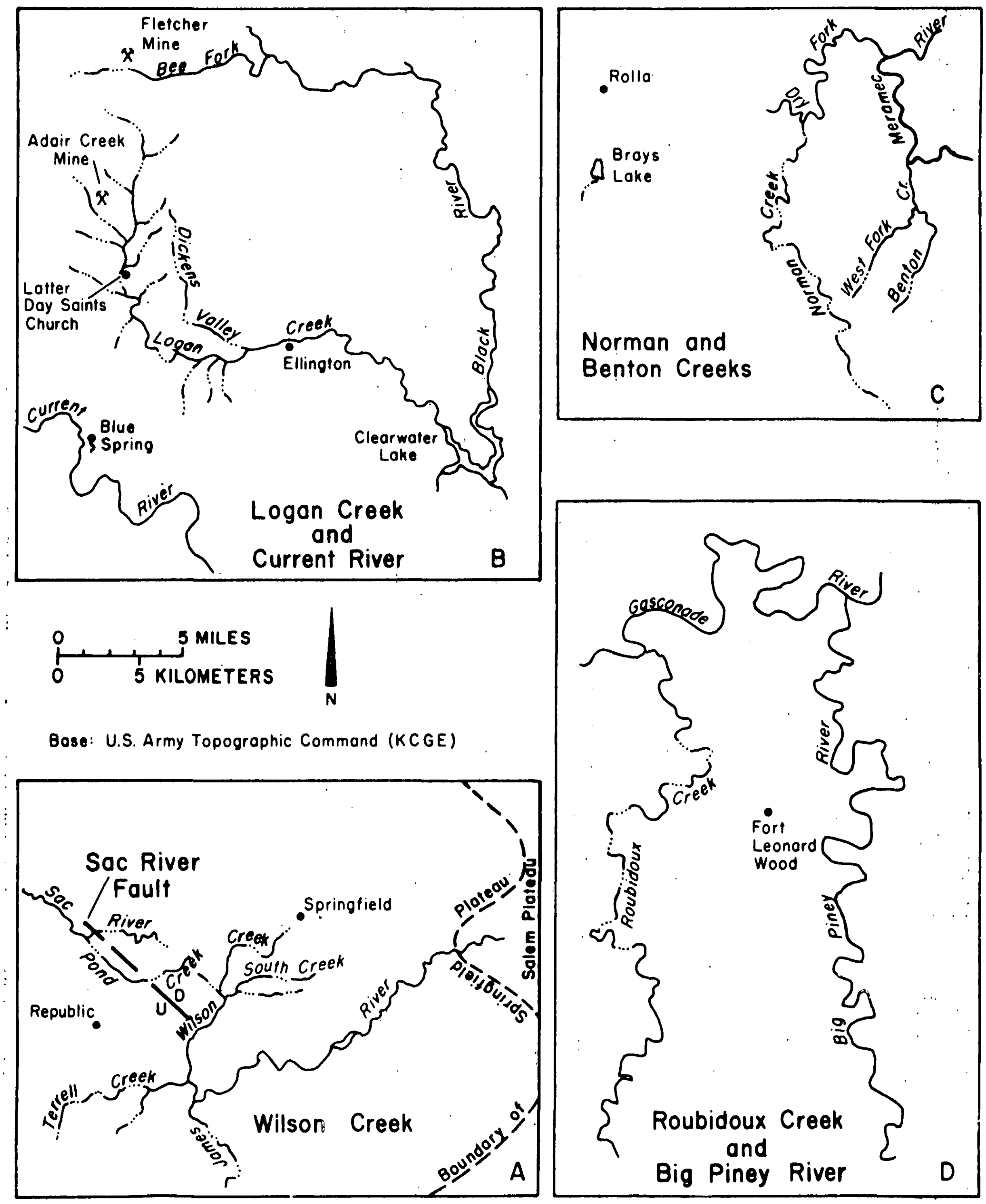


FIGURE 2.--OUTLINE MAPS OF AREAS OF THERMAL RADIATION STUDIES.

of thermal imagery of these features on karst limestone terrane of moderately low relief with dolomite terrane of greater relief and forest cover on the Salem Plateau would be useful in determining the variable effects of soil and rock types, vegetation and land use and topography on recognition of hydrologic characteristics of valley environments.

Much of metropolitan Springfield, with nearly 120,000 people, lies in Wilson Creek basin. Effluent from the Springfield Southwest Sewage Treatment Plant enters Wilson Creek midway between its headwaters and its mouth. The middle segment of Wilson Creek is a losing stream, and prior to 1970 a significant part of the plant effluent entered shallow limestone fissures to emerge downstream in springs. This situation was remedied partly in 1970 by relocation of the sewage outfall below the losing reach and addition of an aeration lagoon to the system.

On the Salem Plateau in south-central Missouri seven basins were included for study. The Current and Big Piney Rivers, Benton Creek and Bee Fork are gaining perennial streams (fig. 2) whereas Norman, Roubidoux, and Logan Creeks are interrupted streams.

Logan Creek on the Salem Plateau was included because it is typical of an interrupted stream consisting of perennial reaches with intervening intermittent or ephemeral reaches in a relatively undeveloped forested part of the Ozarks. Lead is mined and concentrated at an operation in the headwaters of the Logan Creek valley and effluent from the mill is discharged to a tailings pond in a headwaters tributary.

HYDROLOGIC SETTING

The Ozark Plateaus physiographic province is underlain by carbonate rocks, mostly gently dipping and consisting principally of massive cherty limestone on the Springfield Plateau and cherty dolomite on the Salem Plateau. A fundamental difference between the two plateaus is the thickness of the carbonate-rock section which is directly involved in the surface hydrology of the two areas. The limestone section of Mississippian age in the Springfield area averages 300 ft (feet) thick and is separated from the underlying Ordovician and Cambrian dolomite section by the Mississippian Northview Shale. In the Salem Plateau the dolomite section is at the surface and averages about 1,500 ft thick without a consistent confining bed. The cave-spring system is better developed on the Salem Plateau and weathering is deeper. Although these two physiographic subprovinces have somewhat different hydrologic character, the problem of identifying losing streams and hydrologic features related to karst terrane is basically similar.

Table 1.--Seepage characteristics of selected streams in southern Missouri

Stream name (see fig. 2)	Springfield Plateau		Salem Plateau	
	Gaining	Interrupted	Gaining	Interrupted
Pond Creek-----------	-----	X	-----	-------
Wilson Creek---------	-----	X	-----	-------
James River----------	X	-------	-----	-------
Terrell Creek--------	-----	X	-----	-------
Roubidoux Creek------	-----	-------	-----	X
Big Piney River------	-----	-------	X	-------
Norman Creek---------	-----	-------	-----	X
Benton Creek---------	-----	-------	X	-------
Bee Fork-------------	-----	-------	X	-------
Logan Creek----------	-----	-------	-----	X
Current River--------	-----	-------	X	-------
Sac River------------	X	-------	-----	-------
South Creek----------	-----	X	-----	-------

Losing streams in the Springfield and Salem Plateaus have a number of common physical characteristics. These include poorly-sorted alluvial deposits, little development of depositional terraces, often poorly-defined stream channels, irregular valley widths, abnormally flat valley gradients, and dearth of phreatophytes. The irregular widths of the valleys suggest headward growth of the valley by the coalescence and collapse of sinks.

Many Ozarks streams have interrupted flow. The interruption of flow may be due to evapotranspiration in the absence of sufficient ground-water inflow to maintain a perennial stream. The interruption may be caused by loss of flow to subterranean solution cavities.

In the mid-1950's, a network of continuous-record gaging stations was established to provide streamflow data for small watersheds for design purposes. Of the 21 small Ozarks basins instrumented for continuous record, Fudge Hollow and Kings' Creek, 2 basins located on the Salem Plateau, are extremely deficient in runoff because surface flow is lost into bedrock aquifers. Over a period of 15 years, annual runoff from Fudge Hollow and King's Creek (fig. 3) averaged respectively only 1.5 and 1.7 in. (inches) in areas where normal runoff averages 12 to 14 in. Many other basins with deficient runoff are ungaged.

The Springfield Plateau

The Springfield Plateau has a rolling surface of moderately low relief underlain for the most part by limestone of Mississippian age. Karst development is extensive and sinkholes, caves, losing streams and springs are common. Extensive cave-spring systems exist in the limestone in the form of relatively small but continuous conduits which transfer water from the point of loss to springs and wells. Ground-water movement through the cavern system has been measured at a rate as high as 0.4 ft/s (foot per second).

Some faulting exists in the region. The Sac River fault (fig. 2) trends northwest across Wilson Creek and parallels Pond Creek north of Republic. Joint sets are prominent with principal orientations in northeast and northwest directions. Sinkhole alinement and ridges and valleys generally trend in these directions.

The soil on much of the Springfield Plateau is a permeable, stony red clay, 10 to 30 ft thick, formed as an insoluble residuum of the limestone bedrock. Because of intense solution of the bedrock, the soil-rock contact is very uneven, and limestone pinnacles and shallow cave systems have developed at or near the contact. Many cave roofs dome upward into the subsoil, a condition contributing to collapse, particularly following man-induced changes.

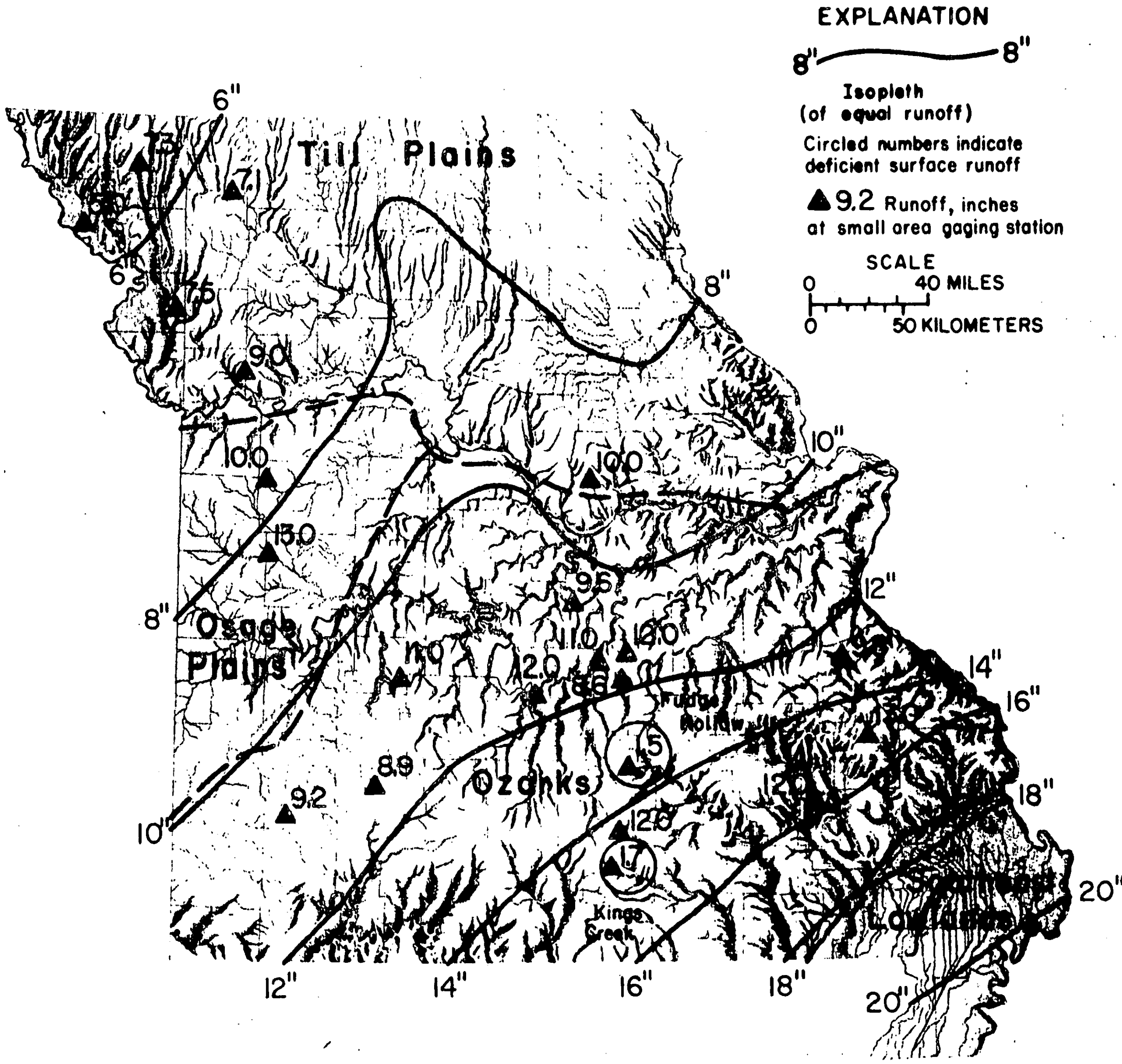


FIGURE 3.--MAP SHOWING LOCATION OF LONG-TERM CONTINUOUS RUNOFF RECORDS FOR SMALL BASINS IN MISSOURI.

Alluvium in the stream valleys may range from 5 to 20 ft thick although many channel reaches have bedrock floors. Stream-channel losses are point losses in that surface flow is captured in sinkholes or solution openings along joints in exposed limestone bedrock. These features are more obvious on the Springfield Plateau than they are on the Salem Plateau because of thinner alluvial deposits on the Springfield Plateau. However, water storage within the shallow limestone fissures of the Springfield Plateau is less than in the cavernous bedrock of the Salem Plateau, and springs are usually small compared to those on the Salem Plateau.

Wilson, Pond, South and Terrell Creeks (fig. 2) near Springfield contain gaining and losing reaches. The losing reaches of Wilson, South and Pond Creeks typify losing streams of the Springfield Plateau in that losses into bedrock fissures are usually visible. Terrell Creek is similar to losing streams of the Salem Plateau. Its flow disappears gradually in a reach of a mile or so depending on the season and the weather. Seepage runs on the four streams show that they gain in reaches containing springs but lose all or part of their flows in intervening reaches.

The James and Sac Rivers are perennial streams. The James River is impounded by a dam and the discharge from the reservoir is heated by mixing with water from a nearby power plant. The Sac River is a springfed stream with a small inflow of treated sewage. The surface flow lost in Pond Creek reappears in springs in Sac River.

Wilson Creek receives most of Springfield's treated sewage which is 50 or more percent of the total low-flow discharge of the stream at its junction with the James River. Dye traces have shown that the system of solution cavities beneath the creek is complex and accounts for the alternating gaining and losing reaches (Harvey and Skelton, 1968, and Gann and others, 1976).

The Salem Plateau

The topography of the Salem Plateau is rugged and densely wooded in some places, rolling and open in others. Loss of surface flow to caverns results in less annual runoff, less dissection and less relief. Logan Creek basin, one of the areas selected for the study, is an example of a low-relief watershed. On side-looking radar imagery (SLAR) the smooth appearance of the basin contrasts with the rugged terrain of contiguous watersheds drained by gaining streams (Harvey and Skelton, 1972).

Normal faults are common structural features in some sections of the Salem Plateau. Streamflow losses occur in the vicinity of some faults while neither significant losses or gains occur at other faults. Prominent joint sets have northwest and northeast directions and exert varying control on drainage development. Bedrock consists of massive dolomite with thin interbedded snadstones and shales of Cambrian and Ordovician age (Gann and others, 1976).

Extensive cavern systems are composed of vast chambers connected by conduits. Ground water in some of these systems has been traced many miles from points of loss to discharge in the scenic springs and rivers of the Salem Plateau (Gann and others, 1976). Nine major springs with average discharges of more than 100 ft^3/s (cubic feet per second) attest to the tremendous storage in the residuum and cavernous bedrock and the recharge capabilities of the karst upland and its system of losing streams (Vineyard and Feder, 1974).

The upland soil cover ranges from 20 to 300 ft in thickness. It is moderately permeable residuum of stony red clay derived from weathering of the underlying bedrock.

Alluvial soil ranges from 10 to 40 ft thick. A silt-loam surface soil 3 or 4 ft thick overlies permeable sand and gravel deposits. Poorly-sorted soil deposits in losing stream channels are the result of storm-surge transport in conjunction with diminishing downstream flow. Gravel-filled stream channels may attain widths of 200 to 300 ft. The underlying bedrock may be deeply weathered, resulting in irregular bedrock profiles.

With only intermittent surface runoff the opportunity for development of terraces is lacking. Little accumulation of fine-textured, colluvial soil occurs at the toes of valley slopes so that a sharp topographic break exists between the flood plain and the base of the upland slope.

Streamflow losses may occur in reaches many miles in length. Within the losing reach ground-water levels usually range from 50 to 250 ft below flood plain level. A change in the depth to the water table may occur abruptly at the boundary between gaining and losing stream segments, or the water-table surface may descend gradually for several miles near the gain-loss boundary. In areas where the water table is far below land surface, the uplands are less dissected and stream gradients are flatter in the losing reach than in the gaining reach. Finally, absence of riparian vegetation is typical of losing streams.

Logan Creek is a typical example of an interrupted stream with gaining and losing reaches (fig. 4). The upstream reach has perennial flow that is sustained by springs, and the ground-water level is near the level of the flood plain. The stream goes dry in the middle reach where ground-water levels are 100 to 250 ft below the flood plain. Only small seeps occur at the base of the bluffs along this part of the stream. The lower reach is a gaining stream and ground-water levels are once again near the level of the flood plain. At least some of the flow lost in the dry middle segment of Logan Creek resurges at Blue Spring (fig. 2) in the Current River basin 8 mi (miles) to the southwest (Feder and Barks, 1972).

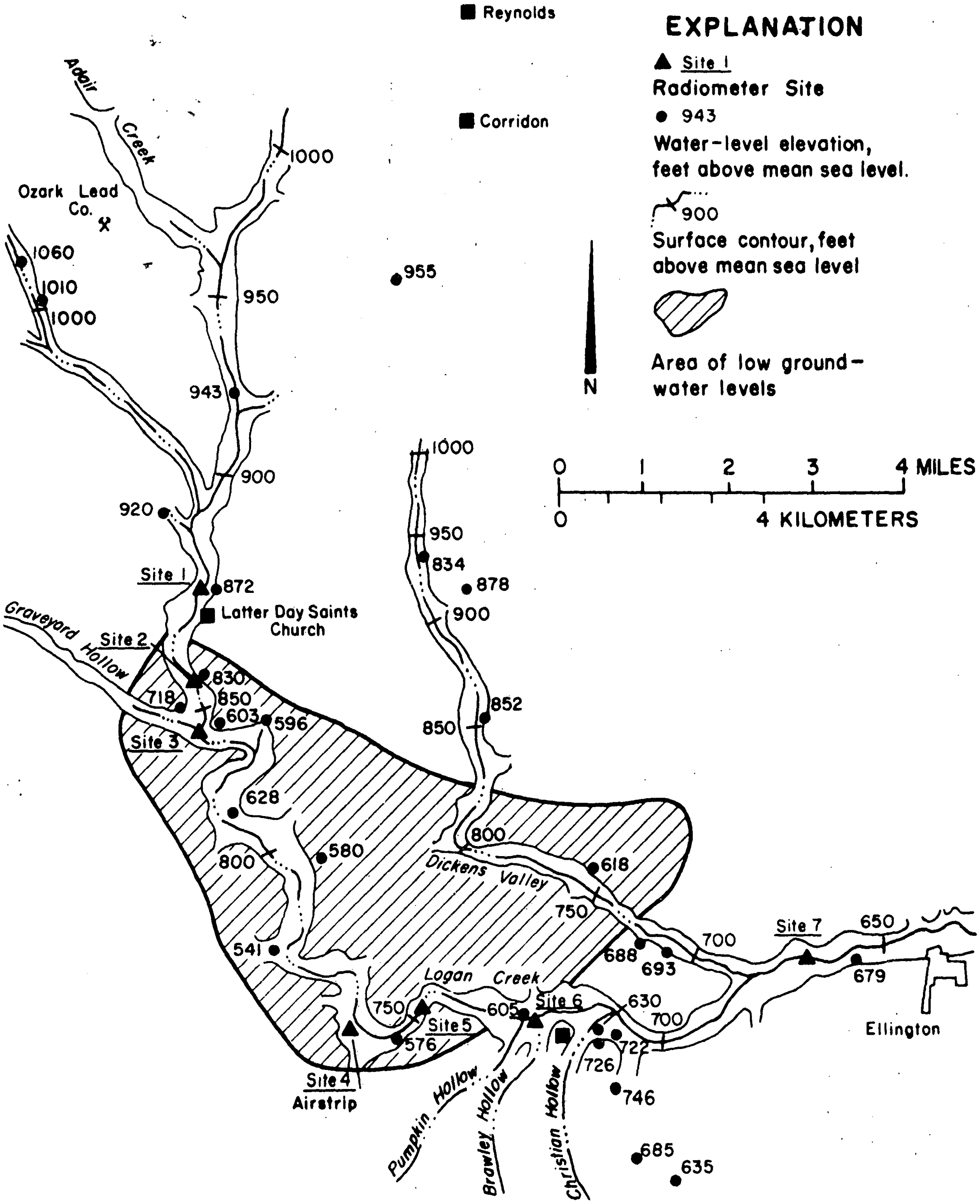


FIGURE 4.--GROUND-WATER LEVELS IN THE LOGAN CREEK BASIN, 1971.

APPROACH

Water has high specific heat compared to specific heats of other common naturally occurring materials. Thus, it has a high heat-storage capacity and is characterized as a heat sink. For this reason, the presence or absence of water is important in discriminating between gaining and losing stream valleys. Determination and comparison of diurnal and seasonal temperature cycles of flood plains should reveal thermal-emission variations which are due to the effects of gross differences in water content (including soil moisture) that occur in the valleys of gaining and losing streams. The assumption is that variations in diurnal and seasonal thermal emission are a function of the soil formation within the flood plain, the presence or absence of water, the resultant vegetative growth and the characteristics imparted to the air mass above the ground. Comparison of these thermal variations should assist in defining the losing stream reaches.

Fine-textured alluvial soils, stratification, and sorting result in a higher moisture level that characterizes gaining stream valleys. Soil deposits in losing streams are poorly sorted, coarse, and well drained. Terraces are generally absent. These features which are indicative of gaining and losing streams, although not necessarily directly related to water-table depth, are indicative of water-table conditions.

The investigation of losing streams included collection of background hydrologic data on stream and springflows and ground-water levels, ground radiometric surveys followed by aerial radiometric surveys of gaining and losing stream valleys using a Barnes PRT-5[1]radiation thermometer and acquisition of aerial photographs and thermal imagery.

The work began in December 1970 with ground- and low-altitude radiometric surveys. Imagery and photographs were acquired on March 7-9, 1972 and June 20-22, 1973.

Ground Surveys

Ground radiometric measurements were made at sites along Roubidoux, Benton, Norman and Logan Creeks (fig. 2). Surveys spanning 24-hour periods were generally made in fair weather in all seasons from December 1970 to March 1972. Circular plots about 2 ft in diameter were selected at each site and the same plots were visited each time radiometric temperatures were measured. Plots consisted of sand, sand and gravel, and water when

[1]The use of brand names in this report is for identification purposes only and does not imply endorsement by the U.S. Geological Survey.

present in the channel, and bare soil and grass on the flood plain. Water temperature was measured with a radiometer and mercury thermometer.

Meteorological factors affect thermal emission from the ground. An understanding of the effect of the factors is necessary to interpretation of radiometric data, whether obtained by a radiometer on the ground or in an aircraft, or by a thermal scanning system. Sky conditions varied from clear to overcast with and without dew, frost, rain, snow or ground fog. Air temperatures and relative humidity were measured and wind and sky conditions noted. The percent cloud cover, cloud type, and atmospheric haze were recorded to help in the surface-temperature analyses.

Airborne Radiometry

The radiometer and a recorder were mounted in a single-engine (PA-32-260) plane. Flights were made in all seasons under a variety of weather conditions during the day and night. Each overflight usually consisted of two passes of the valley. Table 2 is a flight record showing the areas flown, month, and time of day or night.

Flights followed the meandering paths of valleys, but their adjacent slopes and uplands were frequently in the view of the radiometer. A 70-mm camera was used on one flight to assist in definition of the flight line and the radiometer trace. Later a portable TV camera was installed on the plane and alined with the radiometer to record ground truth. The photographs and TV imagery were especially helpful in the interpretation of radiometer data by correlating the radiometer trace with the ground scene. Based upon the results of these flights, calibrated thermal imagery was collected for several basins.

Thermal Imagery

Thermal imagery of Logan Creek valley, the Logan Creek and Current River watersheds, and the Springfield-Republic area was obtained on March 7-9, 1972 and June 20-23, 1973 (table 3.)

March imagery acquired under contract with the Bendix Corporation used a Bendix Thermal Mapper, type LN-3, sensitive in the 8- to 13-micron range. In June, a Bendix 11-channel modular multiband scanner (M^2S) was used. The M^2S scanner obtained imagery in the visible and infrared wavelengths. For purposes of making temperature comparisons between different parts of the watersheds, no gain adjustments were made during imagery acquisition in any of the missions. The time lapse was short between flights in the Springfield-Republic and Logan Creek areas to assure completion of the entire project under reasonably similar weather conditions.

Table 2.--Airborne radiometric surveys of selected basins during 1971-73

[Flight time: D=predawn; M=1100 to 1600 h; S=postsunset

Stream	Month											
	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Logan Creek------	---	D	D	---	D	D	---	D	----	---	D	---
	---	M	---	---	M	M	M	M	----	---	M	---
	---	S	---	---	---	S	---	---	----	---	---	---
Logan Creek and Current River--	---	---	D	---	---	D	---	---	----	---	---	---
	---	---	---	---	---	M	---	---	----	---	M	---
	---	---	---	---	---	S	---	---	----	---	---	---
Big Piney River and Roubidoux Creek----------	D	---	---	---	D	---	---	---	----	---	---	D
	---	---	---	---	M	---	---	---	M	---	M	---
Norman and Benton Creeks--	D	---	D	---	---	---	---	---	----	---	D	---
	M	---	M	---	---	---	---	---	----	---	---	---

Table 3.--Record of times and altitudes of thermal imagery flights. Altitudes are given in parentheses, in feet, above ground level and times are central standard

Date	Springfield-Republic Predawn	Springfield-Republic Midday	Springfield-Republic Postsunset	Logan Creek-Current River Predawn	Logan Creek-Current River Midday	Logan Creek-Current River Postsunset
First mission:						
3-7-72	------	------	----------	------	------	(1600, 3000) 2000 h
3-8-72	------	------	(1600) 2000 h	(1600, 3000) 0500 h	(1600, 3000, 6000, 8000) 1130 h	-----------
3-9-72	(1600) 0600 h	(1600, 8000 1200 h	----------	------	------	----------
Second Mission:						
6-20-73	------	(1600, 8000) 1230 h	(1600) 2100 h	------	------	----------
6-21-73	(1600) 0300 h	------	----------	------	------	(3500) 2030 h
6-22-73	------	------	----------	(3500) 0400 h	(3500, 6000, 8000) 1030 h	----------

Thermal data were recorded on magnetic tapes and later printed on 70-mm film strips for preliminary analysis. The calibrated scanner recorded thermal emissions using an instantaneous field of view of 2.5 milliradians with a scan angle of 90° and roll compensation up to 10°.

Weather conditions were clear during the March 1972, and June 1973, flights except for small areas of ground fog at predawn on Logan Creek and scattered clouds during the midday June overflights of Logan Creek. Winds at ground level were generally light, except for 12 to 17 mph (miles per hour) wind during the midday flights. Dew which occurred during the June predawn overflights of Logan Creek began to form late in the post-sunset flight.

The scanner was flown in March 1972 at low levels for detailed recording of data along stream channels and at higher levels for a general view of watersheds (table 3). In March, two parallel low-level overflights of Logan Creek were made at 1,600 ft above ground level (AGL) in order to view the entire flood plain. As a result, the flood plain at times was in the center of the imagery, and at other times was at the edge where distortion was greatest. Also, it was necessary to match the two imagery strips for a complete view of the valley. In June 1973 the Logan Creek low-level flights were 3,500 ft AGL for detailed imagery. It was decided that one flight at this altitude would be more satisfactory despite some loss in detail.

At the time the imagery was flown, ground-truth data were obtained. This included data on streamflow and water temperature, land use, vegetation distribution, soil types, local weather conditions, and soil temperatures.

Photography

Color, color infrared, black and white infrared, and black and white 70-mm film (filtered to enhance the red part of the spectrum) were used in the March midday flight. Only color and color infrared film were used in June.

SALEM PLATEAU STUDY AREA

Ground Data

Norman and Benton Creeks.--Ground radiometer work on Norman and Benton Creeks, small adjacent watersheds in the Meramec Basin on the Salem Plateau (fig. 2), was carried out concurrently with the work on Logan Creek in 1971 and 1972. The reasons for selecting Benton and Norman Creeks were their proximity to the Rolla, Mo., headquarters and availability of hydrologic data for the valleys. Relief in the two valleys is similar, Norman Creek is a losing stream except in the headwater area. Benton Creek is a gaining stream throughout its length. Ground-water levels are as much as 100 ft below ground surface along the losing reach of Norman Creek while they are near flood-plain level on Benton Creek. Ground radiometry on February 17-18, 1971, showed that the alluvial sand and gravel (fig. 5B) along Benton Creek were warmer than that in the losing reach of Norman Creek throughout the diurnal cycle. On June 29-30, 1971, however, Benton Creek alluvium, both channel fill and flood-plain soil, was cooler than that in Norman Creek (fig. 5A and 5B). This tends to confirm the original hypothesis of this study that the alluvial soil of gaining streams has less seasonal temperature variation than that along losing streams. Usually the diurnal variation in temperature along Benton Creek was smaller than the variation along Norman Creek.

Normally minimum air and land-surface temperatures occurred in both valleys near sunrise. A comparison of the graphs of the February and June 1971 data shows the effect of local climatic conditions on air and land temperatures, time, and their importance to interpretation of thermal data.

The surveys of July 9 and August 17-18, 1971, were made for the purpose of comparing the diurnal heating and cooling cycles of coarse and fine-textured saturated alluvium of Benton Creek (gaining) valley with the unsaturated alluvium in Norman Creek (losing) valley. Coarse sand and fine and coarse gravel existed at the nine sample sites in the alluvial fill of the channels.

The graphs (fig. 6) show that in both surveys predawn temperatures of Benton Creek alluvium averaged 2° to 3°C (Celsius) lower than those of Norman Creek regardless of texture. The effect of texture is shown in figure 7. The curves for Norman Creek show the relation between coarse and fine material in the absence of water. Dry coarse material has higher thermal inertia than fine material. This is to be expected because of the greater air-filled void space in fine than in coarse textured material.

The presence of moisture in Benton Creek alluvium however has caused the fine material to be nearly the same temperature as the coarse material in the nighttime hours. At midday, however, the relation of coarse and fine material on Benton Creek is the same as it is on Norman Creek.

The depressant effects of cool ground-water temperatures have a significant influence on the diurnal cycle and predawn temperatures. Fine-textured soils and high ground-water tables are more common to gaining than to losing reaches and tend to reinforce each other, aiding in thermal identification of gaining or losing streams.

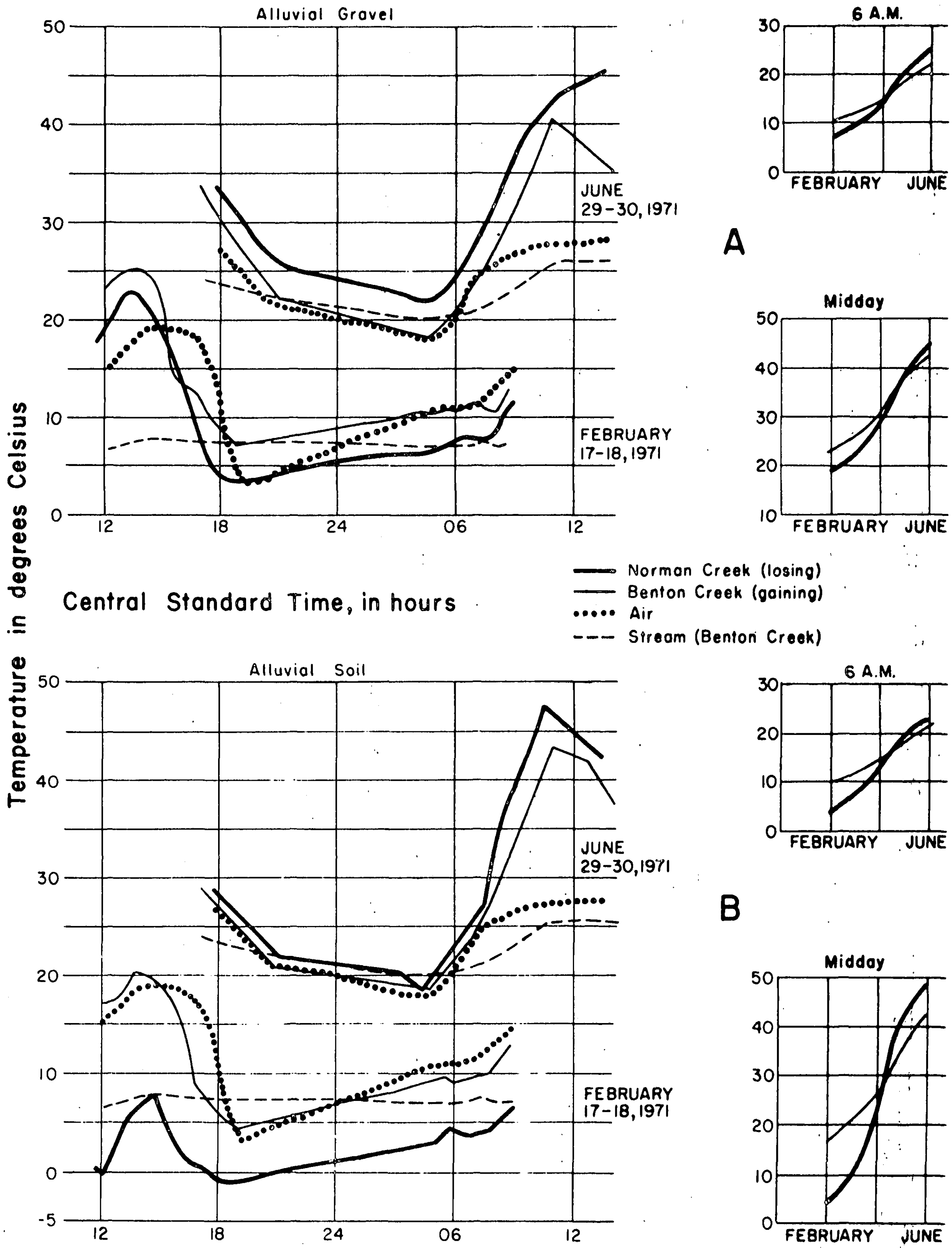


FIGURE 5.--WINTER-SUMMER RADIOMETRIC COMPARISONS OF ALLUVIAL GRAVEL (A) AND ALLUVIAL SOIL (B) ALONG BENTON AND NORMAN CREEKS.

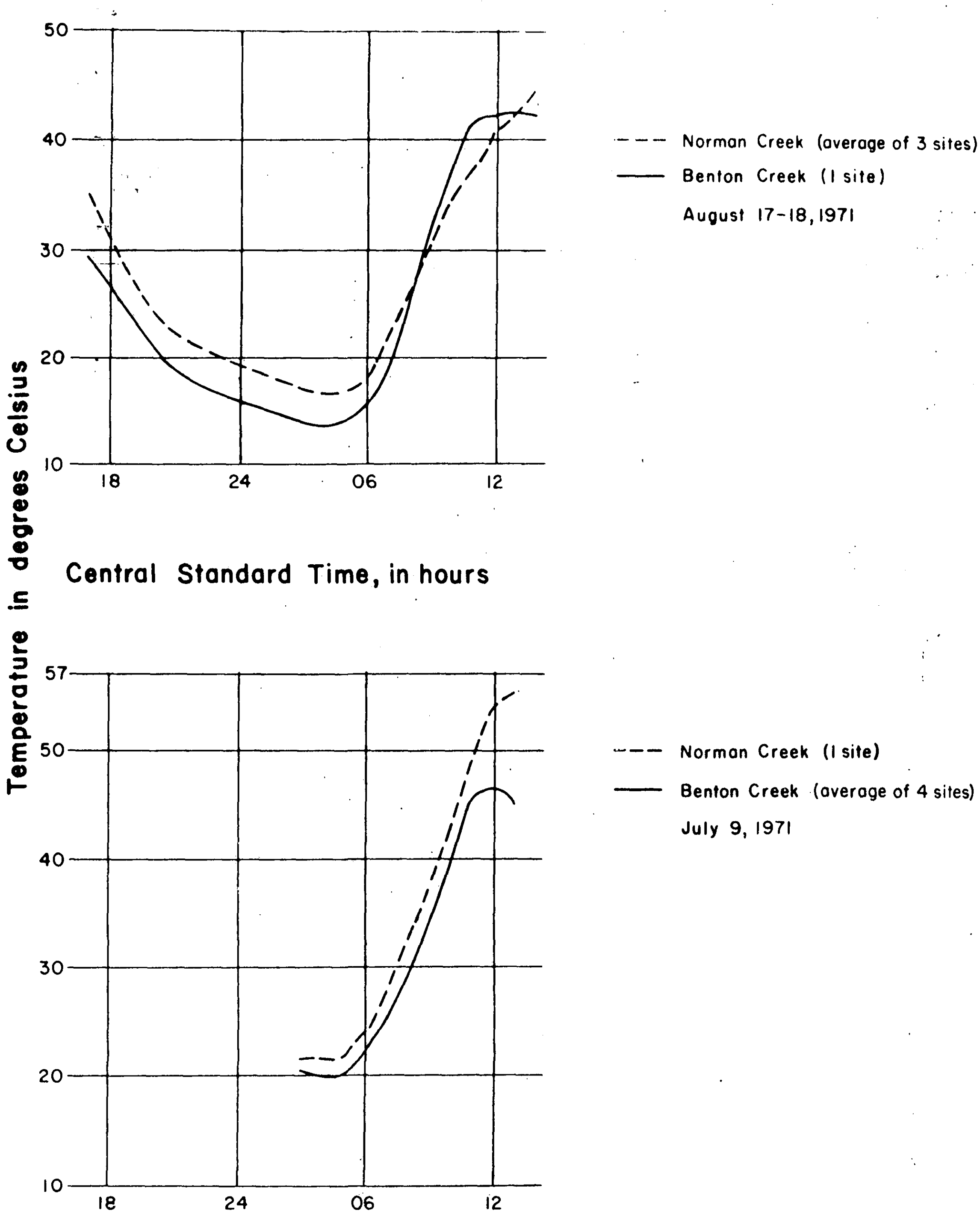


FIGURE 6.--DIURNAL VARIATIONS IN RADIOMETRIC TEMPERATURE OF COARSE ALLUVIAL FILL IN CHANNELS OF BENTON AND NORMAN CREEKS.

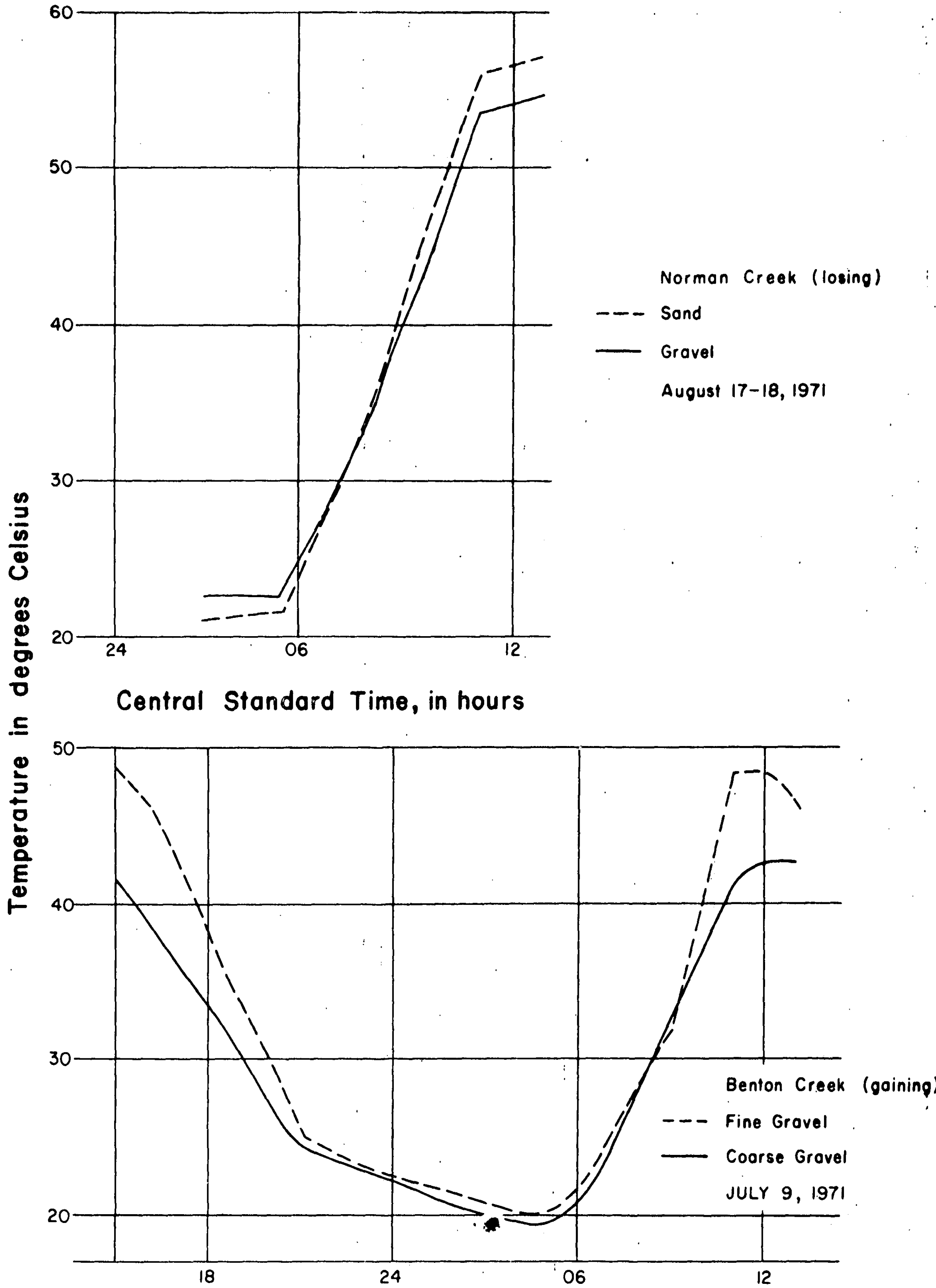


FIGURE 7.--DIURNAL TEMPERATURE CYCLES OF COARSE ALLUVIAL MATERIALS WITH DIFFERENT TEXTURES ALONG BENTON AND NORMAN CREEKS.

The greater moisture content and shallow depth to the water table in the gaining reach provide the reach with large thermal storage capacity compared to that of the losing reach. Diurnally and seasonally the thermal reservoir in the gaining reach acts as a heat sink during the day and throughout the summer while providing heat to land surfaces during the night and winter.

One might intuitively expect the temperature curve for Norman Creek (losing) to drop below that of Benton Creek (gaining) on a summer night because of the relatively low heat storage capacity and high rate of long-wave nighttime radiation of dry sand and gravel. Instead, in many of the surveys the temperature of the gaining reach was lower than that of the losing reach on summer nights (figs. 5 and 6). At the lower temperatures maintained by a saturated body, the quantity of long-wave radiation given off is not as large as that of a dry body of smaller heat capacity and higher temperature (Geiger, 1960, p. 8).

Several factors contribute to a lower temperature at predawn on Benton Creek (gaining) than Norman Creek (losing). Ground-water temperatures in the sand and gravel ranged from 14° to 16°C. This will have a depressing effect on temperature of the sand and gravel fill in the gaining reach.

Nighttime cooling due to evaporation has received considerable attention in the past (Geiger, 1960, p. 10-11; Sabins, 1969, p. 400; Rowen and others, 1970, p. 35-49; and Wolfe, 1971, p. 51). It appears to the authors of this report that the lower temperature of saturated alluvium has greater influence on maintaining cool nighttime temperatures in the gaining reach of a stream valley than has evaporation. Under dry atmospheric conditions, evaporative cooling may have increased importance.

That evaporative cooling is a factor in the interpretation of daytime thermal imagery and radiometric temperature data and may be important at times during the night is indicated in a comparison of water temperatures measured by thermometer and radiation thermometer through a diurnal cycle on February 17-18, 1971 (fig. 8). The radiometer records the surface-skin temperature of the water and is a measure of the energy emitted at the air-water interface. In the daylight hours when solar heating occurs the difference between the actual water temperature near the surface and the surface-skin temperature measured by the radiation thermometer is largest, about 2°C. The difference decreases into the night until near dawn when the actual water temperature and radiant temperature of the skin surface are within a degree of each other and follow each other closely. When measurements were made at 0722 hours (h), the breeze was gentle and the water was in the shade, but by 0800 h, a stiff breeze had risen. While the water temperature had continued to rise, the radiometric temperature dropped markedly, probably because of the increase in evaporative cooling.

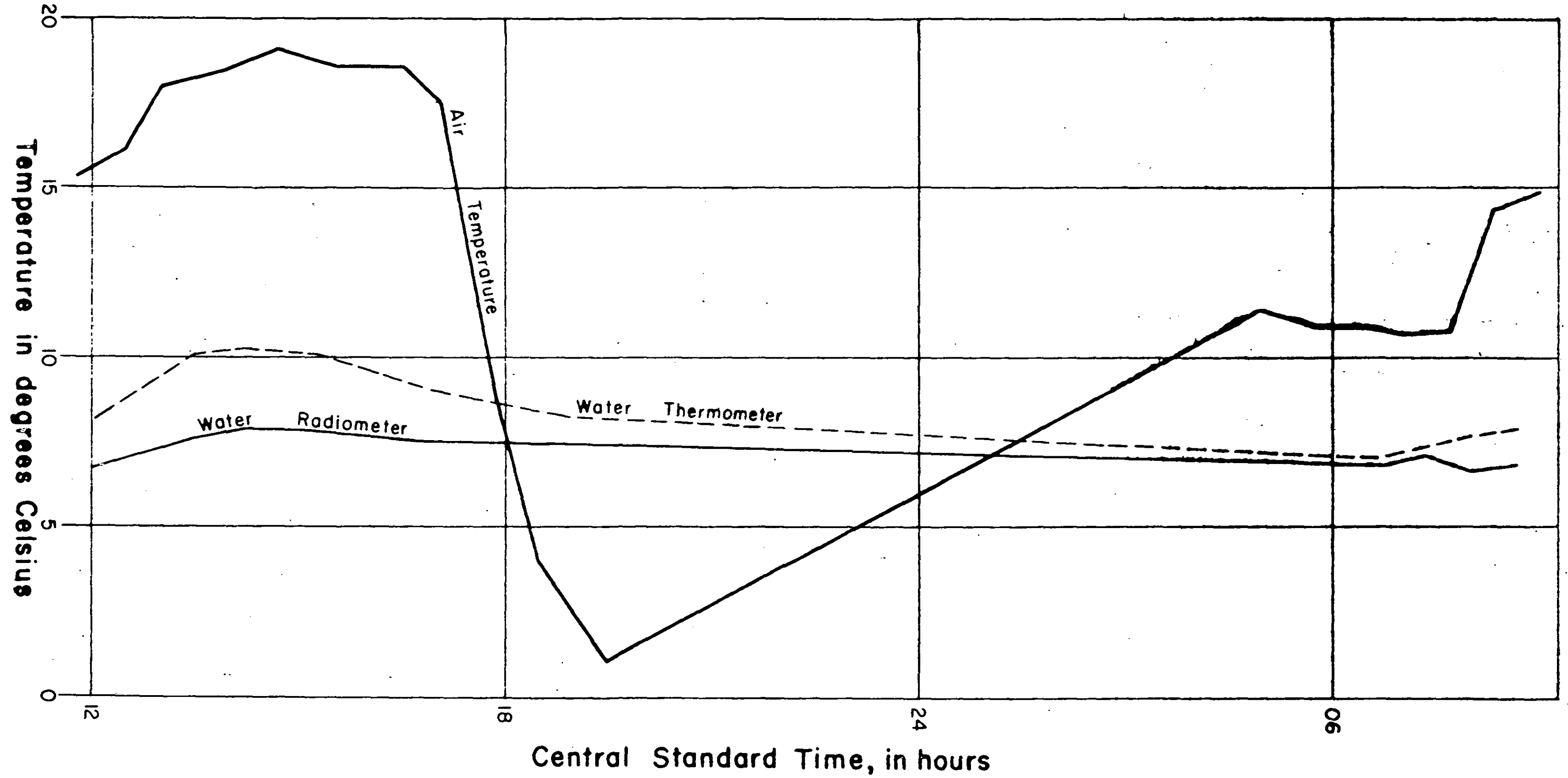


FIGURE 8.--COMPARISON OF RADIOMETRIC AND THERMOMETER TEMPERATURES OF WATER, BENTON CREEK, FEBRUARY 17 AND 18, 1971.

The ground-level radiometer surveys carried out early in the project formed the basis, in part, for interpretation of aerial radiometery and thermal imagery obtained later. Figure 9 shows diagrammatically the relation between stream temperature and ground temperatures in the gaining and losing reaches of Benton and Norman Creeks. The curves are based on average conditions measured in five surveys.

Insolation (solar radiation) is an important factor regulating surface temperatures of gaining and losing stream reaches. In winter, insolation is minimal and diurnal temperature variations are usually small (fig. 9A). The gaining valley has a greater water content and does not cool as fast as the losing valley at night. Often ground radiometer measurements made at midday during the winter demonstrate inconclusive temperature relationships between wet and dry valleys. Similarly, midday winter aerial radiometer surveys did not show a distinct temperature differentiation between the gaining and losing reaches.

In mid-summer insolation is large and diurnal surface-temperature variations are near maximum levels (fig. 9B). The greater moisture content in the gaining valley prevents it from reaching the high midday temperatures occurring in the losing valley. In the predawn hours the streams were the warmest part of the scene, and land surfaces which were warmest at midday were coolest at night (fig. 9B). At night the valley of the gaining reach of the stream was cooler than the losing reach in summer. Thus, two distinct temperature curves for the land surface of the valleys were identified, one for the gaining stream and one for the losing stream. The temperature curves for the gaining and losing reaches generally agree with the observed temperature relationship developed for Norman Creek (losing) and Benton Creek (gaining). (See figure 5.)

Figure 9C illustrates the crossover for predawn hours in the spring when the temperature difference between gaining and losing reaches of a valley is negligible. A similar condition will occur again in the fall to complete the annual cycle. These crossover periods are obviously poor times to schedule flights.

Temperature surveys in a water well in glacial drift in South Dakota made by E. F. LeRoux and presented by Myers and Moore (1972, p. 727) were replotted in figure 10. Surface temperatures were extrapolated from the curves given in the paper. The curves in figure 10 show that a crossover occurs in the spring and autumn that corresponds with that observed in the radiometric surveys.

Winter midday ground radiometric temperatures of the flood plains of losing and gaining streams were often about equal (fig. 9D). Midday ground radiometric work was generally inconclusive.

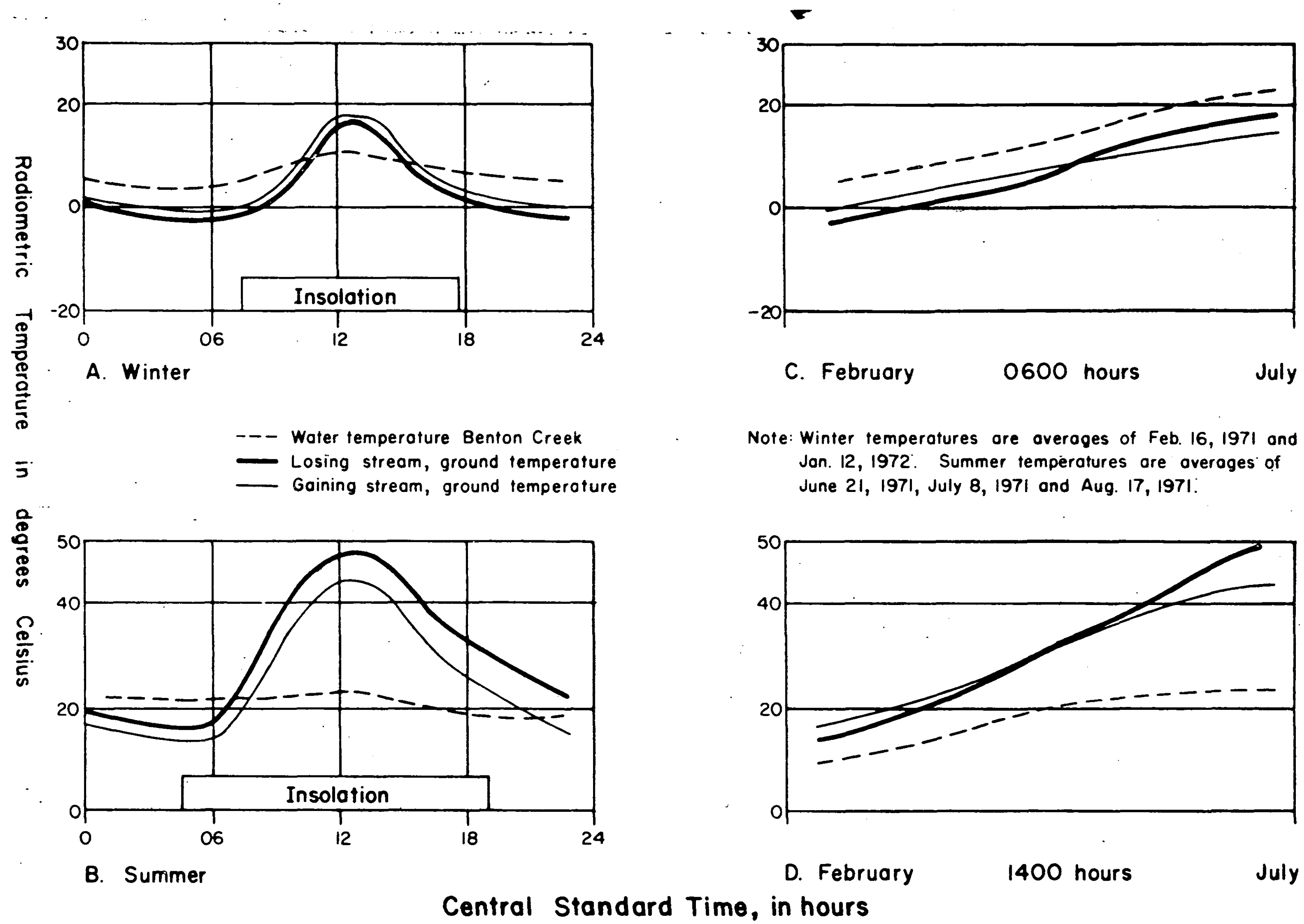
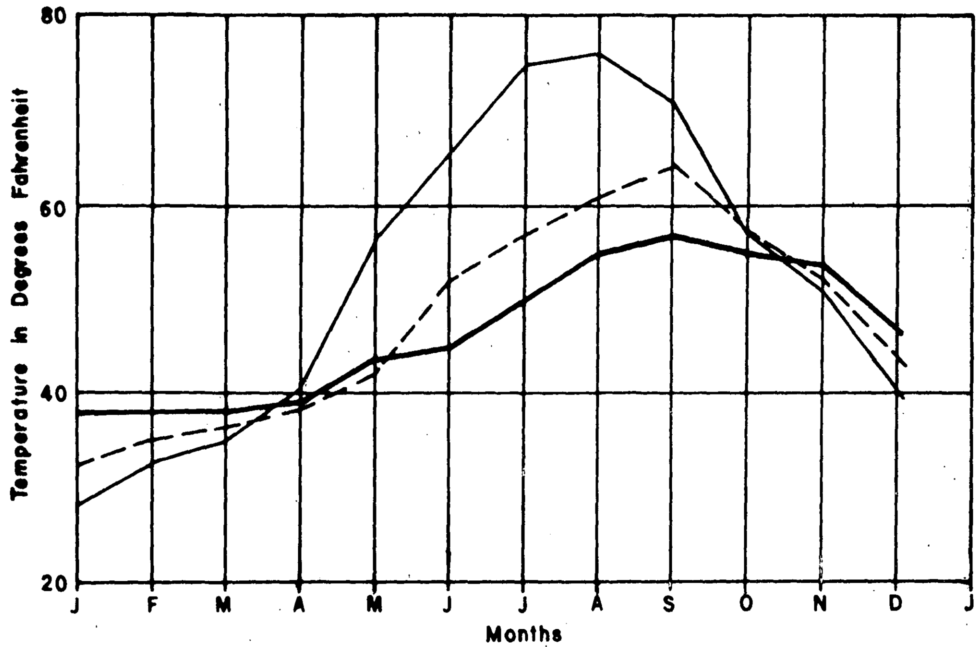


FIGURE 9.--DIURNAL AND SEASONAL TEMPERATURE RELATIONSHIPS ON BENTON AND NORMAN CREEKS.



0 ft depth
5 ft depth (1.524 m)
10 ft depth (3.048 m)

NOTE: Curves based on data from Meyers (1972, fig. 4). 0 feet depth values extrapolated from data.

FIGURE 10.--GROUND-WATER TEMPERATURE VARIATIONS WITH DEPTH.

Logan Creek.--Radiometric measurements were made at various times between January 1971 and March 1972 at seven localities along Logan Creek (fig. 4). All sites were located on the alluvial flood plain with sites 1 and 7 in the upstream and downstream gaining reaches and sites 2, 3, 4, 5, and 6 in the losing reach. In winter, predawn radiometric temperatures of the coarse gravelly alluvium averaged 0.5° to 2.5°C warmer at site 7 (gaining) than at sites 2-6 (losing). Temperature measurements were not made at site 1 in the winter. In summer, predawn temperatures of the coarse alluvium at sites 1 and 7 averaged 0.5° to 2.5°C cooler than those at sites 2-6. These results correlated well with those obtained on Benton and Norman Creeks (fig. 5 and 6).

The differences in predawn radiation temperatures of fine-textured flood-plain soils in the gaining and losing reaches in both summer and winter were generally smaller than the differences for coarse gravelly alluvium. Though the differences were generally smaller, the soils in the gaining reach tended to be warmer than those in the losing reach in the winter and cooler in the summer in more than 50 percent of the surveys.

Airborne Data

Radiometry.--Continuous radiometric traces were obtained on flights along all study reaches. Flights were also made across basins to compare temperature relationships between gaining and losing valleys. The radiometer registered in degrees Celsius, while the graph is continuously recorded in millivolts. Temperatures read from the radiometer were recorded manually on the graph during the flight.

The recorder trace shows variations in heat emission from the ground measured by the radiometer and converted to millivolts by the recorder. The trace represents a strip of ground about 18 ft wide directly under the plane along the flight path.

Three procedures for data analysis were used in studying radiometric temperature traces. The simplest procedure was to overlay the trace of the gaining reach on that of the losing reach as shown in figure 11. A second procedure was to draw cumulative curves based on the voltage levels in the radiometer traces for the gaining and losing reaches. A third procedure was to determine the mean, variance and significance of the radiometer data by standard statistical methods.

Graphical methods

Four radiometric traces from predawn overflights of Logan Creek representative of each of the seasons were selected for comparison in figure 12. Control locations, referenced in figure 12 at the beginning and end of each trace, are shown on figure 13 to indicate the stream reaches compared. Note that the reference temperature is for Bray's Lake (fig. 2) overflown immediately before and after each overflight. Comparison of the graphs indicates

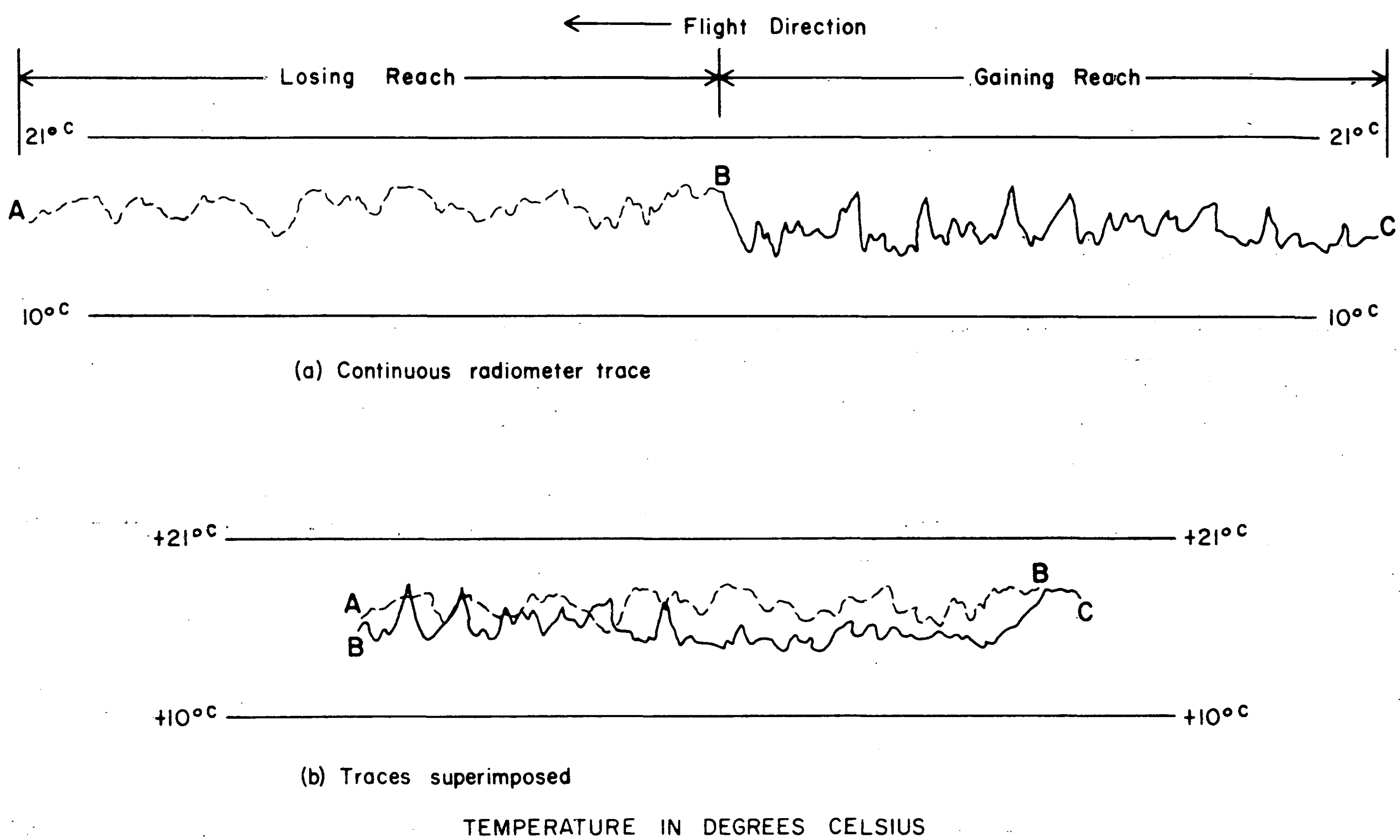
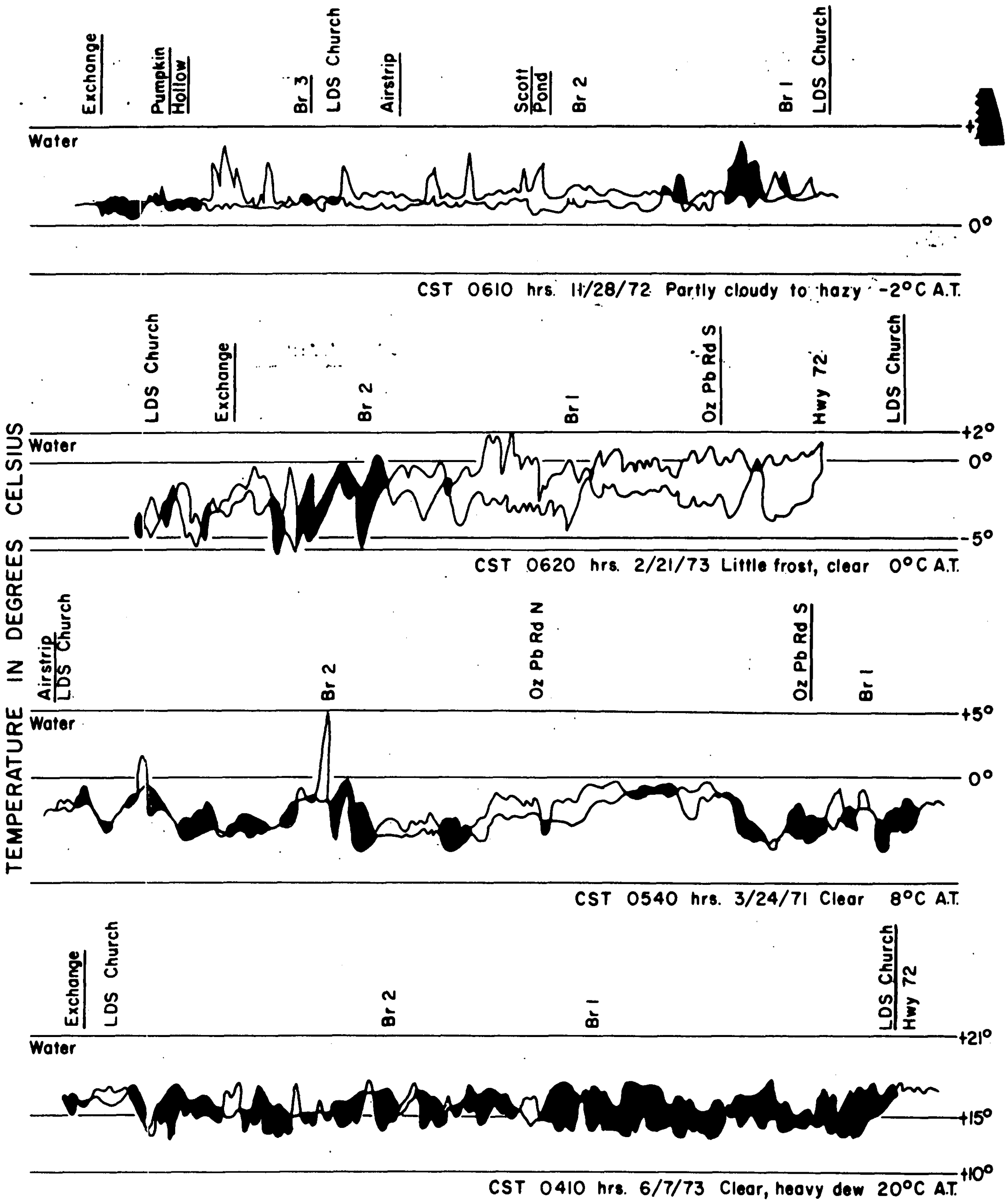


FIGURE 11.--METHOD OF OVERLAYING RADIOMETER TRACES FROM GAINING AND LOSING STREAM REACHES.



■ Downstream (losing) reach warmer than upstream (gaining) reach.

□ Upstream (gaining) reach warmer than downstream (losing) reach.

<u>Exchange</u> Control location downstream. See fig 13

FIGURE 12.--OVERLAYS OF RADIOMETER TRACES FROM PREDAWN LOGAN CREEK FLIGHTS SHOWING LAND-SURFACE TEMPERATURES IN GAINING AND LOSING ENVIRONMENTS.

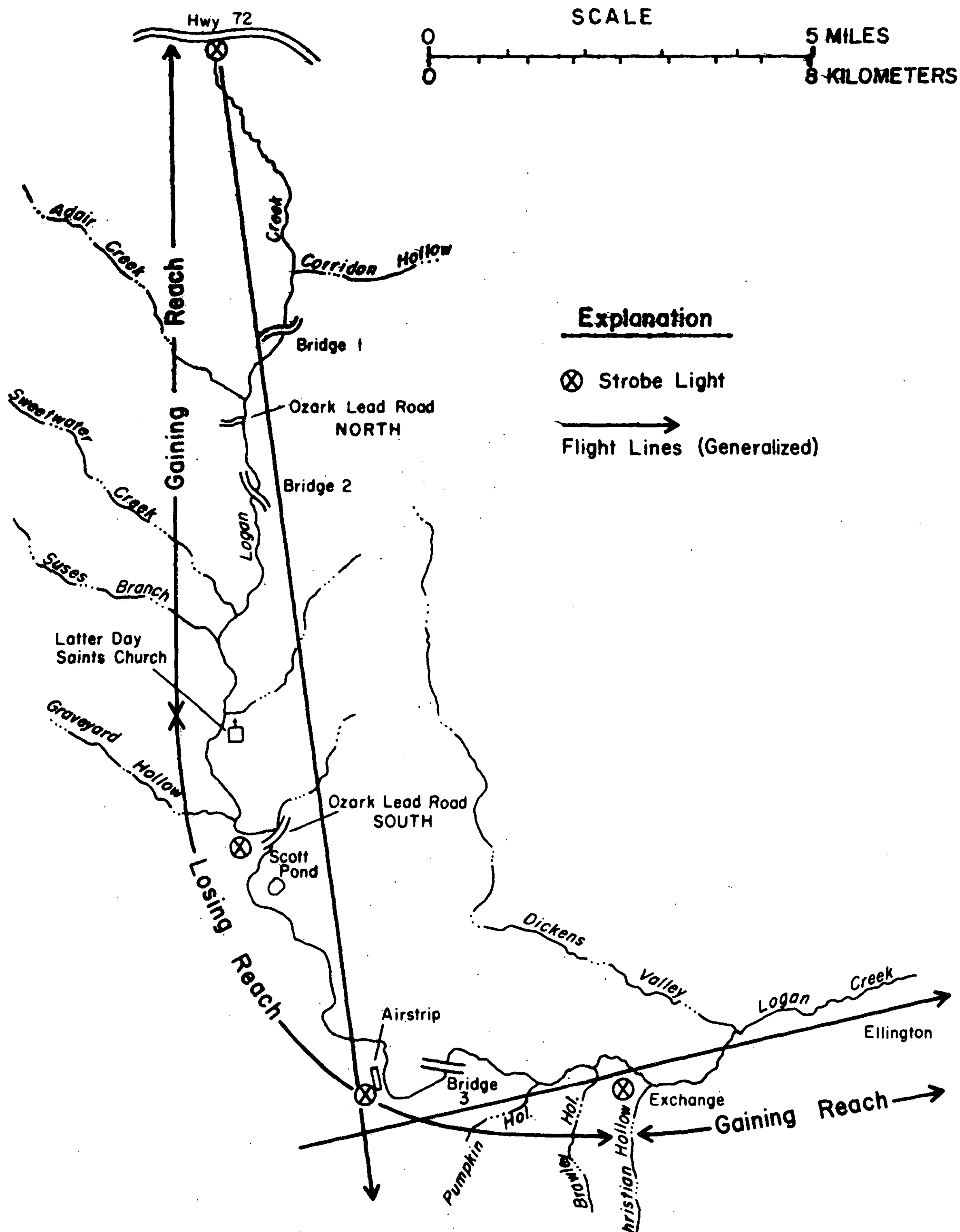


FIGURE 13.--FLIGHT LINES AND LOCATIONS ALONG LOGAN CREEK REFERENCED ON FIGURE 12.

that the emitted energy and temperature of the gaining reach was generally higher than that of the losing reach on November 28, 1972 and February 21, 1973, and lower on June 7, 1973. A comparison of the February trace with that for the March 24, 1971, trace suggests that the March trace was in the spring-crossover thermal pattern.

Peaks occurred in the traces when the plane flew over water. The peaks are more pronounced in the February flight trace than in the June flight trace. This seasonal difference between water and land temperatures agrees with the relationship in figure 9C for ground surveys and with figure 14.

The lower graph of figure 14 is a plot of the differences between predawn radiometric water temperatures and the average predawn radiometric temperature of the various components of the land surface obtained from 21 ground surveys. Included in the average of the various components of the land surface are the measurements for the plots of sand, gravel, soil and grass along both the gaining and losing reaches of the stream.

The graph shows that in winter, land temperatures in predawn hours may be 8°to 14°C colder than water temperatures. In summer they are only 1° to 5°C colder. Therefore, temperature peaks may be more prominent on traces made in the winter.

Table 4 is a summary of the computations made from data acquired during the winter and summer on 18 midday and predawn flights. The tabulation shows that for summer predawn flights losing streams were warmer than gaining streams 70 to 88 percent of the time. In winter, however, gaining streams were warmer than losing streams 60 to 93 percent of the time.

Midday flights were generally less conclusive. In summer, losing streams were warmer than gaining streams 53 to 81 percent of the time. In winter, losing streams were warmer than gaining streams 45 to 52 percent of the time.

While midday flights may seem generally less conclusive, in late summer when the valleys are drier than they are early in the summer, temperature differences between flood plains of gaining and losing streams are greater than they are early in the summer. The following tabulation gives the results of four summer midday flights in clear weather.

	Percentage of time losing reach was warmer than gaining reach
June 21, 1973 - Logan Creek (losing reach versus gaining reach)----------	53
August 28, 1973 - Logan Creek (losing reach versus gaining reach)----------	67
September 14, 1971 - Roubidoux Creek (losing) versus Big Piney River (gaining)----------------------------	73
September 14, 197 - Roubidoux Creek (losing reach) versus Roubidoux (gaining reach)----------------------	81

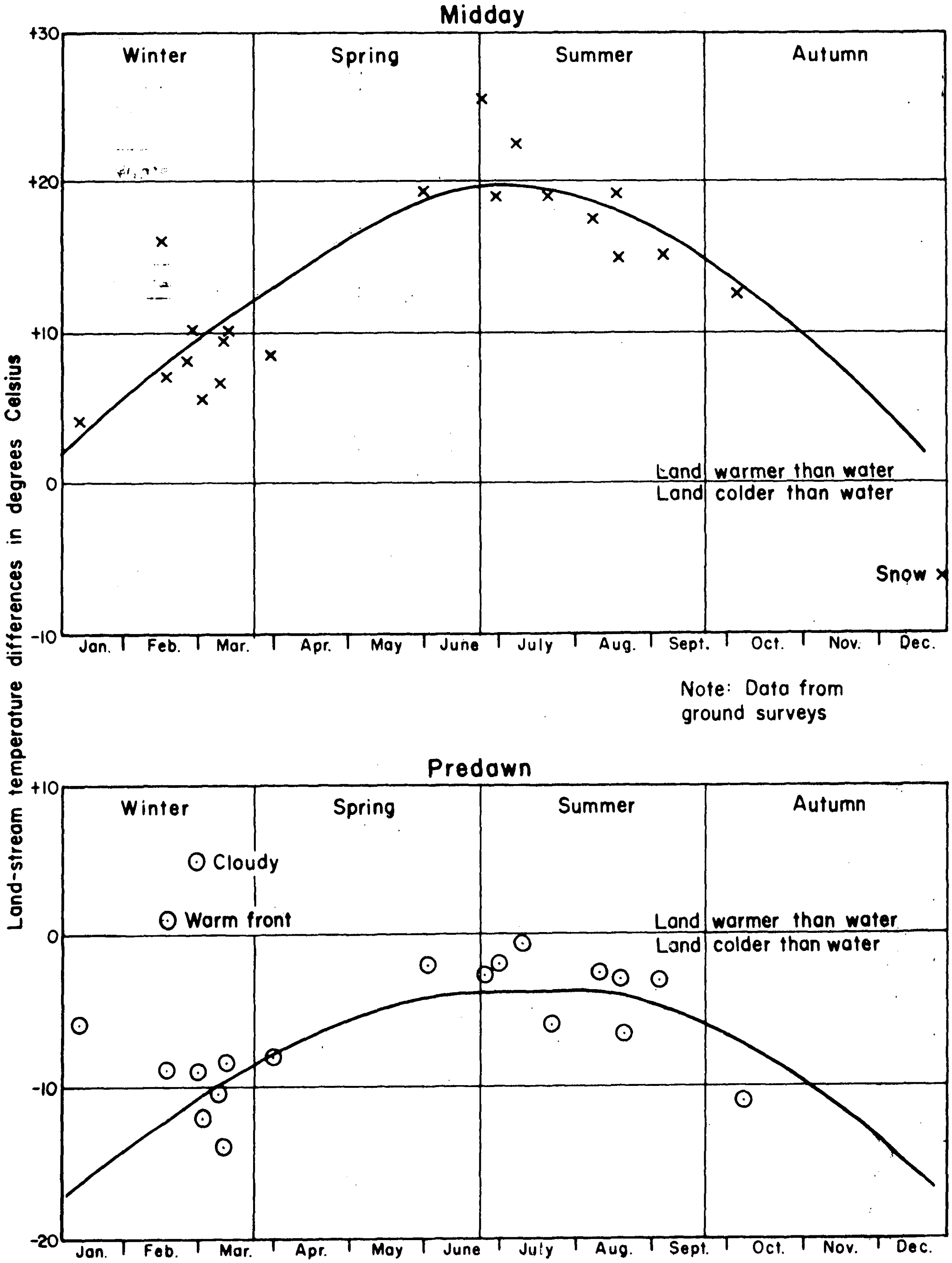


FIGURE 14.--RADIOMETRIC TEMPERATURE DIFFERENCES BETWEEN LAND AND WATER IN THE VALLEYS OF ROUBIDOUX, BENTON, NORMAN AND LOGAN CREEKS.

Table 4.--Percentage of flight paths in which valley of gaining stream is warmer or cooler than valley of losing stream

Season	Time	Streamflow regimen	Thermal level	Percent warmer
Summer-------	Predawn	Gaining / Losing	Warmer	70 to 88
	Midday	Gaining / Losing	Warmer	53 to 81
Winter-------	Predawn	Gaining / Losing	Warmer	60 to 93
	Midday	Gaining / Losing	Inconclusive	45 to 52

These percentages suggest that in June considerable moisture may still be available in the flood plains in all reaches of valleys, whether gaining or losing, but by late summer vegetation stress in the losing reach may be greater and radiation differences are enhanced. Late summer at midday before the autumnal equinox may be an excellent time to obtain thermal data.

Cumulative curves show the seasonal relationships between predawn ground surface temperatures along gaining and losing streams (fig. 15). Overflights of Logan Creek were used to illustrate the relationship because the results of a substantial number of flights with good seasonal distribution were available. The standard method used for constructing cumulative distribution curves is that in Dixon and Massey (1957, p. 10). Comparison of figure 15 with values given in the last column of table 4 shows fairly good agreement. For example, on November 9, 1972, the valley of the gaining reach was considerable warmer than the losing reach (fig. 15) and table 4 shows that in winter 60 to 93 percent of the flight paths over the gaining reaches were warmer than those over the losing reaches. On June 9, 1973, the ground surface in the losing reach was considerably warmer than that in the gaining reach (fig. 15) and table 4 shows that in the summer 70 to 88 percent of the flight paths over the losing reaches were warmer than those over the gaining reaches.

The flood plain of the losing reach of Logan Creek was cooler than the gaining reach on November 9, 1972, and February 21, 1973 (fig. 15). On March 24, 1971, during the crossover period the graph shows the two reaches have similar temperature distributions. The May 4, June 9, and August 28, 1973, graphs show that the losing reach was warmer than the gaining reach. The curve for the flight on August 28, under clear skies, may show the effect of dense haze that occurred that morning in attenuating the signal received by the radiometer. The curves for the gaining and losing reaches on August 28 are much closer together than they were for the June flight which was also made on a clear morning but without appreciable haze.

Statistical analysis

Statistical tests were made on the radiometer traces to define further the differences in the thermal characteristics of losing and gaining streams. The streams or reaches of streams included are shown on figures 2 and 4. Each radiometer trace from both losing and gaining reaches was treated as a number of randomly sampled temperatures expressed in millivolts on the recorder chart. Statistical measures such as average temperature, standard deviation and variance may be used as an aid in determining the environmental components controlling surface temperatures.

The results of these statistical computations are summarized in table 5. As can be seen from review of the table, there are significant differences in predawn temperatures between gaining and losing stream valleys. However, one-half of the losing and gaining reaches sampled for temperatures at midday could not be distinguished statistically on the basis of temperature differences. The statistical tests used for the radiometer data are described in Dixon and Massey (1957, p. 106, 120, and 123). A plot of the mean temperatures of losing versus the gaining reaches of streams (fig. 16) shows

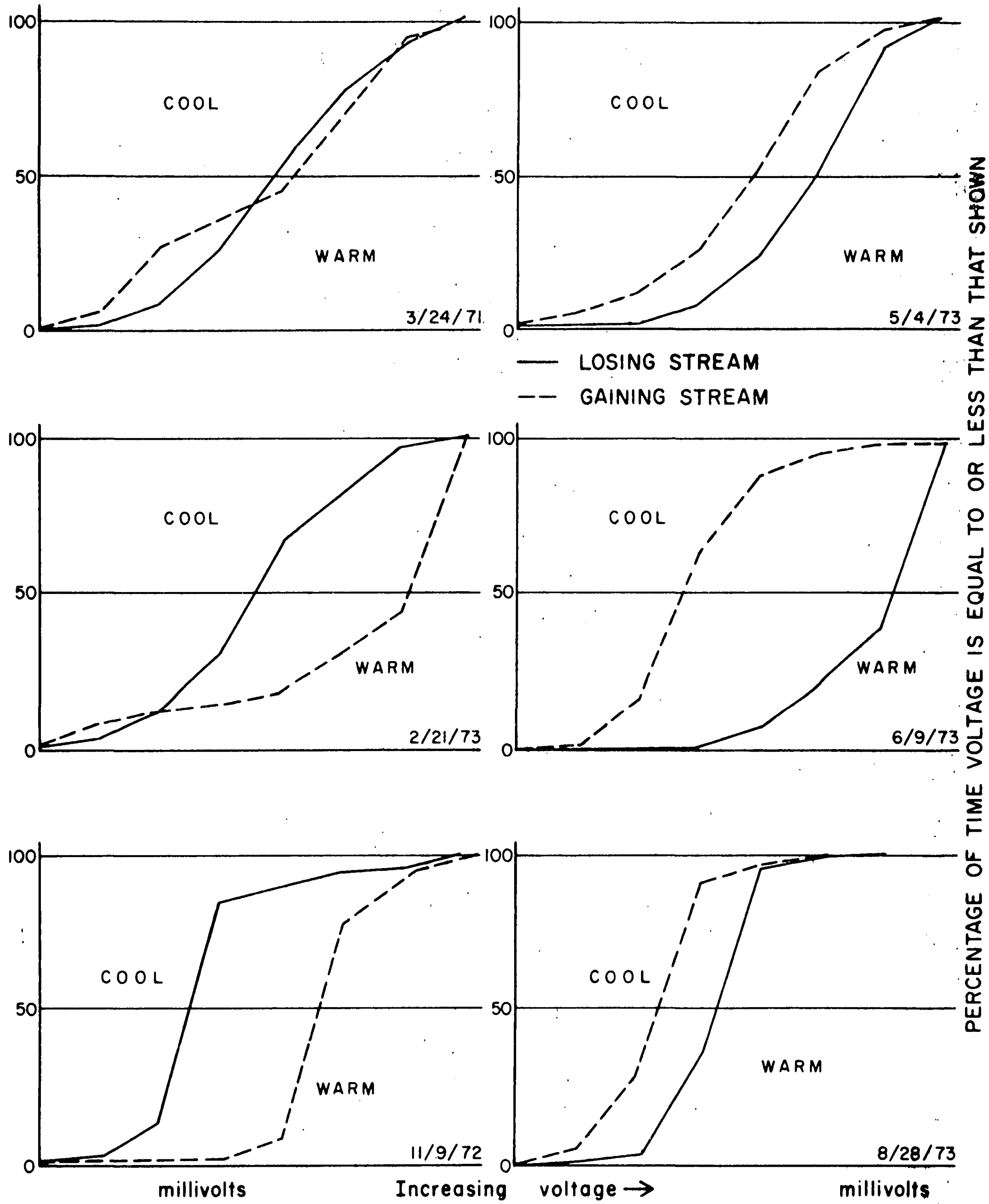


FIGURE 15.--CUMULATIVE CURVES FROM PREDAWN RADIOMETER TRACES SHOWING TEMPERATURE COMPARISONS OF LOSING AND GAINING REACHES OF LOGAN CREEK.

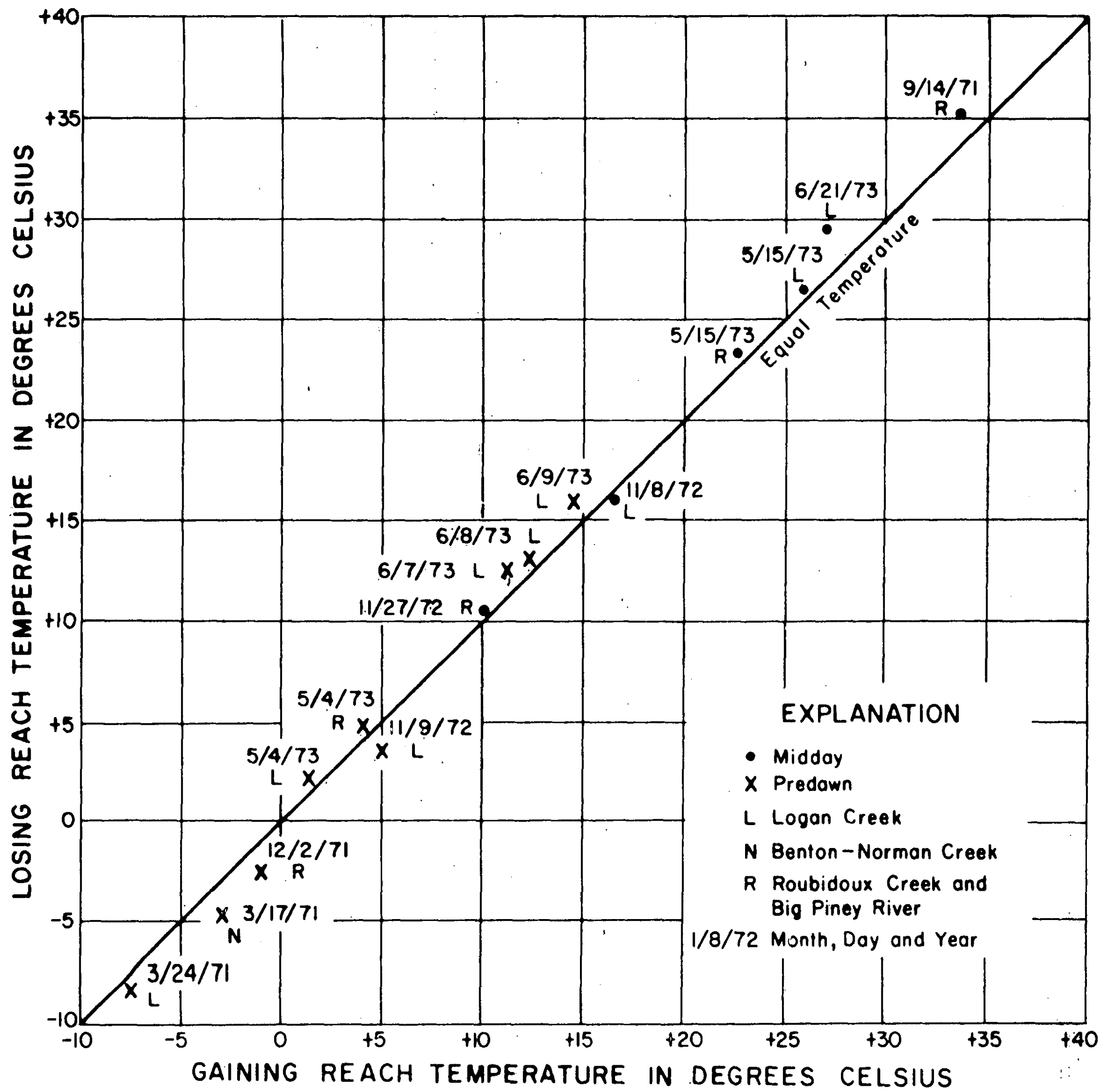


FIGURE 16.--COMPARISON OF MIDDAY AND PREDAWN MEAN RADIOMETRIC TEMPERATURES OF LOSING AND GAINING REACHES.

Table 5.--Means and variances determined from aerial radiometer work

Date	Streams[a]	Mean temperature (°C)[b]		Mean temperature, in millivolts		Variance, in millivolts		Results of F and T tests[d]	
		G	L	G	L[c]	G	L	F	T
Predawn flights:									
11-9-72---	LO	4.0	3.7	71.8	67.2	3.4	8.2	S	S
12-2-71---	R-B.P.	-1.3	-2.3	48.1	45.6	63.0	35.2	S	S
3-17-71---	N-B	-3.9	-4.2	34.4	33.6	13.4	6.1	S	S
3-24-71---	LO	-7.5	-7.9	23.9	22.6	19.3	10.5	S	S
5-4-73----	LO	1.6	2.1	54.5	56.0	13.4	5.5	S	S
5-4-73----	R-B.P.	4.0	4.7	61.4	63.4	38.3	24.9	S	S
6-7-73----	LO	11.5	12.8	19.9	22.9	6.0	4.2	S	S
6-8-73----	LO	12.3	13.3	22.2	24.8	4.6	2.8	S	S
6-9-73----	LO	14.5	16.0	28.1	32.4	4.7	4.9	NS	S
Midday flights:									
11-8-72---	LO	16.5	16.2	14.2	13.5	15.4	14.6	NS	NS
11-27-72--	R-B.P.	10.1	10.6	77.8	79.1	3.6	3.1	NS	S
5-15-73---	LO	25.8	26.5	38.9	40.7	49.3	55.2	S	S
5-15-73---	R-B.P.	22.6	23.4	30.6	32.6	38.5	46.3	NS	S
6-21-73---	LO	27.0	29.5	55.2	61.2	62.0	73.8	NS	S
9-14-71---	R-B.P.	33.6	35.3	61.7	66.6	34.9	67.0	S	S

[a]LO=Logan; R-B.P.-Roubidoux-Big Piney N-B=Norman-Benton.

[b]Due to range and gain settings on the recorder the same millivolt readings might not convert to the same temperature.

[c]G=Gaining; L=Losing.

[d]S indicates that differences between means (T test) and (or) variances (F ratio), are significant at $P \leq .05$. NS differences are not significant.

differences in heating and cooling characteristics. Figure 16 shows that for predawn and midday flights in the warm season, surface temperatures in the losing reaches were higher than along the gaining reaches. For predawn flights in the cold season, the losing reach was colder than the gaining reach. Temperature relations between gaining and losing reaches were inconclusive during the cold season at midday although figure 9A and 9D show some separation between the curves for midday data collected on the ground in that season.

The graph of temperature (millivolt) variance for the late spring and summer midday flights, figure 17, shows that the temperatures for the losing reach have larger variances than the gaining reach (9/14/71 R, 5/15/73 R, 5/15/73 L, 6/21/73 L). The probable reason is that the assumed greater midday evapotranspiration rate in a gaining reach exerts a greater cooling effect on many of the components in the scene as compared to a losing reach. Also, heat flux from solar radiation into the ground profile is greater in gaining reaches owing to the shallow depth to the water table in such areas, the high specific heat of water, and higher heat conductivity of wet soils. This tends to attenuate diurnal temperature fluctuations in gaining reaches. In winter the variances of losing and gaining reaches are generally small.

In predawn, however, the presence of streamflow is probably the cause of greater variances in gaining reaches (fig. 17) because the water is considerably warmer than the land surface in all seasons especially in the winter (fig. 14). Streamflow normally is not present in the losing reach so that only ponds influence the data. As the radiometer views the water numerous times in the gaining reach, the voltage peaks occurring each time the stream is crossed enter into the statistics to increase the variance of the gaining reach.

The predawn surface-temperature variance generally will be more affected by the presence of surface water in the winter than in the summer as the graph figure 14 shows. Thus, the variance of the gaining reach for the December 2, 1971, predawn flight (fig. 17) is the largest and those for the summer are usually small.

The effect of water on variances is greater at midday in the summer than it is in winter (fig. 14). On clear days land is generally warmer than water at midday in all seasons provided that the ground is not frozen or covered by snow or ice. Midday land-water temperature differences on clear days in the winter ranged from 5° to 10°C, while in the summer the differences were 15° to 25°C . Temperature differences due to slope direction, land use, fertility, and other factors result in emitted energy variations that far outweigh the effects caused by the occasional viewing of water. The effect of water on variances was greater at predawn in the winter and at midday in the summer than it was at predawn in the summer and at midday in the winter.

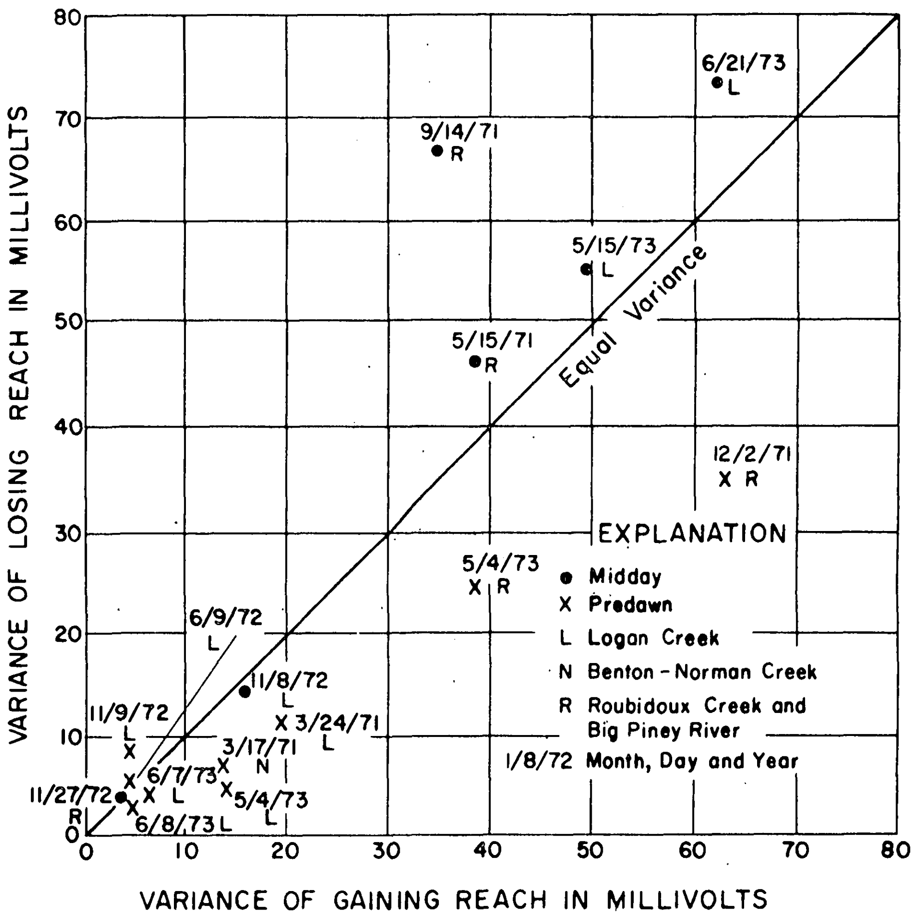


FIGURE 17.--COMPARISON OF MIDDAY AND PREDAWN VARIANCES IN RADIOMETRIC TEMPERATURES (MILLIVOLTS) OF LOSING AND GAINING REACHES.

Figure 18 shows four radiometer traces of the gaining reach of Logan Creek from flights made at predawn and midday in late spring and winter. The traces illustrate the amplitude of temperature variations in the two seasons and the relationship of land and water temperatures. The reference temperature for water shown on each of the graphs is that of Bray's Lake (fig. 2), which was overflown before and after each flight. Stream temperatures are usually a degree or two warmer in the winter and cooler in the summer than the lake temperature references shown (titled "water").

The radiometer needle often registered a lower midday or higher predawn water temperature than the trace exhibits because of the time lag between the radiometer and recorder trace as the plane crossed a narrow creek. However, for broad fields and forests the time lag for recorder response was a problem for only a short distance after entering a new field having a different temperature. The variances shown in table 5 and figure 17 would be larger if the recorder had had time to reach the true water temperature.

Data collected on magnetic tape from the predawn flight on March 7, 1972, were used by Robert Dye and Richard Blythe, Bendix staff scientists, in a statistical analysis of the gaining and losing reaches of Logan Creek. The data analyzed were apparent temperature samples from a series of adjacent scan lines extending across the entire width of imagery including valley and slopes. The following is a quotation from a letter report by Richard Blythe (Dec. 8, 1972) concerning the statistical analysis of part of the predawn imagery obtained from Logan Creek.

"The...Training Sets - Scatter Diagram [figure 19, upper part], show the distribution of the points calculated by canonical analysis from a training area upstream of the Latter Day Saints Church [figure 13] (marked A) and a corresponding plot of the data from a downstream area (marked B)." The training sets or training areas are sections of thermal imagery consisting of a large number of scan lines. The scatter diagrams are visual displays of variances.

"The physical reasons for this difference may require considerable study, but it is quite evident from these diagrams that the distribution of the emitted thermal energies from the two areas is different, and the difference is quite marked. We could not observe this on the original imagery..."

"The following scatter diagrams, labelled SCAT II, [figure 19, lower part] contain other areas of the gaining reaches (A), and losing reaches (B) plotted using the coefficients from the training set scatter diagram to make the separations. This augurs well for the use of statistical analysis to actually find gaining and losing stream reaches on an area basis."

Although the data on variance appear to conflict with results of statistical analysis of the radiometer data[high predawn variance in the losing reach in late winter based on scanner data versus low predawn variance based on radiometer data (fig. 17)], note the tremendous difference in sample size between the scanner and radiometer. The scanner samples about three orders of magnitude more data points than does the radiometer. Thus, the effect of

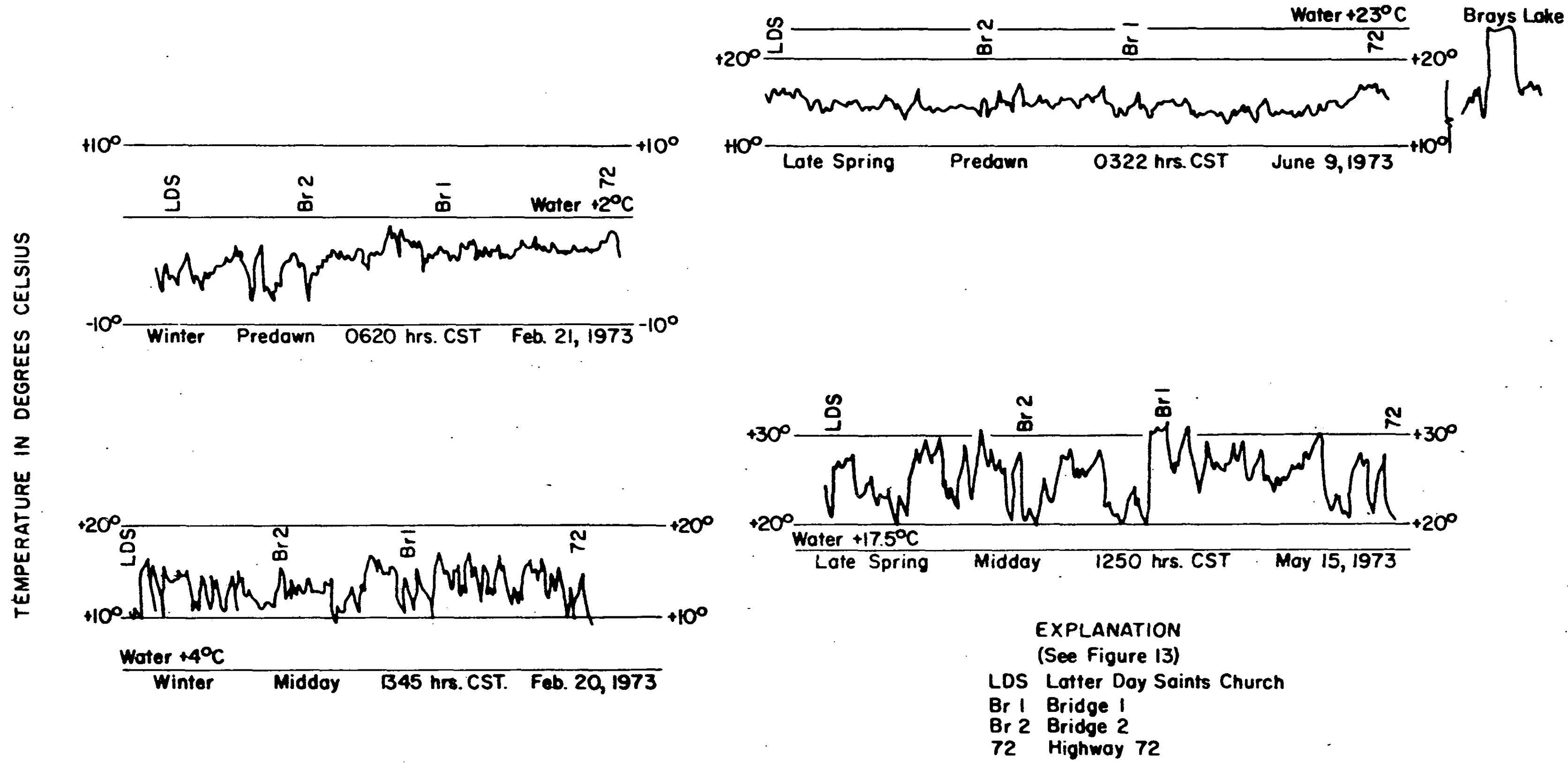


FIGURE 18.--TYPICAL RADIOMETER TRACES OF THE GAINING REACH OF LOGAN CREEK.

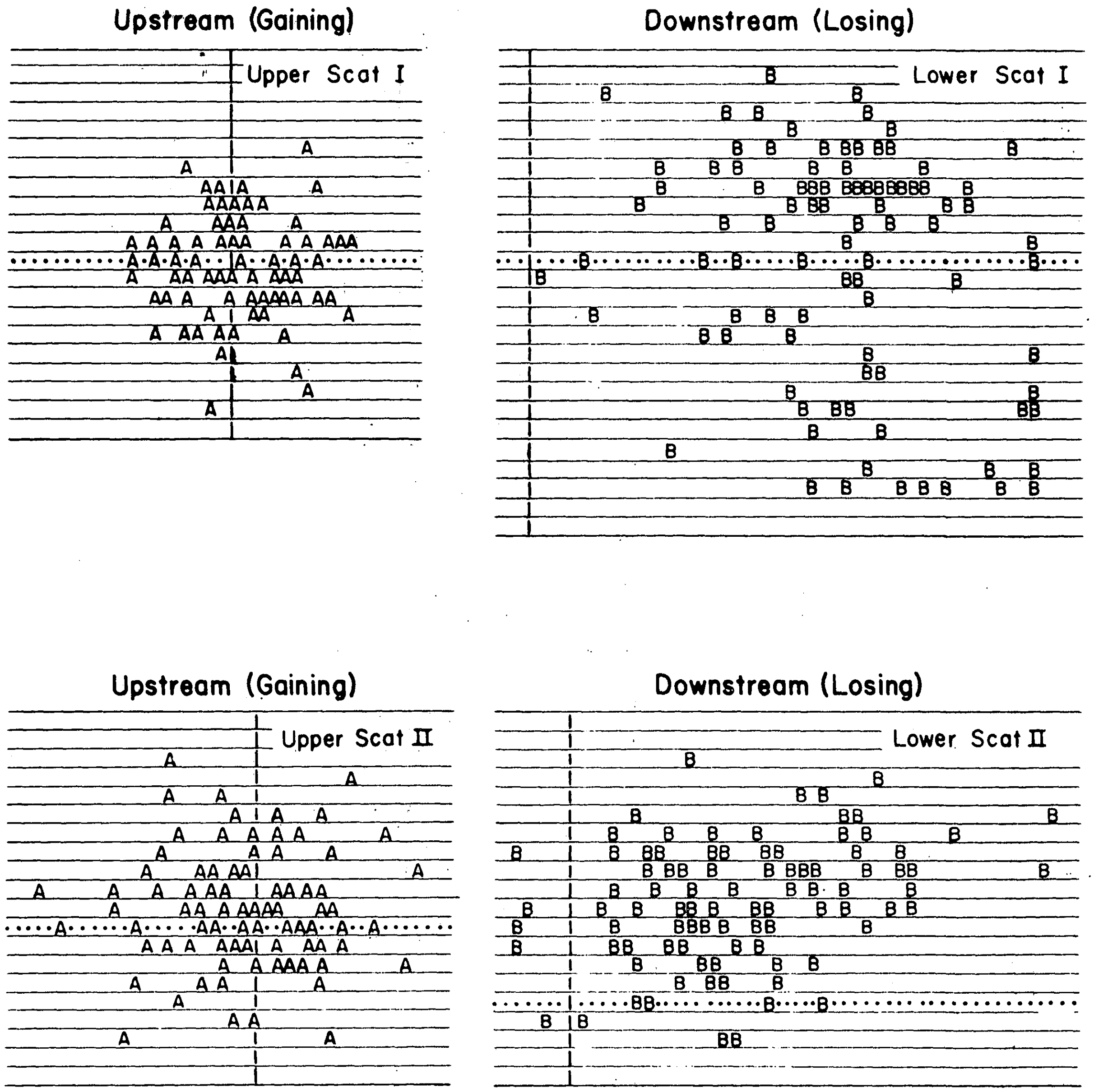


FIGURE 19.--TRAINING SETS - SCATTER DIAGRAMS FOR PREDAWN IMAGERY OF LOGAN CREEK, MARCH 8, 1972.

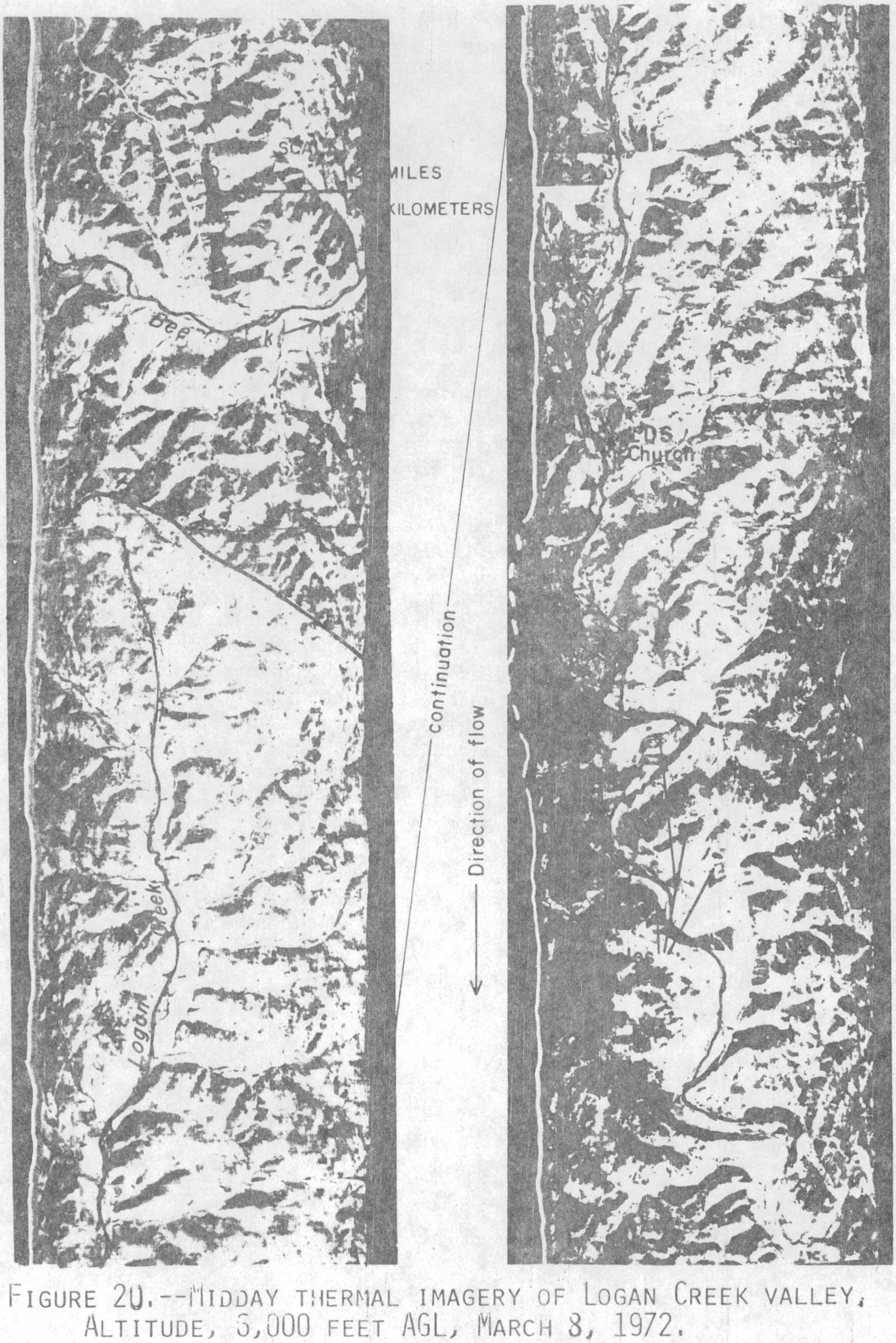


FIGURE 20.--MIDDAY THERMAL IMAGERY OF LOGAN CREEK VALLEY, ALTITUDE, 6,000 FEET AGL, MARCH 8, 1972.

warm surface-water temperatures on statistical analysis of the radiometer data is greater than it is on the scanner data. The radiometer data are biased by the effect of water. However, radiometer data statistics, though biased, are useful in comparing thermal data from one season with that from another and for various times of the day and night.

Imagery

Logan Creek, March 7 and 8, 1972 flights

Losing and gaining reaches of Logan Creek could not be differentiated by visual analysis of predawn, midday and postsunset thermal imagery. The topography and vegetation in the two reaches have similarities but riparian vegetation is much more abundant in the upstream gaining reach than it is in the losing reach. The ground and aerial radiometer surveys made before and after the flights indicated that the imagery was collected too near the spring transition for visual discrimination of gaining and losing streams, and statistical analysis of the imagery was necessary for interpretation. Dye and Blythe's statistical analysis revealed that a significant difference did exist in land-temperature variances in the two reaches even though no visual difference in the imagery was apparent.

Thermal imagery of Bee Fork basin and Logan Creek was obtained at midday on March 8, 1972, from an altitude of 6,000 ft. (See figure 20.) The location of the imagery is shown on figure 21. Missouri State Highway 72 follows the divide between the two basins. Bee Fork is a perennial, gaining stream throughout its length occupying a narrow valley between steep forested slopes. Logan Creek is perennial down to the Latter Day Saints Church and loses its flow at that location. It is believed the contrast between the two basins is due to lower thermal emission (dark tones) from the forested steep slopes of Bee Fork, a thoroughly dissected basin characteristic of a gaining stream, and higher thermal emission (light tones) from the more open, less forested Logan Creek basin. Here the interpretation of gaining and losing streams is determined by shadowing due to relief, not by temperature differences of the flood plain.

A feature of the postsunset imagery from the March 7, 1972, Logan Creek-Current River flight, altitude 3,000 AGL, is the strong contrast between the valleys (dark tones - cold) and ridges (light tones - warm) in the Logan Creek basin (losing) and the small contrast between valleys and ridges of the Current River basin (gaining). (See figure 22.)

On the following predawn imagery of March 8, 1972 (fig. 22), of approximately the same flight line the valleys in the Current River basin (gaining) still have light tones (warm) but the adjacent high ridge areas now have dark tones (cool). The light tone extends for several miles across the valleys and adjacent low ridges. Along Logan Creek (losing) and Dickens Valley

FIGURE 21.--INDEX MAP OF THERMAL IMAGERY DISCUSSED IN THE TEXT.

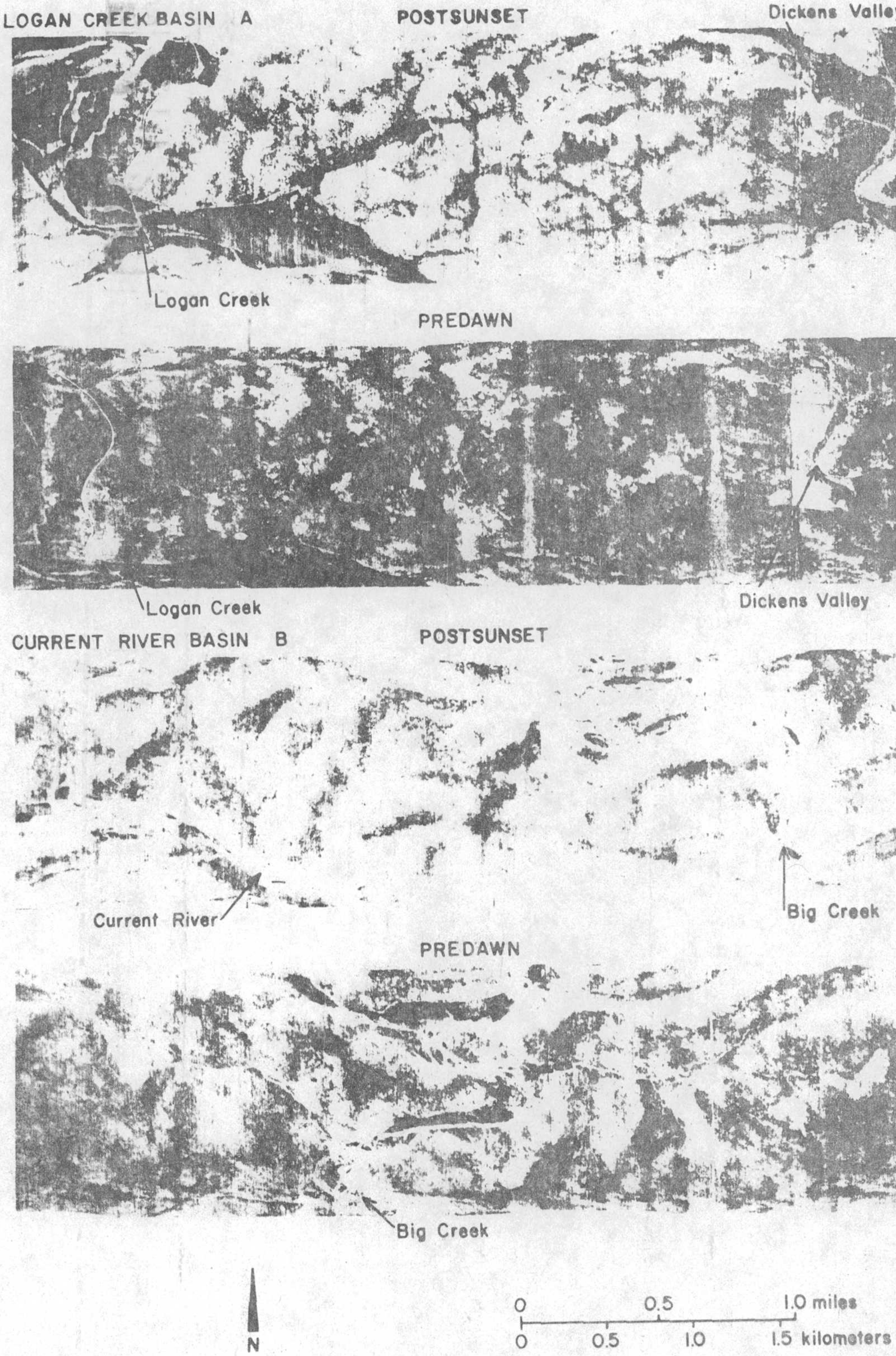


FIGURE 22.--POSTSUNSET AND PREDAWN THERMAL IMAGERY OF LOGAN CREEK-CURRENT RIVER FLIGHTS. ALTITUDE, 3,000 FEET AGL, MARCH 7 AND 8, 1972.

(losing), flood plains appear as dark (cool) features. Also, there is little contrast on the imagery between the ridges and valleys of the Logan Creek basin. This suggests that Logan Creek basin, its valleys and ridges, considered collectively, cooled more between the two flights than the Current River basin. One possible explanation for the overall predawn cooling pattern of the basins may be that the higher ground-water levels and gaining streams of the Current River basin result in greater thermal inertia in the Current River basin and more heat flow toward the valley floor, mitigating the influence of cold air drainage and outgoing radiation losses.

Logan Creek - June 21 and 22, 1973 flights

The postsunset (2030 h central standard time) and predawn (0400 h central standard time) thermal imagery of Logan Creek obtained on June 21 and 22, 1973, from an altitude of 3,500 ft AGL, showed that the flood plain of the gaining reach is darker (cooler) than that of the losing reach (fig. 23). The predawn imagery shows the same relationship as the predawn radiometer flights of June 7 and 9 (fig. 12 and 15).

The flood plain of the gaining reach is distinct at postsunset while the flood plain of the losing reach is indistinct. At predawn, the flood plain of the gaining reach is indistinct while that of the losing reach is distinct. The relationship to temperature levels is given in the table below.

	Postsunset		Predawn	
	Upstream (gaining)	Downstream (losing)	Upstream (gaining)	Downstream (losing)
Temperature----------	Cold	Warm	Cold	Warm
Thermal contrast-----	Distinct	Indistinct	Indistinct	Distinct

Dry-weather streamflow normally disappears into the channel at the Latter Day Saints Church. Also, depth to ground water increases markedly about 1 mi downstream from the church. Even though surface flow extended about 1.3 mi downstream from the church at the time of the flight, the flow did not noticeably affect the gross thermal character of the losing reach.

In the June 21 and 22 postsunset and predawn imagery, tributaries entering Logan Creek in the gaining reach are more distinct than those entering the creek in the losing reach. That is, the uplands adjacent to tributary valleys are lighter (warmer) than the valleys which are darker (cooler) in both the gaining and losing reaches but the contrast is greater in the gaining reach than in the losing reach. At the time of the flights, the downstream tributaries were dry while most tributaries of the upstream gaining reach were damp or had trickles of flow. Thus, the downstream part of the basin, as a whole, is dryer than the upstream part of the basin and losses

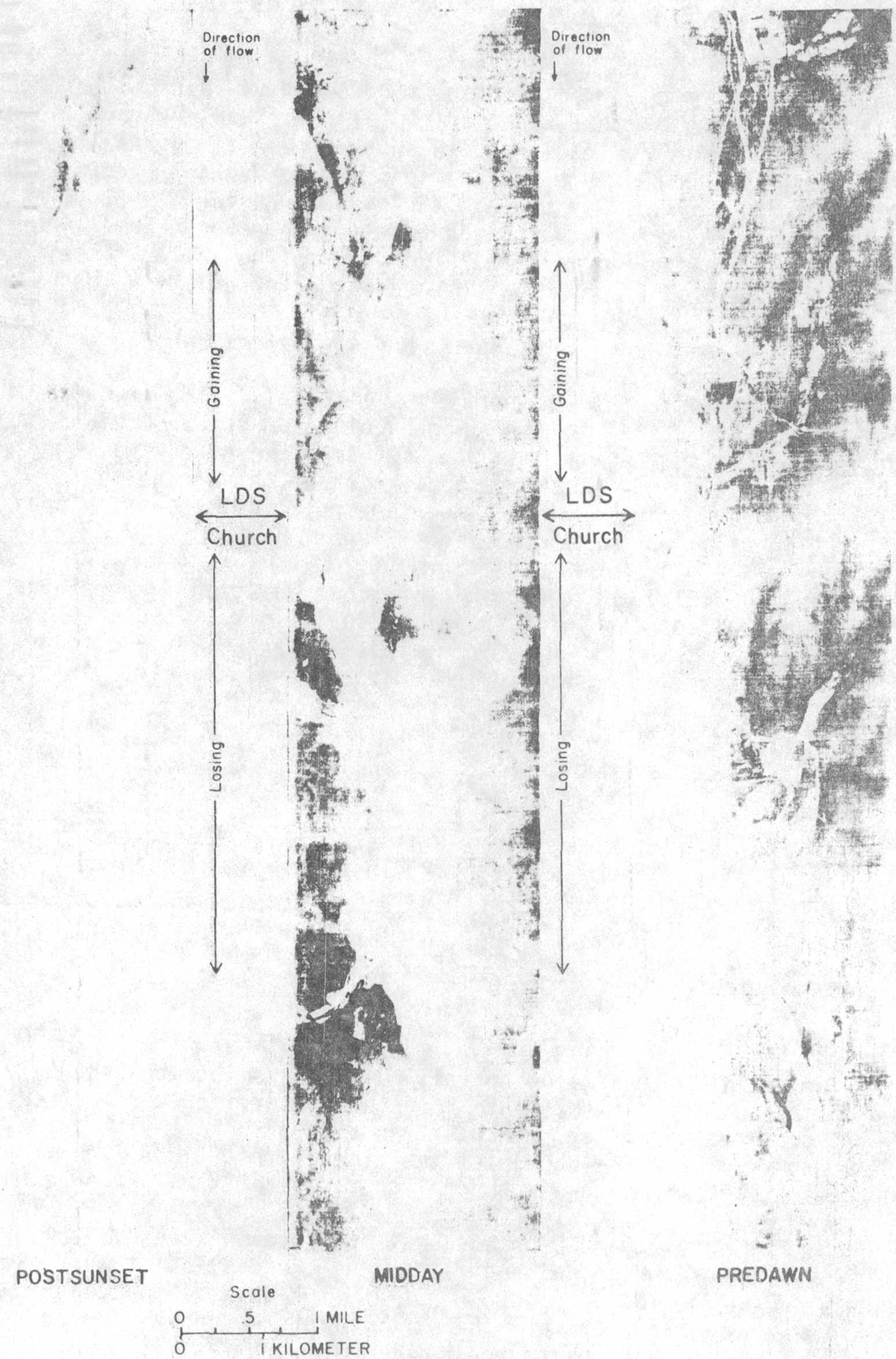


FIGURE 23.--POSTSUNSET, MIDDAY AND PREDAWN THERMAL IMAGERY OF LOGAN CREEK. ALTITUDE, 3,500 FEET AGL, JUNE 21 AND 22, 1973.

are not confined to the mainstem. Rather, loss in flow in the mainstem and the dryness of the tributaries in the losing reach suggest that deficiency of water is a characteristic of the lower part of the basin, not just the mainstem channel.

On the midday imagery, the temperature relation of the upstream (gaining) and downstream (losing) reaches in Logan Creek is obscure due to various factors. Scattered clouds, (the dark areas on the imagery), uneven solar heating, crop cover, grazing and hay cutting in the pastures, and evapotranspiration cause a variety of gray tones in the scene. During the night these factors are largely mitigated so that the hydrologic conditions exert measureable influence on the image tone.

Another factor to consider is the distribution of riparian vegetation such as willows, birches, alders, sedges, grapes and other water-loving vegetation. In the gaining reach of the stream where phreatophytes are abundant and low swampy areas exist, dark (cold) tones occur. In the losing reach dark tones due to phreatophytes are less prominent because the moisture levels are too low to sustain them and the farmer is able to keep the banks clear. Cultivation to the banks of the stream may result in severe bank erosion. In extending pastures to the banks of the stream the battle against phreatophytes is a never-ending one in the gaining reach of the stream and an easy one in the losing reach.

Postsunset and predawn thermal imagery from the June flights did not show the tonal distinction between the losing reach extending from bridge 3 to Exchange (fig. 13) and the gaining reach that begins at Exchange and extends downstream to Ellington. One of the reasons may be that the water table is nearer land surface and losses are not as severe between bridge 3 and Exchange as they are in the losing reach between the Latter Day Saints Church and the airstrip. At the time of the June flights, Logan Creek was not flowing in the losing reach upstream from Exchange. Pumpkin and Brawley Hollows which join Logan Creek on the right bank in the losing reach (fig. 13) were both dry and Christian Hollow which joins Logan Creek at Exchange had a discharge of 0.3 ft^3/s. Logan Creek at its junction with Dickens Valley had a discharge of 3.0 ft^3/s. These facts suggest that the depth to the water table was shallow.

Observations of discharge on November 27, 1973, in Logan Creek contribute evidence that is pertinent to interpretation of the thermal regimen of the valley (no imagery or radiometric data were obtained at this time). The gaining reach from the headwaters to the Latter Day Saints Church (fig. 13) had a discharge of 206 ft^3/s of flow while less than 5 ft^3/s was flowing at bridge 3. Around the bend to the east near Pumpkin Hollow, discharge was estimated at about 10 ft^3/s and it increased downstream to 20 to 30 ft^3/s at the confluence with Dickens Valley (fig. 13). At Ellington the flow was estimated to be 50 to 75 ft^3/s. While the reach between the Latter Day Saints Church and bridge 3 was losing 200 ft^3/s, the flow in the reach downstream from bridge 3 was increasing about 50 ft^3/s.

The three tributaries, Pumpkin, Brawley and Christian Hollows generally cease to flow after a significant rain (fig. 13). Flow ceases first in Pumpkin Hollow followed by Brawley and then Christian in that order. Thus, the area of deficient flow and abnormally deep water levels shown on figure 4 may be compared to a large drawdown cone around a pumping well whose boundaries expand and contract with variations in ground-water supply depending on precipitation and the season.

SPRINGFIELD PLATEAU STUDY AREA

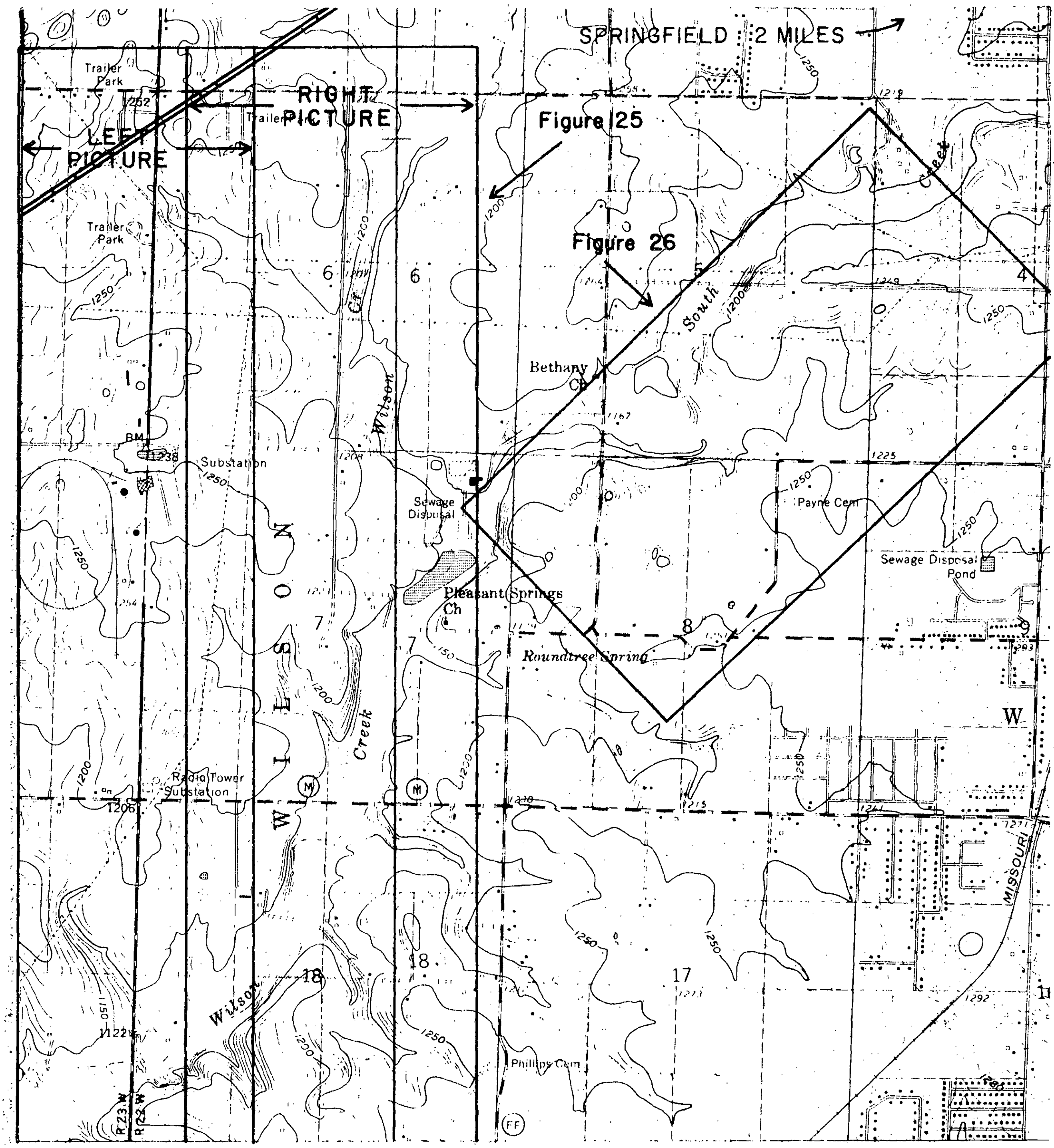
Imagery and Photography - March 8-9, 1972 Flights

The principal reasons for obtaining thermal imagery and photography in the Springfield area were (1) to locate incipient sinkholes, (2) to recognize joint patterns and fault zones, and (3) to determine losing and gaining reaches of streams.

Early ground and aerial radiometer surveys, study of valley characteristics and alluvial thicknesses, and recognition of well-defined points of streamflow losses, indicated that use of thermal imagery in identification of losing streams might be less successful for the Springfield Plateau than it would be for the Salem Plateau. Flood-plain boundaries on the Springfield Plateau are not as prominent as those on the Salem Plateau, and the uplands gradually merge with the flood plains of the streams often without an abrupt change in slope. Relief is generally low. Figure 24 is a map of Wilson Creek and environs southwest of Springfield showing thermal imagery discussed in the report.

Sinkhole detection.--Thermal imagery shown in figure 25 was obtained at midday on March 9, 1972, from an altitude of 1,600 ft AGL. Most sinkholes with topographic expression could be located by combined study of stereophotographic pairs and daytime and nighttime thermal imagery. Sinkholes were fairly easy to detect in fields of uniform vegetative cover; however, even some sinkholes with topographic expression were rather difficult to detect in fields that contained tonal anomalies due to non-uniform vegetative cover.

Some thermal anomalies having the round or elliptical configuration of a sinkhole proved to be formed as the result of farming practices. For example, feeding cattle by throwing feed in all directions from a wagon led to thick growths of Bermuda grass in circular plots surrounded by fescue and orchard grass (D, fig. 25). The growths of Bermuda grass appeared on midday thermal imagery as a series of pale grey (warm) circles suggestive of sinkholes in a dark grey (cold) field. Vegetative variations may be due to differences in soil texture and moisture and can have sink-like patterns in a relatively flat terrain. Some of these may be incipient sinks. Sinkholes in wooded areas are less easily recognized than those in cleared areas. However, they can frequently be recognized in deciduous woods when the trees are dormant.



Base from U.S. Geological Survey
Brookline 7 1/2' 1960 Quadrangle
Springfield 7 1/2' 1960 Quadrangle

0 — 1 MILE
0 — 1 KILOMETER

FIGURE 24.--INDEX MAP OF THERMAL IMAGERY OF SPRINGIELD AREA.

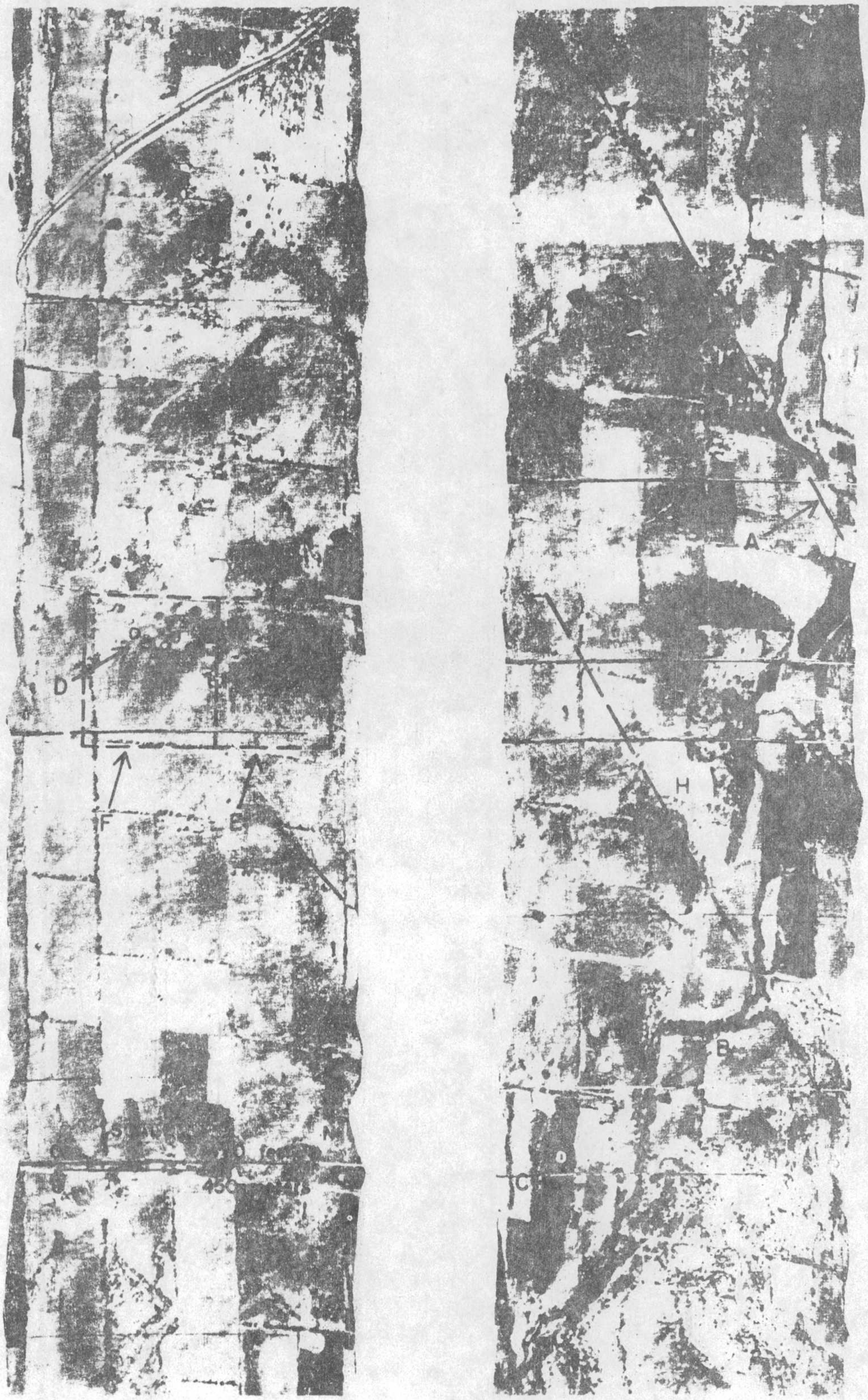


Figure 25.--Midday thermal imagery showing joints and sinkholes along Wilson Creek southwest of Springfield, Mo. Altitude, 1,600 feet AGL, March 9, 1972.

Earth-filled sinks with little or no topographic expression, located when test drilling for a power plant site near the city of Springfield, were not recognized on either the imagery (E, fig. 25) or the photographs. Faint thermal anomalies examined on the ground in the 40 acres to the west of the plant site (F, fig. 25) were very shallow, almost imperceptible depressions less than 1 ft in depth. Because it is an area of intensive sinkhole development, even the very shallow depressions should be suspect. Test drilling would be needed to prove whether or not they are sinkholes.

Joint detection.--Recognition of major joint trends and their relation to the development of incipient sinks is important to construction activities. A prominent set of northwest-trending joints is well displayed where they cross Wilson Creek (G, H, fig. 25). A second set strikes northeast paralleling Wilson Creek in several reaches. Exploration trenches dug with a backhoe were oriented to cross the joint (H, fig. 25). The trenches located several small, 1- to 6-ft diameter, cavernous openings at the soil-bedrock interface. No surface expression of the cavernous openings was detected on either the photographs or imagery.

Channel gain and loss detection.--Although Wilson Creek loses water at several places along its length it usually has continuous flow. No indication of the losing character of the stream is apparent in the March imagery (fig. 25). Wilson Creek is in the right-hand strip of imagery in the figure. Losses of as much as 5 to 10 ft^3/s occur at the two points marked A and B. At A the loss is into fissures in the bed of the stream while some of the surface flow continues past the fracture zone. At B the loss is into a sinkhole on the east bank. Here again, some surface flow continues downstream past the point of loss. Dye traces showed that water lost at A and B emerges at C, a downstream spring (Harvey and Skelton, 1968).

A tributary of South Creek (fig. 26) showed up most clearly as a dark (cold) tone on postsunset imagery. The stream flows only during heavy rains. The valley is poorly defined on midday March imagery because of differential heating patterns that obscure the trace of the valley. The stream was not overflown in the predawn flight. Terrell Creek was recognized on photographs as an interrupted stream because of cessation of flow and later field checking indicated that it is a losing stream. Pond Creek is an interrupted stream in extremely dry weather; however, at the time of the March flights streamflow was continuous. The use of imagery and photographs for hydrologic analysis of Pond Creek would have lead one to conclude it was a gaining stream.

Imagery and Photography-June 20 and 21, 1973 Flights

Sinkhole detection.--Photographs and thermal imagery collected in June were more useful for identification of sinkholes in open fields than that obtained in March because of the luxuriant growth of grass in the sinkholes. On thermal-infrared imagery, very shallow sinkholes, without ponds, are usually more easily discerned on predawn imagery than on postsunset and

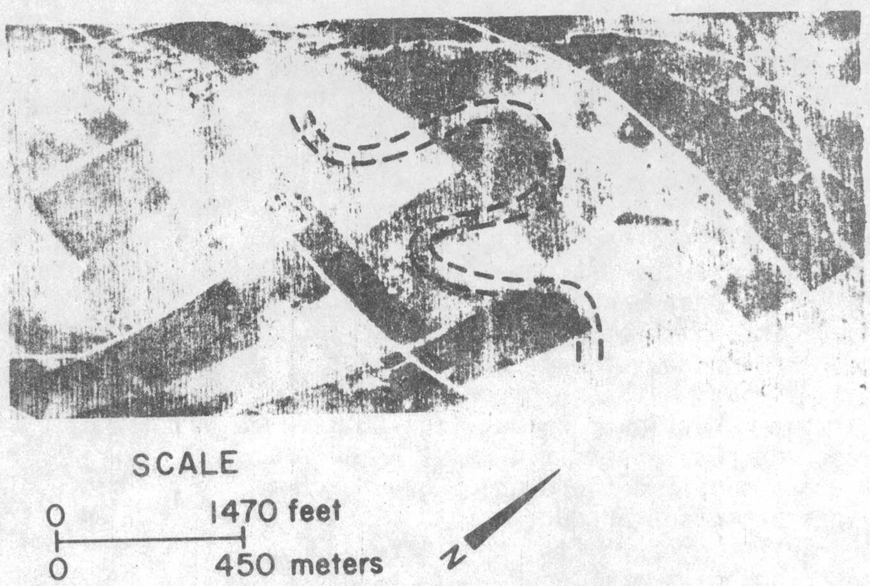


FIGURE 26.--POSTSUNSET THERMAL IMAGERY SHOWING A LOSING STREAM, TRIBUTARY TO WILSON CREEK, IN VICINITY OF SOUTHWEST TREATMENT WORKS, SPRINGFIELD, MO. ALTITUDE 1,600 FEET AGL, MARCH 8, 1972.

midday imagery. Sinkholes appeared bright pink on color-infrared photographs and contrast with the pale to brownish pink colors of the surrounding fields. In color photographs, vegetation in the sinkholes appeared bright green contrasting with the dull green of the surrounding field. Stereopairs of either color or color-infrared film are useful in locating sinks with relief greater than a few feet. Depressions with less relief were difficult to detect because contrast with the soil and vegetation of the surrounding land surface was minimal.

Investigation of sinkholes in a 20-acre pasture of uniform growth using color and color-infrared photographs and thermal imagery disclosed nine sinkholes of which three were shown on a topographic map with a 10-ft contour interval. The other six ranged from 1 ft to 8 to 10 ft in depth. On color and color-infrared photographs from 8,000 ft AGL only the deepest sinkhole, 35 ft deep, in the 20-acre pasture could be definitely verified using a steroviewer. In other nearby fields, with photographic coverage obtained from 1,600 ft, shallow sinkholes were more easily distinguished using color and color-infrared photographs than on predawn, midday, or postsunset imagery.

Channel gain and loss detection.--Study of the June imagery shows that the flood plain of the losing reach of Terrell Creek is warmer than that of the gaining reach on predawn and postsunset thermal imagery. At the time of the flight, Terrell Creek had continuous flow. Land surface tonal contrasts and flood plains were more distinct on predawn imagery than on midday and postsunset imagery.

Pond Creek was flowing through the losing reach at the time of the June flights. As in March, Pond Creek did not show evidence of being a losing stream. Similarly, Wilson Creek (fig. 25) showed no evidence of being a losing stream. The tributary of South Creek which had the tonal character of a losing stream on the postsunset March imagery had been excavated along its length for a sewer line prior to the June flight. The alteration of the natural condition probably resulted in loss of the natural tonal character of the valley due to vegetation changes, dirt moving, and drainage alterations.

CONCLUSIONS

1. Thermal differences were used to discriminate between gaining and losing reaches of karst stream valleys on the Salem and Springfield Plateaus of the Ozarks in Missouri. However, the degree to which some streams lose water may be temporally or spatially so slight that discrimination of losing and gaining conditions may be unsuccessful.

2. The use of a radiometer on the ground and aboard a light aircraft is an excellent tool for determining the most appropriate periods for scheduling thermal imagery flights. Such radiometric data in itself may be useful in evaluation of hydrologic conditions in other karst areas.

3. For acquiring hydrologic information thermal imagery obtained in the study area in June was preferable to that obtained in March. Imagery obtained in March was superior to that obtained in June for identifying faults and joint systems. The best periods in the day to acquire imagery are during summer and winter predawn hours and in late summer at midday during periods of moisture stress.

4. The physiographic character of the Salem Plateau is more favorable than that of the Springfield Plateau for the discrimination of gaining and losing reaches of streams by analysis of thermal data.

5. Topographic relief, due to its influence on air movement in the valley, apparently is an important factor in intensifying thermal anomalies. Logan Creek on the Salem Plateau showed the most distinct tonal contrasts between gaining and losing reaches of all valleys studied. Topographic relief is 200 ft between the bluffs and the flood plain, water-table relief is 200 ft, and flood-plain boundaries were distinct.

   Along Terrell Creek on the Springfield Plateau, topographic relief is 100 ft, the water table is relatively uniform, the flood plain is less distinct and the tonal range is less than it is on Logan Creek. Topographic relief along Pond Creek, also on the Springfield Plateau, is 50 ft, the water table is relatively flat, the flood plain is poorly defined on the imagery, and there is no visual thermal contrast.

6. Statistical analysis of the imagery from the predawn flight on March 7, 1972, indicated that the variance in land-surface temperatures was greater along the losing reach of Logan Creek than it was along the gaining reach. When losing and gaining conditions cannot be discriminated visually on thermal imagery, statistical analysis of the imagery may show if there are significant differences in hydrologic conditions in the valley.

7. Radiometric measurements in the summer and winter indicated that the thermal inertia of a moist, gaining valley is greater than that of a losing valley. In winter, gaining valleys were warmer in the nighttime and cooler in the daytime than were the losing valleys. In summer gaining valleys were cooler than losing valleys both near midday and at night. However, the temperature range and maximum temperatures were higher for the losing than the gaining valleys.

8. Weather conditions antecedent to and at the time of the flight are of utmost importance in scheduling data collection. Forenoon flights may be needed to avoid uneven cooling due to cloud shadows from cumulus clouds that tend to form in the afternoon. Predawn haze and ground fog reduce thermal contrasts. Data obtained predawn following several clear, dry days produced the most meaningful results. Radiometric data obtained during rainy or cloudy weather or from wet or frozen ground were generally inconclusive.

9. The synoptic view obtained by a thermal imager was very helpful to the investigation of linear features such as stream valleys, faults and joint systems. Preparation of mosaics appears to be unnecessary.

10. The following future uses of thermal imagery acquired by satellite or aircraft for hydrologic studies are suggested by the results of this investigation:

    a. Determination of losing and gaining streams and gross evaluation of water content of basins from thermal scanner data. High resolution satellite data obtained routinely every few days throughout the year may be very useful in identifying gaining and losing streams. It is unlikely that data obtained by aircraft for this study were collected at optimum times, and repetitive coverage would increase the likelihood of data collection at optimum times in the four seasons.

    b. The extensive coverage that will be available through satellite coverage of thermal imagery will facilitate evaluation of watersheds for planning location of water and waste impoundments or waste-water discharges.

    c. Identification of ground-water inflow (and possibly also discharge of waste effluents) to larger bodies of water than those investigated in this project.

    d. Relate the flow regimens of valleys and basins to geologic structure and the areal distribution of highly permeable zones capable of accepting streamflow (losing streams) or discharging ground water (gaining streams).

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