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N78-14563

USE OF THERMAL-INFRARED IMAGERY IN GROUND-WATER INVESTIGATIONS IN MONTANA

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ABSTRACT

Thermal-infrared imagery was used to locate ground-water inflow along three streams and one lake in Montana. The thermal scanner used in May 1972, March 1973, and November 1975 was mounted in a twin-engined aircraft. On the 1973 and 1975 flights, the data were recorded in an analog format on magnetic tape in flight, later were converted to digital format, and were computer-processed using an assignment of patterns to indicate differences in water temperature. Output from the image-processing program was converted to a temperature map having an isotherm spacing of 0.5°C. Computerization was found to be the most efficient method to manipulate data from lakes, large rivers, and narrow sinuous streams.

1. INTRODUCTION

Thermal-infrared sensors enable the hydrologist to detect dispersion and circulation patterns and ground-water discharge in various-sized bodies of water. This information is useful in locating water having desirable fish-rearing characteristics, locating areas of potential water-quality changes, and locating routes of industrial effluents (Whipple, 1972; Pluhowski, 1972).

The purpose of this investigation was (1) to determine if ground-water inflow to lakes and large rivers in Montana could be detected by the use of thermal-infrared imagery, (2) to test the usefulness of computer storage, retrieval, and processing of the data, (3) to demonstrate a useful format for presenting the data, and (4) to determine the usefulness of thermal-scanner data on a narrow sinuous stream.

2. THE THERMAL SCANNER

Temperature data were collected by using a thermal-infrared scanner mounted in a twin-engined aircraft capable of flying 345 km (kilometers) per hour. The scanner has a total field of view of 120°, two black-body calibration sources, and an accuracy of 0.2°C (Celsius) (Boettcher, and others, 1976). The flights were between 455 and 760 m (meters) above the water surface during predawn hours. The 8.5- to 11-μm (micrometer) range of the scanner was used to detect water temperatures.

Data output from the scanner were recorded on film, and during two flights on magnetic tape also. The film was processed in flight by a two-step rapid processor as it was exposed. Thermal data from the scanner, data from the aircraft gyro system, mileage data from the aircraft doppler system, and a voice track of the crew describing geographic locations were recorded on a fourteen-channel magnetic tape.

3. THERMAL-SCANNER EXPERIMENTS

The thermal-scanner experiments were made as part of ground-water investigations conducted in Montana by the U.S. Geological Survey in cooperation with the Montana Bureau of Mines and Geology, Bonneville Power Administration, and Environmental Protection Agency. Imagery was obtained along the Kootenai River and Lake Koocanusa in northwestern Montana, along the Clark Fork of the Columbia River near the Idaho-Montana State line, and along the Tongue River near the Wyoming-Montana State line (Fig. 1).

3.1. KOOTENAI RIVER AND LAKE KOOCANUSA

On May 17, 1972, a flight of about 80 km was made along the Kootenai River as shown by the hachures on figure 1. The purpose of this flight was to determine (1) if ground-water inflow could be detected by using an airborne thermal scanner, (2) if ground-water temperature plumes could be distinguished from other temperature plumes in lakes, and (3) what range of temperature calibration would be necessary to obtain maximum contrast on the film showing water.

The flight was made when the tributaries of Lake Koocanusa and the Kootenai River contained snowmelt runoff having temperatures of about 5^{o} to $7^{o}C$. A temperature differential is apparent on figure 2A, where the measured temperature of the water in the forebay of Libby Dam was $12^{o}C$ and the temperature of the water in the Fisher River was $7^{o}C$. Figure 2B shows a plume of warmer ground water flowing into Lake Koocanusa from an alluvial fan. Water temperatures not affected by ground water can be seen west of the alluvial fan. The temperature difference from black to white on the images is $7^{o}C$ (from 5^{o} to $12^{o}C$), as calibrated on the scanner. This range in temperature produced the maximum contrast.

3.2. CLARK FORK OF THE COLUMBIA RIVER

On March 29, 1973, a flight was made over the Clark Fork of the Columbia River as shown by the hachures shown on figure 1. The purpose of this flight was to (1) determine if ground-water inflow into a large river could be detected by thermal-infrared scanning techniques, and (2) if scanner data recorded on magnetic tape could be enhanced better by computer than by film.

In this reach of the Clark Fork, a deep narrow valley has been eroded into argillite and quartzite of the Belt Supergroup of Precambrian age and partly filled by highly permeable alluvium. Water flows into the alluvium from Noxon and Cabinet Gorge Reservoirs, then downvalley through the alluvium, and reenters the Clark Fork a short distance below the dams. From 28 to 71 m^3/s (cubic meters per second) of inflow from the alluvium has been measured below Noxon Rapids Dam.

The warmer (white) ground-water inflow below Cabinet Gorge Dam can be seen along the left bank of the Clark Fork (fig. 3). Imagery of this area was used to test computer techniques because temperature differences were large in a small area. Small amounts of ground-water inflow would probably be masked by the large quantities of colder river water.

The scanner data were recorded on magnetic tape and converted to digital format. Each number represented the thermal emission from a ground-resolution cell size of about 1.5 m by 0.38 m. A digital image having a ground-resolution size of 1.5 m x 1.5 m was prepared by using every fourth row of data.

Automatic generation of the contours of only the river, required that the digital image be masked, setting to zero areas of land surface and leaving any pixel (picture element) that was water. Then, any pixel having a value of zero and being within a distance of 8 resolution cells of a non-zero pixel, was set to the value of its closest non-zero pixel. This operation in effect extended the boundary of the river.

After the boundary was determined, an averaging technique was used to smooth the image. The smoothed image was then masked with the same mask that had been used to select only water pixels. This masked to zero any pixels composed of averages of water pixels and zero-valued pixels.

To obtain some number, N, of contour levels, the resulting image was equal-interval quantized to N levels. The contours were computed by testing each pixel to determine whether it was a boundary pixel. A boundary pixel is not equal in value to at least one of its four nearest neighbors. Any boundary pixel which had the highest value of its four neighbors was labeled as a contour pixel and assigned its quantized value. All other pixels were set to zero.

The maximum temperature of a mixture of ground-water inflow and river water was 8.5°C, whereas the river water was predominantly at 6.0°C (fig. 4). The stream-bank temperature was 5.5°C. Figure 4 is a computer version of the temperature changes caused by ground-water inflow. The isotherm interval is 0.5°C. The 5.5°C temperature is denoted by zeros and the 8.5°C temperature by 6's. The isotherms were drawn manually; however, they could have been drawn on a plotter. The computer output showed the sizes and locations of the anomalous plumes more distinctly and quantitatively than the film output.

3.3. TONGUE RIVER

On November 19, 1975, a 156-km flight was made over a reach of the Tongue River as shown by the hachures on figure 1. The scanning started at Tongue River Dam which had been closed for repairs for twenty days before the flight, thus affording an opportunity to measure ground-water inflow. About 0.6 m^3/s of water was pumped over the dam to maintain flow for aquatic life.

The purpose of this flight was to (1) determine if ground-water gains to the stream could be detected by thermal-scanning techniques, and (2) determine if inflow to a narrow sinuous stream having low flow could be detected using computer techniques and thermal-scanner data.

In this reach of the Tongue River, the valley has been eroded into the Tongue River Member of the Fort Union Formation of early Tertiary (Paleocene) age. The Tongue River Member consists of sandstone, siltstone, coal, and shale. The valley is about 1 km wide and is partly filled by silt, sand, and gravel from 21 to 30 m thick.

Weather conditions significantly affected streamflow and the timing of the flight. Minimum air temperatures were below freezing for about 2 weeks before the flight, causing the river to be partly covered by ice that periodically melted. On the day of the flight, most of the shore was covered with ice and ice was floating in parts of the river. The river was flown on November 19 because that was the first day in nearly a week that the Tongue River valley was free of clouds.

The scanner data were recorded on magnetic tape and later digitized for computer use. To prepare the river temperature graph to map scale, the digitized-image data were geometrically corrected. The digital image was displayed on a viewing screen and an electronic pointer was used to select the river points whose temperature was required. The program converted the position on the viewing screen to a row/column coordinate on the digitized image and the value of the pixel in the specified row/column position was recorded. The digitized values were converted to temperatures by linear scaling. The coefficients of the scaling were determined from ground-truth data.

The computer output (fig. 5) shows temperatures of the river at selected locations. At each location an "X" is placed on the printout and the temperature in degrees Celsius is printed on the same line at the right of the printout. The approximate configuration of the river was taken from topographic maps. The numbers along the river are locations where streamflow measurements were made.

Figure 6 shows the longitudinal profile of water-surface temperature and discharge in the river. Increases in temperature through the short reaches are believed to indicate ground-water inflow because the ground water was warmer than either the air or the surface water. The lower temperatures could result from the water flowing through shallow reaches of the stream, or be due to melting ice. Weather conditions during the flight were not ideal because ice was melting, which decreased stream temperature and increased discharge. Below Station 12 the temperature of the river decreased greatly, because of melting ice.

The infrared imagery helped delineate specific reaches of the Tongue River that were receiving ground-water inflow. Computer techniques developed during this investigation to enhance the imagery appear to have wide application, especially for narrow streams. The techniques may also prove useful in the detection and documentation of changes in water temperature caused by man's actions.

4. CONCLUSIONS

Ground-water inflow to streams and lakes was observed from an aircraft-mounted thermal-infrared scanner. However, detection of small amounts of ground-water inflow to a sizeable river is difficult. Computerization is the most efficient and accurate method to enhance and manipulate scanner data. Large amounts of nearly error-free temperature data can be stored and retrieved by a computer. Additionally, items such as map-scaling factors and ground-truth data can be entered into the computer system to insure uniform temperature calibration. The computer output can be made to overlay most map scales; therefore, the combination of obtaining data by the thermal scanner and processing it by the computer appears to have wide application. The success of techniques developed during these investigations to enhance thermal-infrared imagery has proven their wide application to the study of lakes, large rivers, and narrow sinuous streams.

5. REFERENCES

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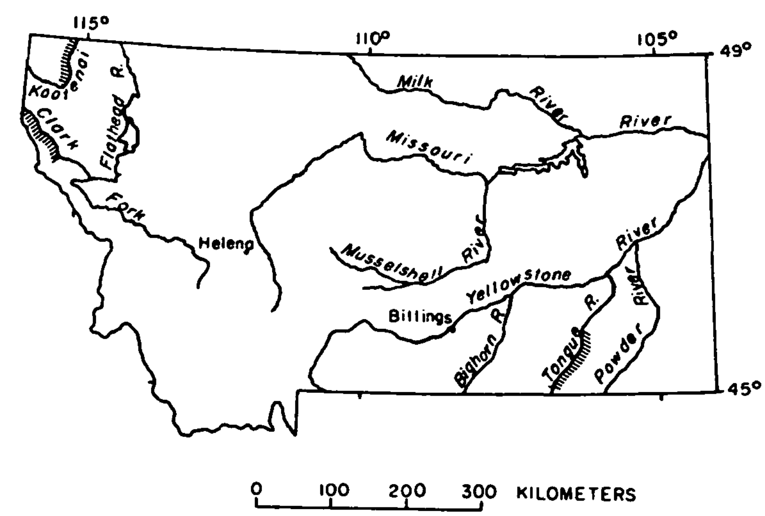


FIGURE 1. INDEX MAP SHOWING AREAS OF INVESTIGATION.

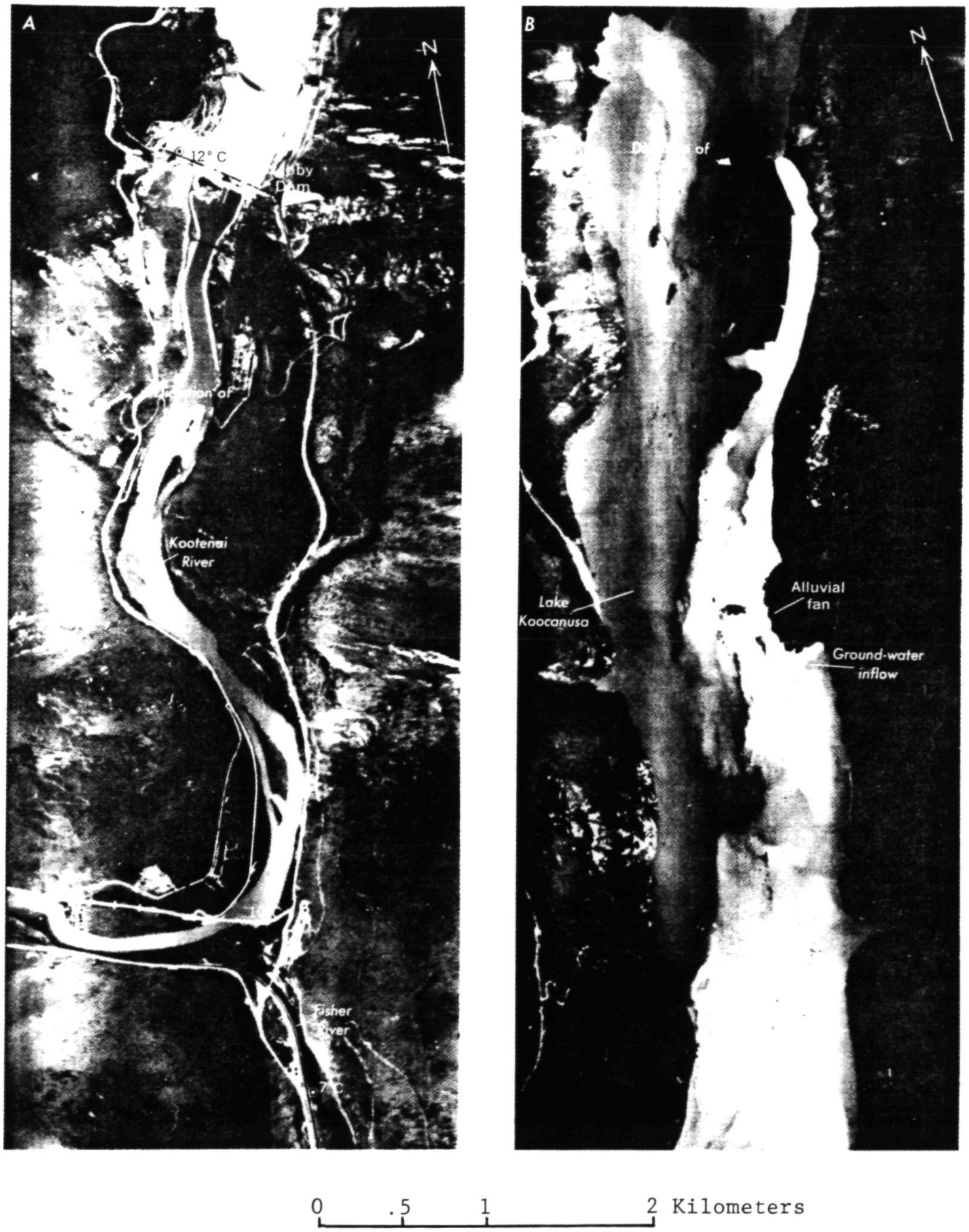
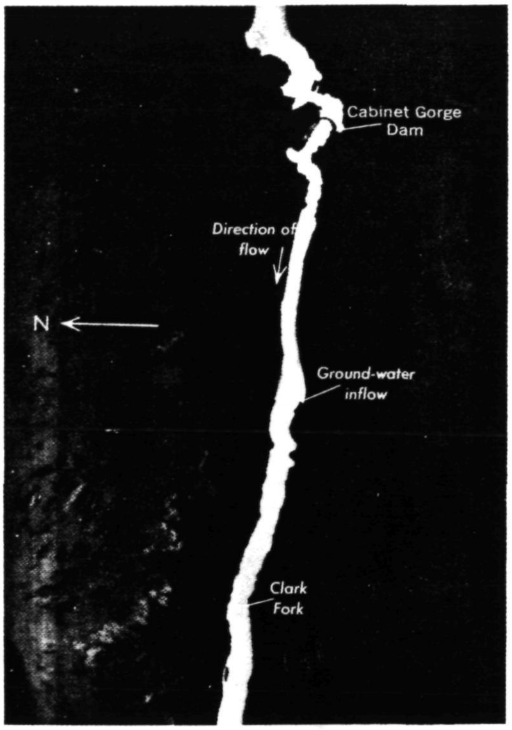


FIGURE 2. THERMAL-INFRARED IMAGERY AROUND LAKE KOOCANUSA.
A. Libby Dam and the confluence of the Fisher and Kootenai Rivers.
B. Ground-water inflow to Lake Koocanusa.
Imagery by U.S. Forest Service



0 .5 1 1.5 2 Kilometers

FIGURE 3. THERMAL-INFRARED IMAGERY BELOW CABINET GORGE DAM. Imagery by U.S. Forest Service.

FIGURE 4. TEMPERATURE DATA COMPUTERIZED.
Isotherm interval is 0.5°C.

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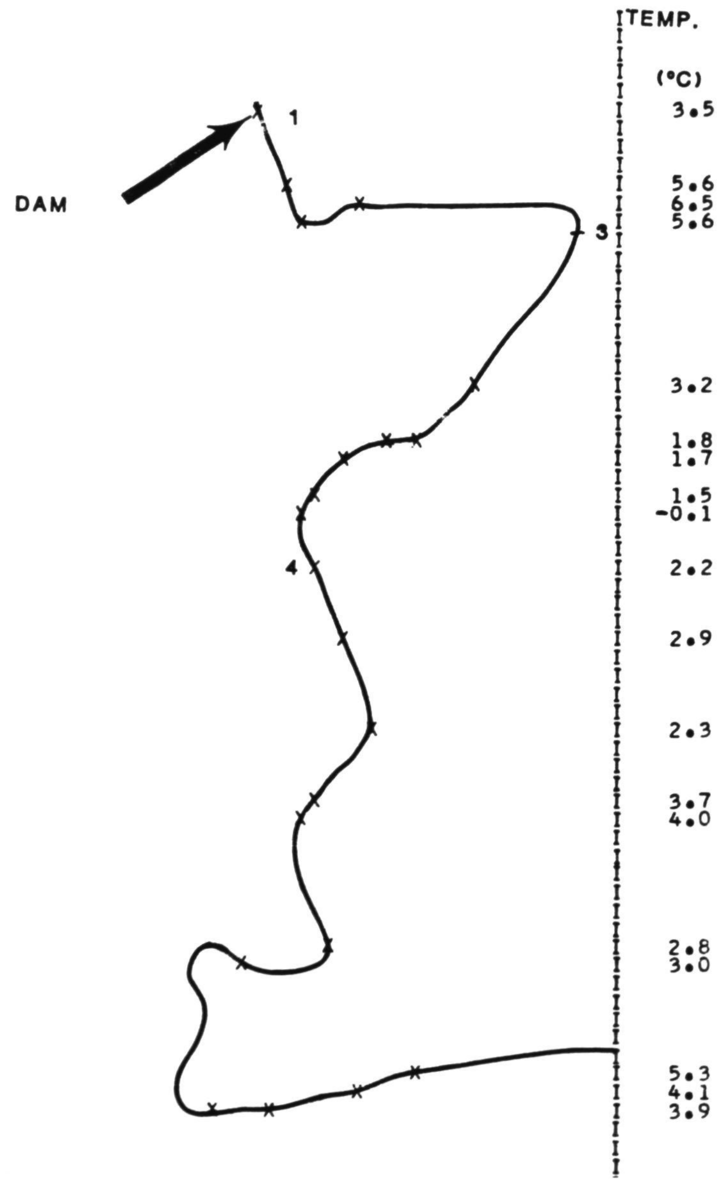

FIGURE 5. TEMPERATURES AT SELECTED LOCATIONS ALONG THE TONGUE RIVER. Temperatures detected by thermal-infrared imagery (Nov. 19, 1975).

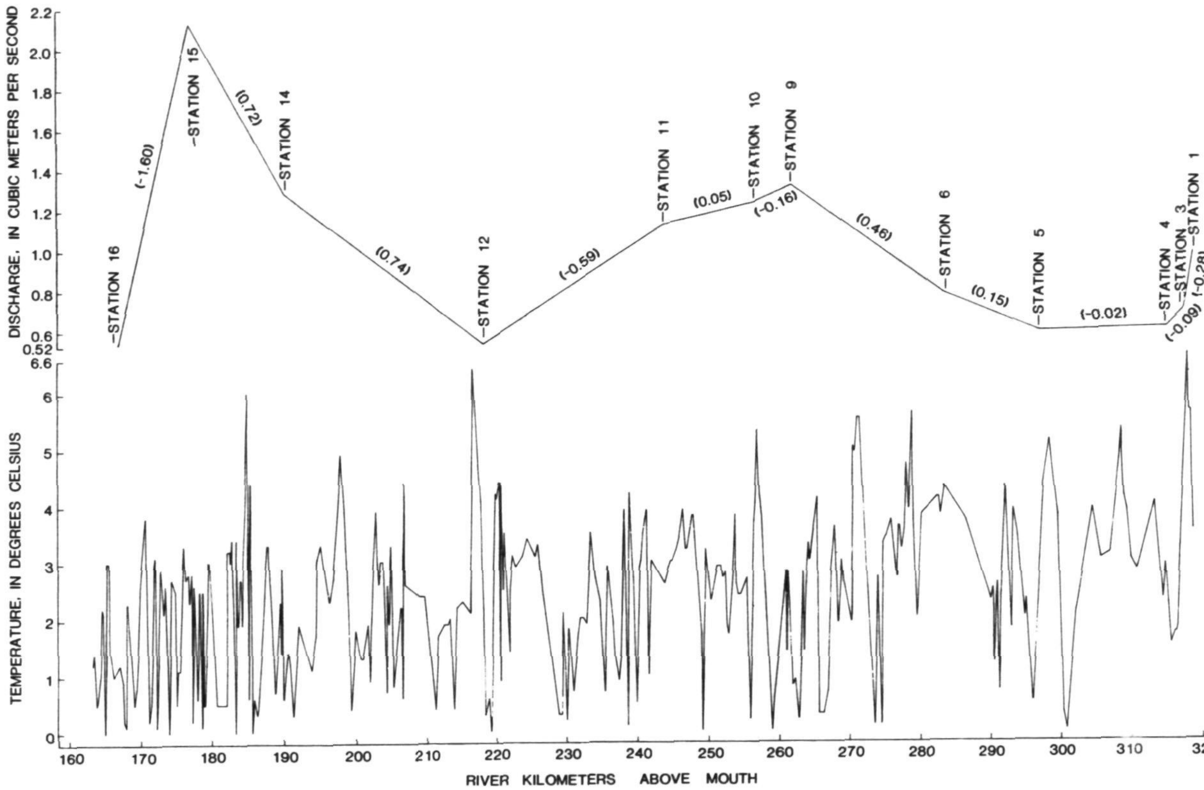

FIGURE 6. TEMPERATURE AND DISCHARGE OF THE TONGUE RIVER ABOVE THE MOUTH. Numbers in parentheses indicate a gain or (-) loss.