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

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Abstract.—Thermal-infrared imagery was used to locate ground-water inflow along a 50-mile (80-kilometre) reach of the Kootenai River and Lake Koocanusa and a 55-mi (88-km) reach of the Clark Fork of the Columbia River in northwestern Montana and northeastern Idaho. The imagery confirmed that measured streamflow gains below Noxon Rapids Dam, ranging from 1,000 to 2,500 cubic feet per second (28 to 71 cubic metres per second), resulted from inflow of ground water, which was about 2.5° Celsius warmer than surface water. The thermal scanner (8.5–11 micrometres) used in May 1972 and March 1973 was mounted in a twin-engined aircraft. On the March 1973 flight, the data were recorded in an analog format on magnetic tape in flight, later were converted to digital format, and then were computer processed using an assignment of patterns to indicate differences in water temperature. Thus, subtle temperature differences are much easier to identify than they are on conventional film-negative displays. The output data from the image-processing program can be converted to temperature maps having an isotherm spacing of 0.5°C.

Ground water flowing into stream channels affects the quantity and quality of many streams in Montana. Identification of the source of the inflow is useful for appraisal and management of water resources.

Infrared photography cannot measure water-surface temperature variations directly. Ground-water inflow may stimulate growth of certain plants. Thus, vigor of growth observed by infrared photography may indicate ground-water inflow. However, this method has no quantitative significance. In contrast, thermal-infrared sensors record an emitted electromagnetic radiation which, with help of computer techniques, can be quantified into spatial surface-temperature information if the following conditions are met: (1) differences in temperature exist between the surface water and ground water, (2) the quantity of surface water is not too large relative to the quantity of ground-water inflow, and (3) the density of the surface water is greater than the ground water, allowing detection of the ground water.

Thermal sensors enable the hydrologist to detect dispersion and circulation patterns and ground-water discharge in large bodies of water. This information is useful in such applications as locating areas having good fish-rearing characteristics and areas of potential water-quality changes, or in differentiating industrial effluent from natural patterns of a stream (Whipple, 1972; Pluhowski, 1972).

Extrapolation of temperature data over large areas from the film output obtained from a thermal scanner is difficult because the human eye cannot compare densities over a large area. Therefore, when thermal imagery has been obtained from a long reach of a river or lake, mechanical density-measuring devices are used to obtain standardization of the gray levels. A densitometer can be used for spot density measurements on the film output to assign temperatures based on ground-truth data. This method is time consuming, however, and cannot be done on the entire film output.

Another method of determining density is by use of a density slicer, which views the negative and portrays the varying densities by colors or binary patterns. Then each pattern or color can be identified by temperature values based on ground-truth data. Though useful, this method also does not work well with a large amount of imagery because of changes in film or developer.

The purpose of this investigation was threefold: (1) to determine if ground-water inflow into lakes and streams in northwestern Montana could be detected by the use of thermal-infrared imagery, (2) to determine the most useful data format on which to present the data, and (3) to test the capability of the digital

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computer for storage, retrieval, and processing of the data collected.

THE THERMAL-INFRARED SCANNER

An aircraft-mounted thermal-infrared scanner senses the distribution of energy radiated by a surface. The detected energy distribution is a function of the surface temperature and emmissivity and is modified by the intervening atmosphere. The thermal emmissivity of water is nearly uniform, which allows small changes in water-surface temperature to be measured. Solar-energy reflections from clouds and shadows complicate thermal scanning during daylight hours. Night and predawn flights are best for thermal scanning because the effects of solar-energy changes then are minimized and the air is calmer (Carr and Gross, 1972).

Temperature data were obtained by using a U.S. Forest Service thermal-infrared scanner mounted in a twin-engined aircraft capable of flying at 215 miles per hour (346 kilometres per hour). The scanner has two black-body calibration sources, which give it an accuracy of 0.2°C (Celsius). The total field of view is 120° and the imagery is processed in flight in near real time by a two-step rapid processor (Wilson and others, 1971). The flights discussed in this paper were flown between 2,000 and 2,500 ft (feet) or 610 and 762 m (metres) above the water surface during predawn hours. The scanner senses the 3- to 4.1- and 8.5- to 11-μm (micrometres) ranges of the electromagnetic spectrum. Only the 8.5- to 11-μm range was used to detect water temperatures in this investigation. The 3- to 4.1-μm range is used for detecting higher temperatures such as forest fires. The visible, infrared photography, and thermal-infrared imagery ranges of the electromagnetic spectrum are shown in figure 1.

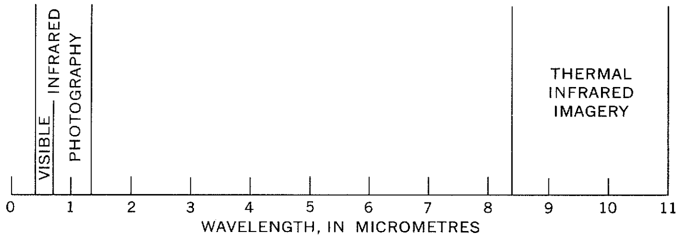

Figure 1.—Electromagnetic spectrum.

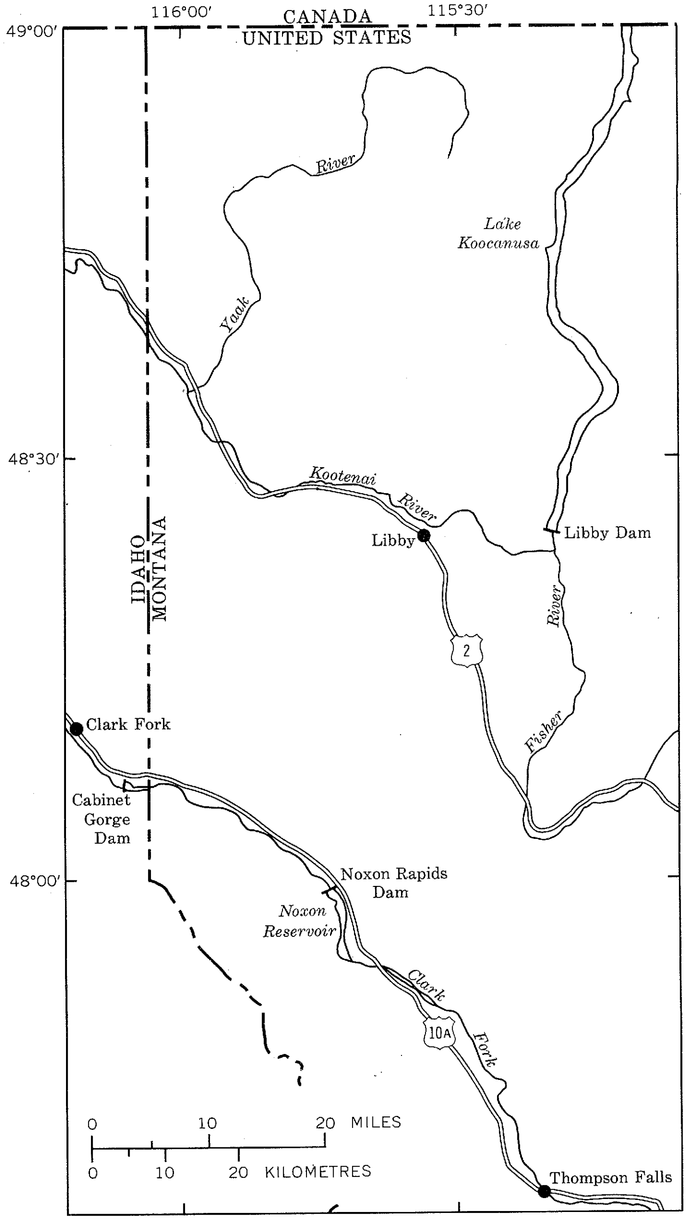

Figure 2.—Index map of the report area.

THERMAL SCANNER IMAGERY EXPERIMENTS

On May 17, 1972, a flight was made along the Kootenai River and Lake Koocanusa from the United States–Canadian boundary to the confluence of the Fisher and Kootenai Rivers (fig. 2). 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 plumes could be distinguished from the normal plumes in lakes, and (3) what range of temperature calibration would be necessary to obtain maximum contrast in the film output when flying over water.

The flight was made when snowmelt was flowing in the tributaries of Lake Koocanusa and the Kootenai River with resulting temperatures of about 5° to 7°C. A 5°C temperature differential is apparent on figure 3*A*, where the measured temperature of the water in the forebay of Libby Dam was 12°C and the temperature of the water in the Fisher River was 7°C. Figure

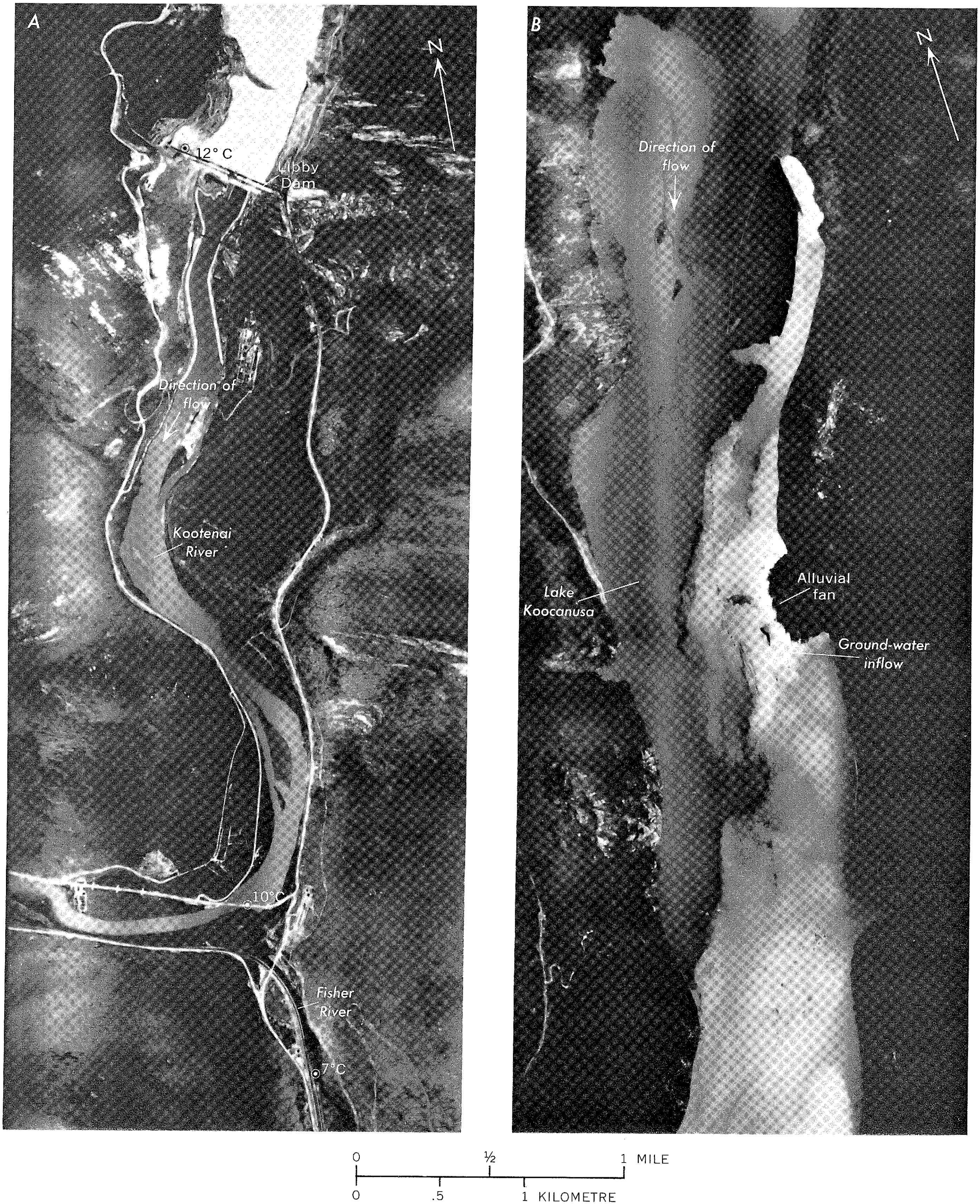

FIGURE 3.—Thermal-infrared imagery around Lake Koocanusa. *A*. Libby Dam and the confluence of the Fisher and the Kootenai Rivers. *B*. Ground-water inflow into Lake Koocanusa. Imagery by U.S. Forest Service

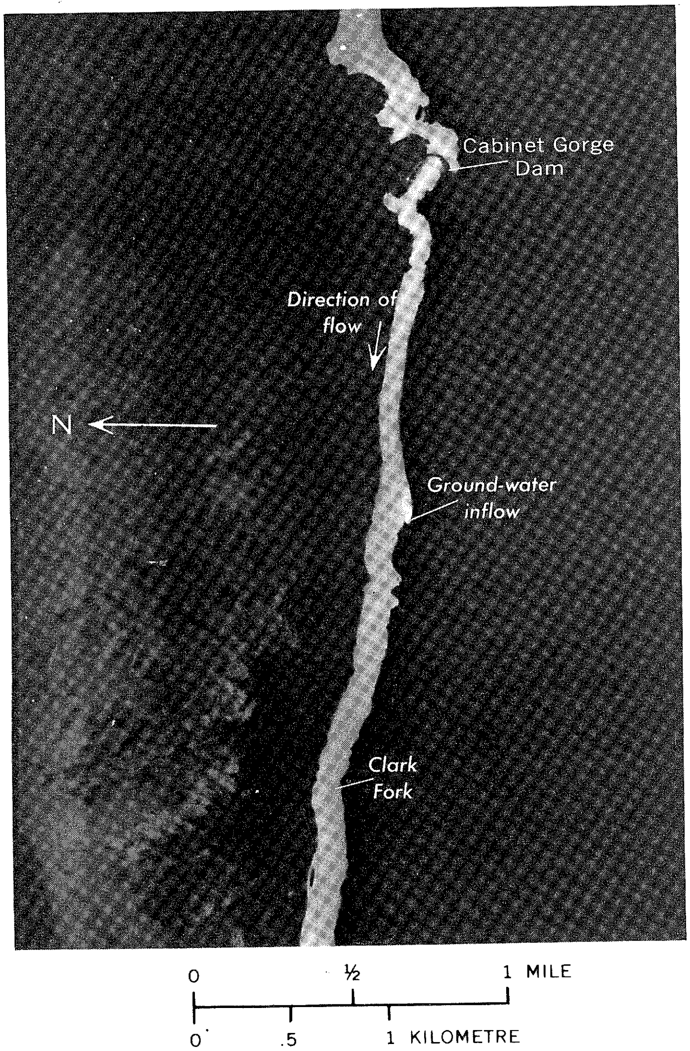

FIGURE 4.—Thermal-infrared imagery below Cabinet Gorge Dam. Imagery by U.S. Forest Service.

3*B* shows a plume of warmer ground water flowing into Lake Koocanusa from an alluvial fan. The temperature difference from black to white on the images is 7°C (from 5° to 12°C), as calibrated on the scanner.

On March 29, 1973 a flight was made over the Clark Fork of the Columbia River from Thompson Falls, Mont., to Clark Fork, Idaho (see fig. 2). The purpose of this flight was to determine if areas of ground-water inflow could be detected by thermal-infrared scanning techniques and if the data could be processed by computer to enhance the output. During the flight, scanner data were transferred to magnetic tape by a recorder attached to the scanner.

In this reach, the Clark Fork has eroded a deep narrow valley into rocks of the Belt Supergroup of Precambrian age. These rocks consist primarily of argillites and quartzites near Noxon Rapids and Cabinet Gorge Dams. The valley has been partly filled by semiconsolidated sand, gravel, and clay that form the Quaternary alluvium. Water flows from Noxon and Cabinet Gorge Reservoirs into the alluvium, then downvalley through the alluvium, and reenters the Clark Fork a short distance below the dams. From 1,000 to 2,500 ft^3/s (cubic feet per second) or 28 to 71 m^3/s (cubic metres per second) of water inflow from the alluvium has been measured below Noxon Rapids Dam.

The warmer ground-water inflow below Cabinet Gorge Dam can be seen along the left bank of the Clark Fork (fig. 4). Imagery of this area was used to test computer techniques because of a large temperature difference in a small area.

The five channels of the magnetic tape recorder recorded the various voltages of the scanner. The tape was later converted to a digital format for computer processing. Ground-truth and map-scaling factors were entered into the program to serve as a check on the computer.

After analog-to-digital conversion, the thermal-infrared imagery was a large matrix of numbers. This matrix is called a digital image. Each number represents the average temperature of a 5 by 5 ft (1.5 by 1.5 m) ground area. To draw lines of equal temperature, the first computer process consisted of a spatial averaging or defocusing of the data. The averaging, sometimes called convoluting, is done by generating a new digital image where the temperature of each resolution cell is computed to be the equally weighted average of the nearby temperatures of the resolution cells of a 8-node by 8-node window centered around it.

Because a 0.5°C-isotherm interval was needed, the second computer process consisted of an equal-interval quantizing of the smoothed digital display so that the smallest distinguishable difference between any two temperatures became 0.5°C. The final operation consisted of setting of blanks any resolution cell satisfying the condition that (1) its nearest vertical and horizontal neighbors have the same temperature it does or (2) its temperature is smaller than or equal to the temperatures of its nearest vertical and horizontal neighbors and one of these neighbors has a different temperature than it does.

The temperature of a mixture of ground-water inflow and river water was 8.5°C, whereas the river water was predominantly 6.0°C (fig. 5). Figure 5*A* 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 0's and the 8.5°C temperature by 6's (fig. 5*A*). These data could be drawn on a plotter although figure 5*B* was drawn manually. The computer output described the sizes and locations of the anomalous plumes more distinctly

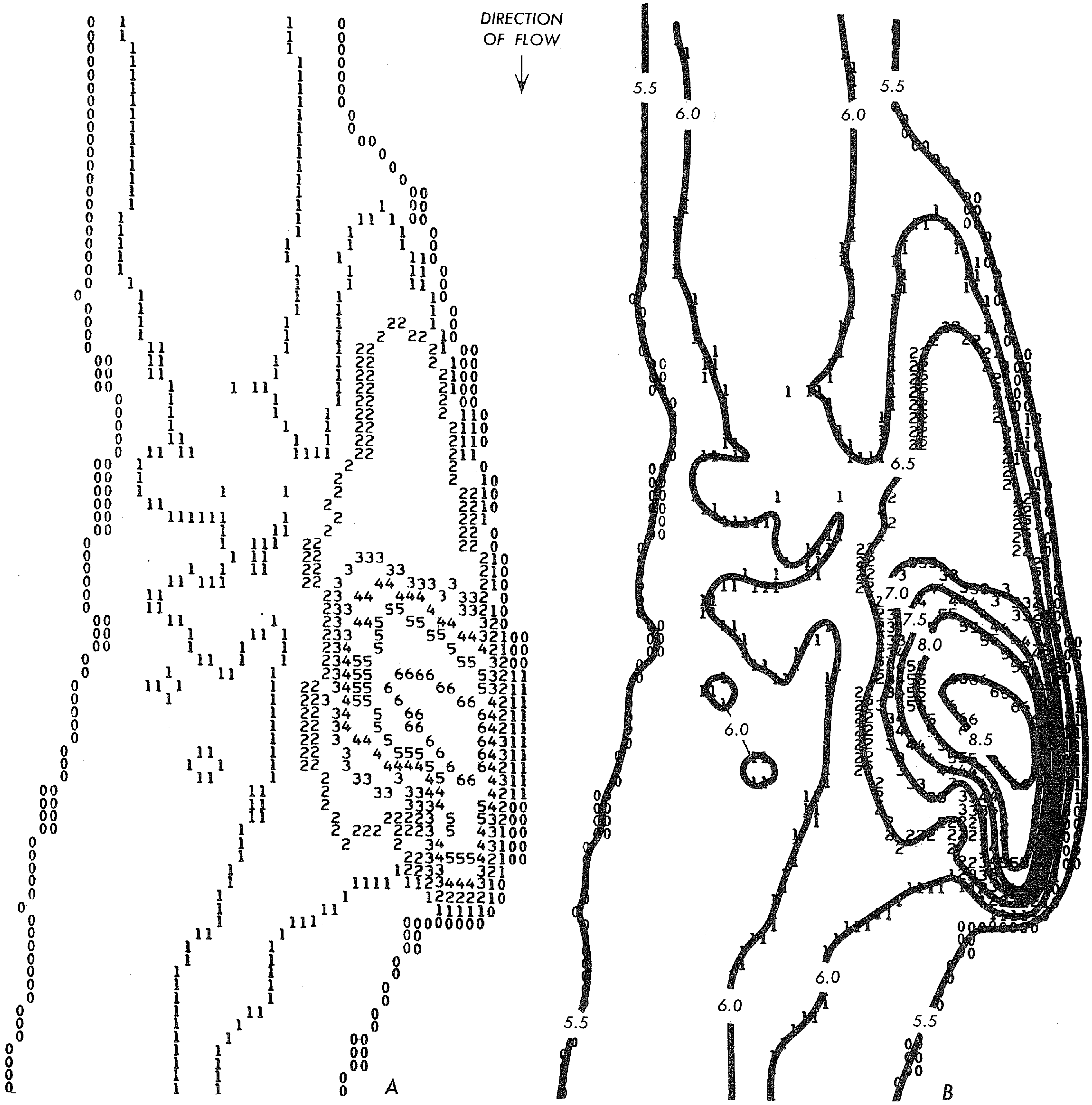

FIGURE 5.—Temperature data computerized. *A*. Computerized data showing numbers representing 0.5°C interval. *B*. Same as *A* except the isotherms have been manually drawn.

than the film output and can be reduced or enlarged much easier and more efficiently than the film output.

CONCLUSIONS

Ground-water inflow to streams and lakes was observed from an aircraft-mounted thermal-infrared scanner. Detection of small amounts of ground-water inflow to a sizeable river would be difficult because the large amount of river water would dilute the ground water rapidly. Computerization of the temperature data was found to be the most efficient way to manipulate the data because computer techniques are the most accurate. Large amounts of 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. Two ground-truth data points were used in figure 5 and four points were used for a 20-mi (32-km) reach. 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 has furnished the hydrologist with a useful tool.

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