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THERMAL STUDY OF THE MISSOURI RIVER IN NORTH DAKOTA USING INFRARED IMAGERY

By

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ABSTRACT

Studies of infrared imagery obtained from aircraft at 305- to 1,524-meter altitudes indicate the feasibility of monitoring thermal changes attributable to the operation of thermal-electric plants and storage reservoirs, as well as natural phenomena such as tributary inflow and ground-water seeps, in large rivers. No identifiable sources of ground-water inflow below the surface of the river could be found in the imagery. The thermal patterns from the generating plants and the major tributary inflow are readily apparent in imagery obtained from an altitude of 305 meters. Though the patterns are generally discernible in the imagery from 1,067-meter and 1,524-meter altitudes, there is not sufficient ground resolution to make any but the most general qualitative analyses. The quality of the imagery varied with land-water temperature relations as well as with instrument properties.

Portions of the tape-recorded imagery were processed in a color-coded quantization to enhance the displays and to attach quantitative significance to the data. Apparent radiant temperature computations from the 305-meter imagery were generally within 1°Celsius of ground-truth data.

The study indicates a marked decrease in water temperature in the Missouri River prior to early fall and a moderate increase in temperature in late fall because of the Lake Sakakawea impoundment. At the present time, thermal additions generated by the powerplants have little effect on the temperature regimen of the Missouri River at high rates of river discharge.

INTRODUCTION

Purpose of Study

The study was made to evaluate the infrared-imagery spatial and thermal requirements in remote sensing necessary to define the thermal anomalies in a major river. In view of the critical problems that have developed in some areas because of excessive thermal pollution, an investigation into methods of evaluating the present and future thermal conditions was desirable.

The temperatures of the Missouri River in North Dakota are normally affected by atmospheric temperatures, insolation, emitted radiation, tributary inflow, and ground-water inflow The present temperature regimen of the river has been markedly influenced by the impoundment of Lake Sakakawea and to a lesser extent by the operation of lignite-fueled thermal-electric generating plants. Infrared imagery was used in an attempt to (1) identify possible sources of ground-water inflow, (2) define the dispersion pattern of thermal additions, and (3) indicate general temperature changes laterally and longitudinally.

A secondary benefit realized from a combination of the imagery and ground-truth data is a definition of the present late-summer temperature regimen for the Missouri River. This temperature information can be used in the planning of future developments along the river and in the evaluation of the effects of further thermal additions.

Area of Study

The segment of the Missouri River selected for study was between Garrison Dam and the headwaters of Oahe Reservoir, 148 km (kilometers) downstream (fig. 1). The drainage area above Garrison Dam is about 470,000 km^2 (square kilometers),

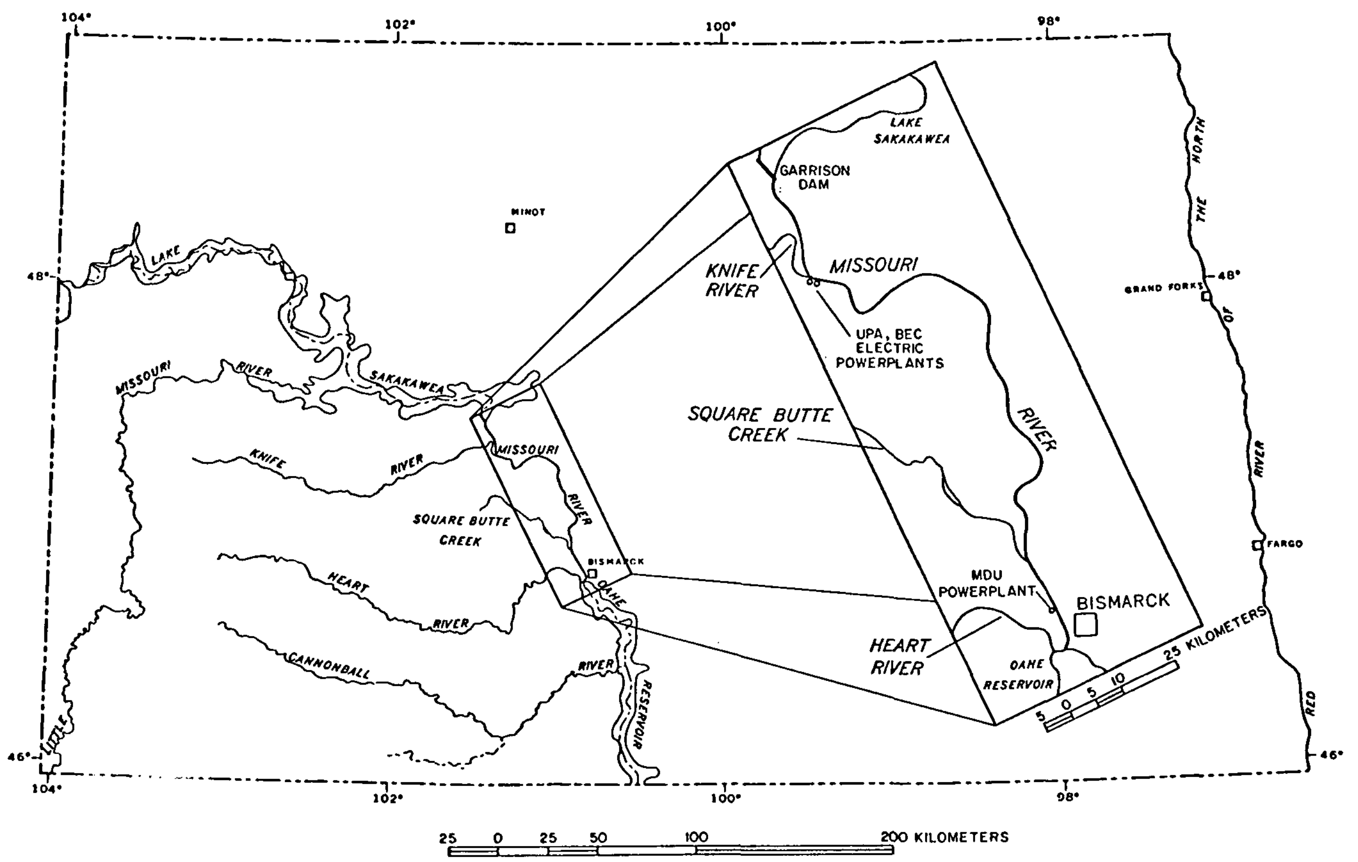


Figure 1.—Segment of the Missouri River investigated in North Dakota.

and the mean annual flow is about 600 m^3/sec (cubic meters per second). The average width of the river is about 450 meters.

The major tributaries are the Knife River (drainage area 6,400 km^2) and the Heart River (drainage area 8,660 km^2). There are two 200,000 kw (kilowatt) generating plants, United Power Association (UPA) and Basin Electric Cooperative (BEC), 20 km below Garrison Dam, and one 75,000 kw generating plant, Montana-Dakota Utilities (MDU), 114 km below Garrison Dam. The only major irrigation unit is the Fort Clark project (730 hectares), with the pumping station 19 km below Garrison Dam. County ground-water studies are completed or are in progress in the counties bordering the river.

Acknowledgments

This study has been supported by the National Aeronautics and Space Administration. The first two flights were made by NASA aircraft and the imagery data were processed in the NASA laboratories. The third flight was made by University of Michigan aircraft and the imagery data were processed at the University of Michigan's Willow Run Laboratories under contract with NASA. Much of the imagery interpretation and the

appendixes in full were supplied by personnel of the Willow Run Laboratories.

The study was made under the direction of the Office of Remote Sensing, U.S. Geological Survey.

DATA COLLECTION

Flight and Weather Data

Infrared imagery and ground-truth data were desired at high flows (about 1,100 m^3/sec) and at low flows (about 300 m^3/sec). Only high-flow data were obtained, however, owing to difficulties encountered in coordinating reservoir releases, aircraft availability, and favorable weather conditions. The dates of the flights were determined by the availability of the aircraft.

The first flight was made August 1, 1967, between 5:42 a.m. and 6:37 a.m. cdt (central daylight time), or from one-half hour before sunrise to one-half hour after sunrise. Visibility in the area was 25 km with light haze. The air temperature was 18°C (Celsius) with a relative humidity of 80 to 85 percent. The Corps of Engineers maintained a constant release of 1,100 m^3/sec from Garrison Dam for some time prior to the flight, resulting in a nearly uniform discharge in the study reach. Imagery was obtained from an altitude of

305 meters agl (above ground level) moving upstream and from 1,524 meters agl moving downstream. The imager used was a Reconofax IV utilizing a mercury-doped germanium (Ge:Hg) detector sensitive in the 8 to 14 μm (micrometer) band and having a scan angle of 2.4 radians (140 degrees) and an instantaneous field of view of 3 milliradians. The data were recorded in flight on 70 mm (millimeter) film strip.

The second flight was made September 26, 1968. It was a predawn to postdawn flight with imagery obtained from 6:14 a.m. to 7:13 a.m. cdt. The release from Garrison Dam was held nearly constant at 1,020 m^3/sec; considerably greater than desired. Visibility was good, but there were several small patches of early morning fog on several areas of the river. No effects from the fog could be identified on the imagery. The air temperature was 6°C with a relative humidity of about 95 percent. Imagery was obtained with the Reconofax IV from a 305-meter altitude moving upstream and a 1,067-meter altitude moving downstream. The data were recorded in flight on a 70 mm film strip.

A third flight was made July 23, 1969, between 5:16 a.m. and 6:42 a.m. cdt by the University of Michigan. Releases from Garrison Dam were varied, resulting in discharges from 720 m^3/sec to 975 m^3/sec in the study reach; again considerably higher than desired. The atmosphere was clear with visibility unlimited. The air temperature was 14°C with a relative humidity of 87 to 95 percent. Imagery was obtained from a 1,067-meter altitude moving upstream and a 305-meter altitude moving downstream. Imagery was obtained from two scanners. Scanner 1, which has a 0.6 radian (34 degree) total scan angle, was operated with a single element Ge:Hg detector sensitive in the 8 to 13.5 μm band. It was equipped with two thermal-radiation reference sources, which are high emissivity plates located in each side of the scanner. They have relatively constant temperatures that bracket the variations in the apparent temperatures being scanned. Scanner 2, which has a total scan angle of 1.4 radians (80 degrees), was operated with a mercury cadmium telluride (MCT) detector sensitive in the 3.5 to 12.5 μm band. This scanner was not equipped with thermal-radiation reference sources. An attempt was made to obtain imagery in the 4.5 to 5.5 μm band using an indium antimonide (Insb) detector, but the noise qualities and detector problems precluded the use of the data in this band. The data were recorded in flight on magnetic tape and later recorded on 70 mm film strip.

Ground-Truth Data

Ground-truth data were collected during, and for some time before and after, all flights by the use of water-temperature recorders, hygrothermograph recorders, and manual temperature readings at selected points and cross sections. The water-temperature recording devices consisted of six recording thermographs mounted on rafts anchored in the river with the temperature-sensing bulb fastened so as to remain just under the water surface; two underwater recorders fastened under anchored rafts; and four permanently installed water-temperature recorders at gaging sites, these being some depth below the surface. All recorders were readable to 0.5°C. Two hygrothermograph stations were used, one at the Environmental Science Services Administration center at Bismarck (121 km below Garrison Dam), and the other near the site of the two large generating plants (20 km below Garrison Dam). A direct-reading underwater thermometer was used for the thermal cross sectioning. Manual temperatures were taken with alcohol and mercury thermometers that were accurate to about 0.5°C. All temperatures were taken in moving water, if possible.

The quantity and temperature of the tributary inflow and the powerplant discharges were monitored; the plant data being furnished by powerplant personnel.

EVALUATION OF IMAGERY

Imagery Quality

The imagery obtained from 305 meters on the flight of August 1, 1967, proved satisfactory for a qualitative analysis of the dispersion of the various thermal additions, but the ground resolution and (or) the attenuation of the radiance from 1,524 meters precluded distinguishing any but the most pronounced thermal variations. Limited quantitative analysis is possible through use of the ground-truth data.

The imagery obtained from the flight of September 26, 1968, gave results of questionable value in identifying thermal variations in the river. At the time of the flight, the ground temperatures were much colder than those of the surface of the river, causing the automatic gain control to adjust to the predominant land signals, thereby forcing the water signal into a compressed part of the dynamic range of the film.

The imagery obtained from the flight of July 23, 1969, was satisfactory for qualitative analysis and, in some instances, good for quantitative analysis. It was not possible to have an on-board observer on this flight and the pilot attempted to follow the river meanders more closely than did the preceding pilots. As a result, some of the imagery was distorted or obscured owing to plane roll, and some critical areas were missed.

Temperature Computation

Apparent radiant temperatures could be computed for the 8 to 13.5 μm data from the Michigan scanner (see Appendix A). The apparent radiant temperature for a designated point is obtained by photographing a scanline through the point including signals from the hot and cold reference plates. The effective radiance of the hot plate and the cold plate was calculated and the apparent radiance of the point derived by a linear interpolation between the cold- and hot-plate radiances.

Color-Coded Quantization

Color-coded quantization of the imagery can enhance or identify thermal anomalies not readily apparent on the gray-level film strips (see Appendix B). The color-coded quantization is effected by voltage-level slicing of the data on magnetic taps by recording a response only to a signal between two voltage levels. The response at different levels is recorded on film strips, which in turn are used to produce a multicolored sandwich. The layered film strips can be photographed to produce a color transparency. Apparent radiant temperatures can be assigned to the various colors by the means described in Appendix A when there are reference data available.

ANALYSIS OF IMAGERY FEATURES

Ground-Water Inflow

The segment of the Missouri River valley used in this study is underlain by thick deposits of alluvium and glacial outwash that form significant aquifers. Potentiometric-surface maps of these aquifers indicate ground-water movement toward the river. The only ground-water inflow to the river identified on imagery obtained August 1, 1967, from an altitude of 305 meters is shown in figure 2 as a dark area. The area is a bank seep about 20 meters long and 10 meters wide. The temperature of the seep is 7°C as compared to a river temperature of 15°C. Though the seep was evident at ground level during the following flights, it was not detectable on the imagery.

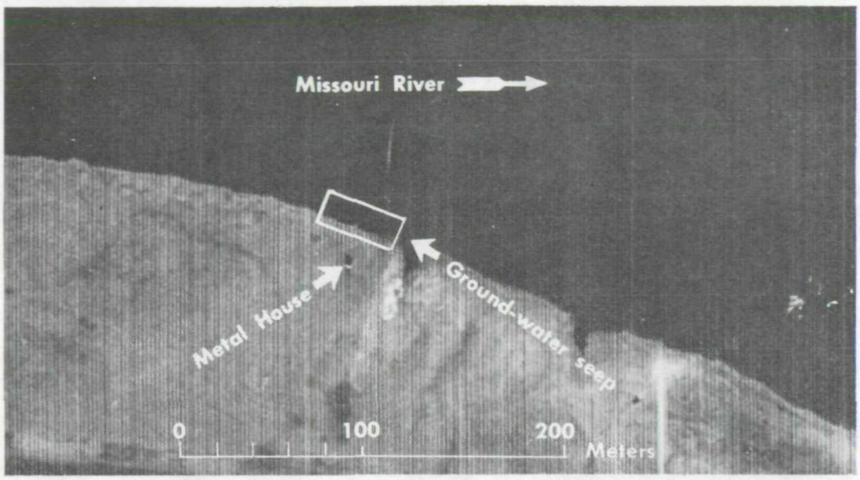


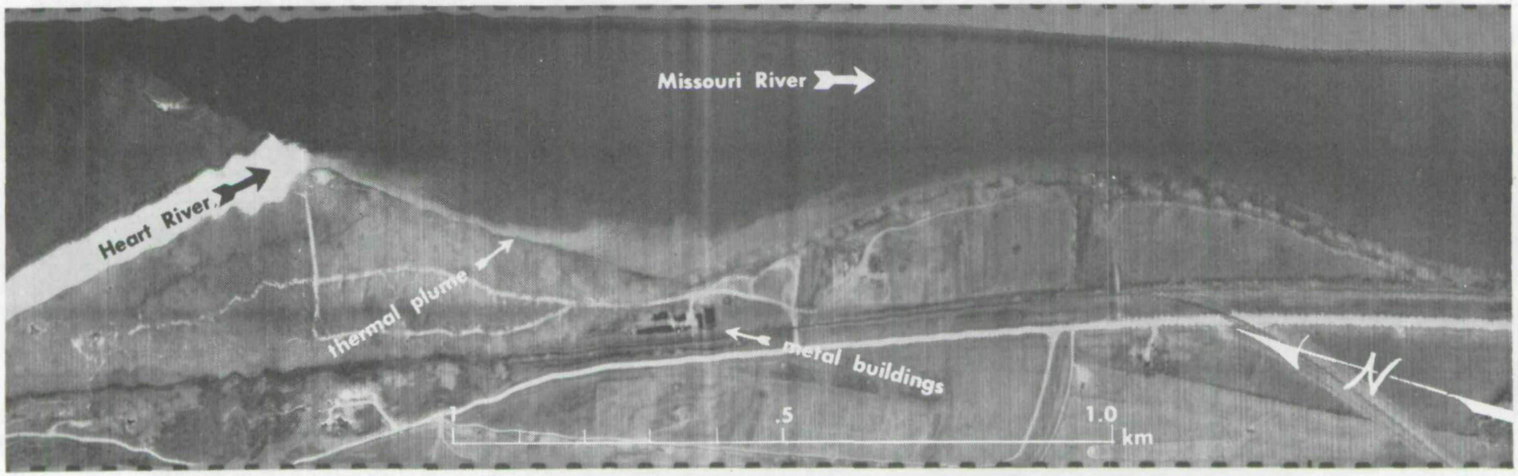
Figure 2.—Infrared imagery of ground-water seep in the 8 to 14 μm band from 305 meters. 8-1-67

Tributary Inflow

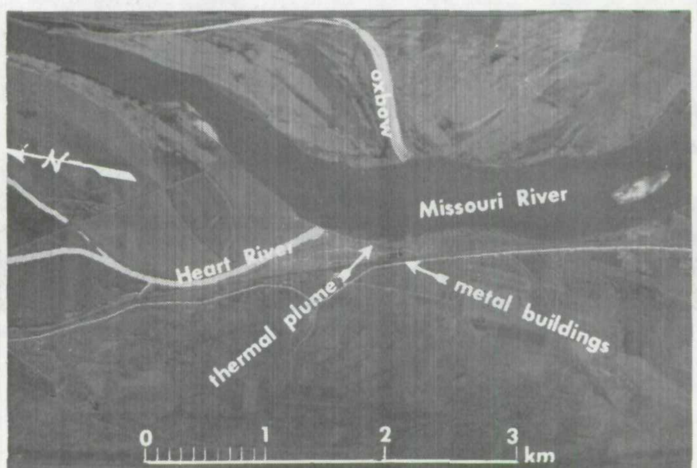
Heart River

The inflow of the Heart River (127 km below Garrison Dam) and the pattern of dispersion of the warmer water into the Missouri River are shown in figure 3. Figures 3a and 3b are prints of the imagery from 305 meters and 1,524 meters, respectively, obtained on the flight of August 1, 1967. The discharge of the Heart River was 2.7 m^3/sec at a temperature of 21°C, as compared to 1,100 m^3/sec at 15°C in the Missouri River. Calculations indicate the Heart River would cause an overall temperature rise of about 0.02°C in the Missouri River under these conditions. Imagery of the surface temperatures of the Missouri River indicates a slow dispersion of the thermal addition, with a lateral spread of 90 to 120 meters from shore and traceable temperature variations for more than 1,600 meters downstream.

The discharge of the Heart River during the flight of July 23, 1969, was 13.1 m^3/sec at a temperature of 24°C, as compared to a Missouri River discharge of 975 m^3/sec at 15°C. Figure 4a is a print of the 3.5 to 12.5 µm imagery from 305 meters. The aircraft was in a steep bank at this point and the left edge of the thermal dispersion is obscured.

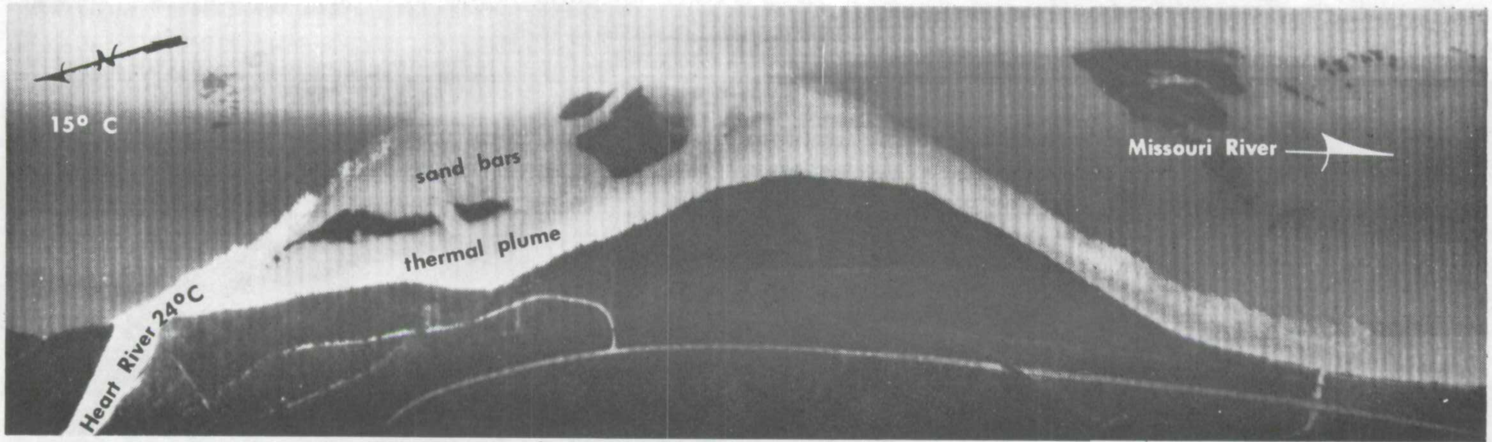


a/ Taken from an altitude of 305 meters.

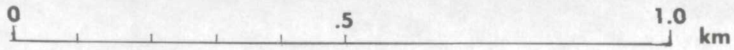


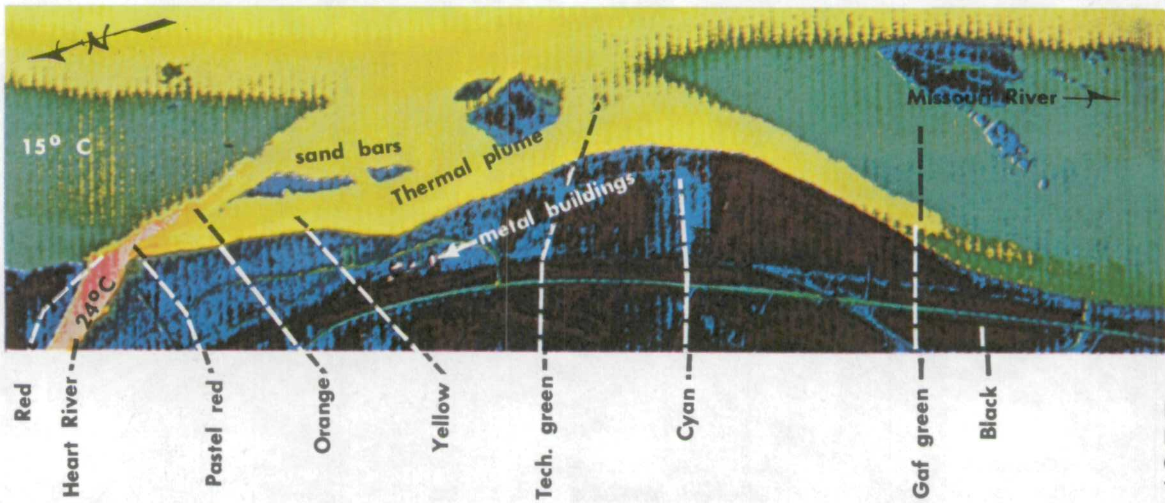
b/ Taken from an altitude of 1,524 meters.

Figure 3.—Infrared imagery in the 8 to 14 μm band of the confluence of the Heart and Missouri Rivers. 8-1-67.



a/ Image obtained from 305 meters.





b/ Color-coded quantization of image in (a).

COLOR SCALE

Red — Hot
Pastel red
Orange
Yellow — to
Tech. green
GAF green
Cyan
Black — Cold

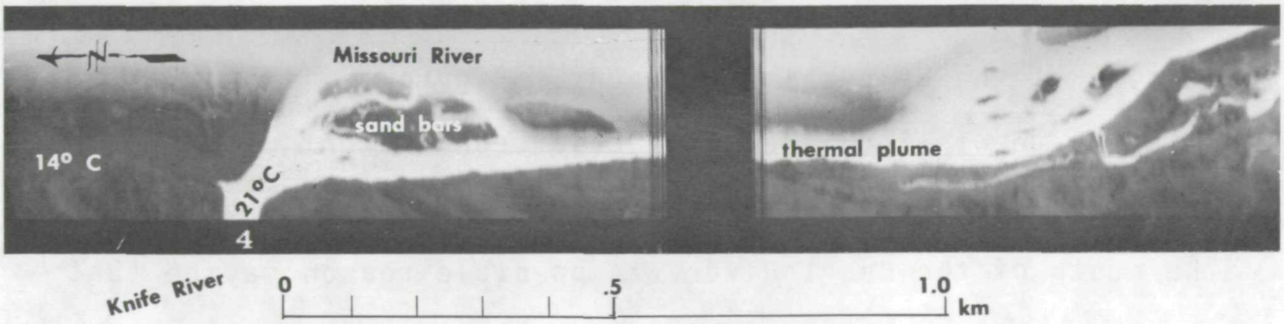
Figure 4.—Infrared imagery in the 3.5 to 12.5 μm band of the confluence of the Heart and Missouri Rivers. 7-23-69

The steep bank and turn also distorts the stream meander (shown by a comparison with figure 3), resulting in a distortion of the dispersion geometry. Figure 4b is a color-coded image of figure 4a. The color enhancement of the image brings out an apparent temperature anomaly (warm spot) near the mouth of the Heart River. A possible reason may be that the low-temperature nighttime air cooled the surface and turbulence at the mouth is exposing some warmer water. The shift from GAF green to yellow at the top of the print is a characteristic of the scanning system and not of the river. A computation of the apparent radiant temperature from the 8 to 13.5 µm imagery of the Missouri River 0.25 km above the mouth of the Heart River (GAF green) was 15°C (verified by ground-truth data).

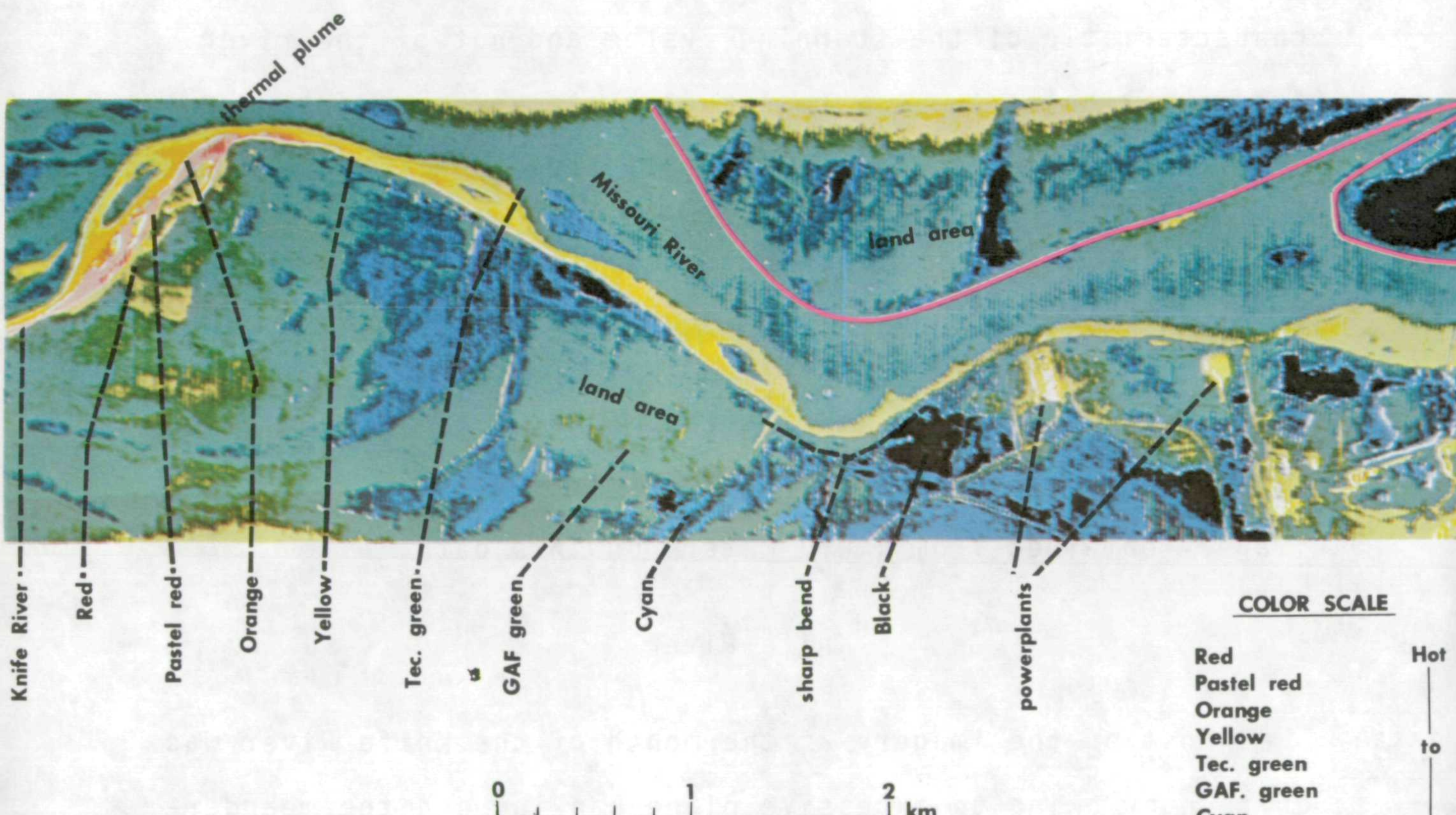
There was a loss of signal for scanner 2 in this area because of plane roll, and imagery in the 8 to 13.5 µm range was not obtained. The same area was missed entirely on the imagery obtained from 1,067 meters on this date.

Knife River

Most of the imagery at the mouth of the Knife River was quite poor owing to excessive plane banking and the meandering type of entry of the Knife River into the Missouri River. Figure 5a is a print of the 8 to 13.5 µm imagery from 305



a/ Imagery in 8 to 13.5 μm from 305 meters.



b/ Color-coded quantization of imagery in 3.5 to 12.5 μm from 1,067 meters.

Figure 5.—Infrared imagery of the confluence of the Knife and Missouri Rivers. 7-23-69

meters. The discharge of the Knife River was about 14 m^3/sec at a temperature of 21°C, as compared to 720 m^3/sec at 14°C in the Missouri River. A greater field of view is needed if the dispersion is to be adequately defined.

A color-coded quantization of the 3.5 to 12.5 μm imagery from 1,067 meters is shown in figure 5b. Considering the signal amplitude, the noise, and the number of available colors, this quantization was deemed the best that could be obtained. The thread of the Knife River with its variations in temperature show up well, but the Missouri River and much of the land are indistinguishable. The distortion of the river meanders, effected on the image by the plane following the river, is markedly evident in this image. The bend in the river in the center of the figure is actually about a 1.3 radian angle rather than the 2.1 radian angle indicated. Though not as readily apparent, this distortion is also present in the pattern of the thermal dispersions.

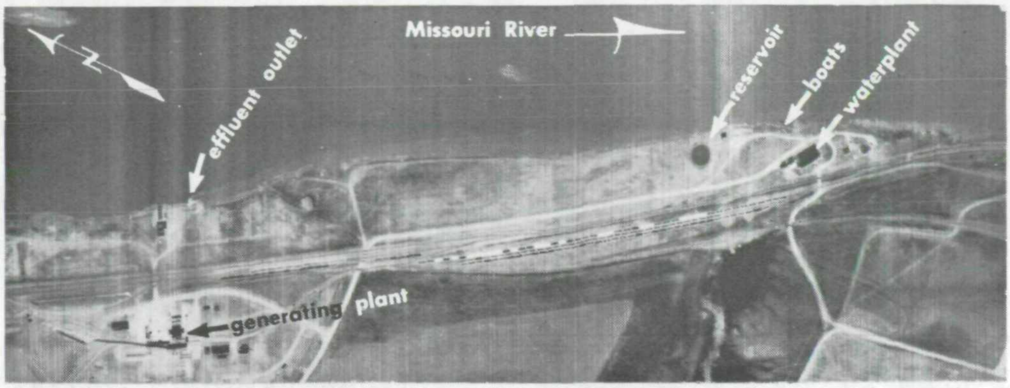
Other Tributaries

The small tributaries generally contributed very little water (less than 0.2 m^3/sec) and showed no thermal anomalies. The one exception was Square Butte Creek (fig. 1), which enters the Missouri River 67 km below Garrison Dam. It was probably discharging about 1.5 m^3/sec on July 23, 1969, owing to a local thunderstorm in the upper reaches. The quantity of flow and temperature were not monitored near the mouth, but the temperature plume as it entered the Missouri River was very evident on the imagery obtained this date. There is a 6 million cubic meter reservoir on this stream used as a cooling pond for a 200,000 kw generating plant.

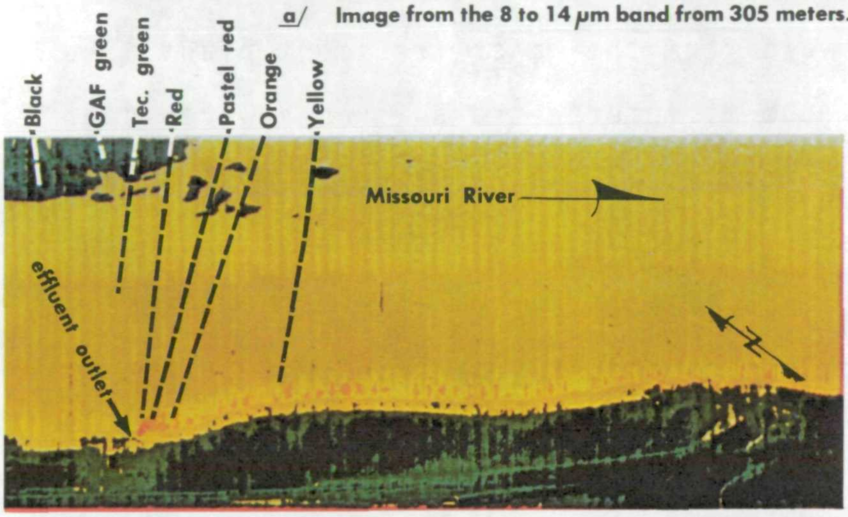
Generating Plant Effluents

Montana-Dakota Utilities

The cooling-water effluent from the Montana-Dakota Utilities (MDU) 75,000 kw generating plant, 114 km below Garrison Dam near Bismarck, is shown in the three imagery prints in figure 6. This effluent discharges from a conduit above the surface of the river. At the time of the imagery flights, the discharge rate was about 0.5 m^3/sec at a temperature of 21°C to 23°C; about 6°C to 7°C warmer than the river. The fact that the effluent discharges on the surface in a straight relatively shallow area of the river probably accounts for the great distance (more than 1 km) that such a small quantity can be traced. Though readily apparent on the imagery from 305 meters, the effluent could not be detected on the imagery from 1,524 meters; and though detectable on



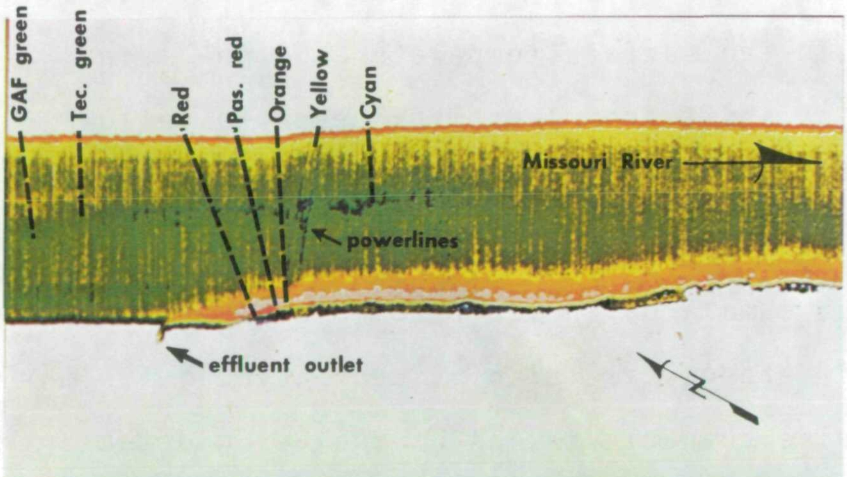
a/ Image from the 8 to 14 μm band from 305 meters. 8-1-67



COLOR SCALE

Red	Hot
Pastel red	
Orange	
Yellow	
Tec. green	to
GAF green	
Cyan	
Black	Cold

b/ Color-coded quantization of image from 3.5 to 12.5 μm band from 305 meters. 7-23-69.



COLOR SCALE

Color	° Celsius
Red	15.6-15.8
Pas. red	15.3-15.6
Orange	15.0-15.3
Yellow	14.7-15.0
Tec. green	14.4-14.7
GAF green	14.2-14.4
Cyan	13.9-14.2
Black	13.4-13.9

c/ Color-coded quantization of image from 8 to 13.5 μm band from 305 meters. 7-23-69.

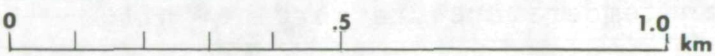


Figure 6.—Infrared imagery of the cooling-water effluent from Montana-Dakota Utilities generating plant.

the imagery from 1,067 meters, there is insufficient ground resolution or too much atmospheric attenuation for reasonable analysis.

Figure 6a is a print of the imagery obtained August 1, 1967, from 305 meters. The effluent dispersion is easily identified. Streamward from the water-treatment plant is a cold area that could be misinterpreted as ground-water seepage; whereas, in reality, it is two large boats moored to shore.

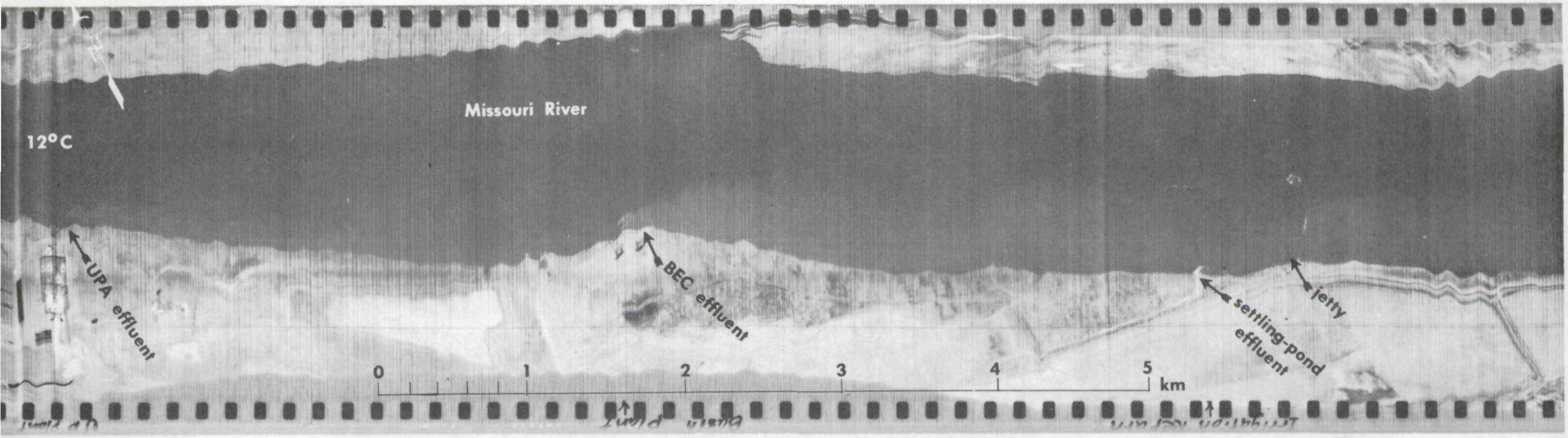
Figure 6b is a color-coded quantization of the 3.5 to 12.5 μm imagery obtained July 23, 1969, from 305 meters. The quantization was not very successful because most of the visible effluent anomaly appears only slightly warmer than the river water. With the fine voltage slicing necessary to achieve color gradation over the effluent, the unusually high noise level of the detector limited the quality of the result. The apparent change in the surface temperature of the main body of the river (the shift from Technifax green to yellow) is probably a characteristic of the system, as this was not evident in the thermal cross section.

Figure 6c is the same area in the 8 to 13.5 μm band. Small temperature differences are also evident here, but with the better signal/noise characteristics of the Ge:Hg detector, the quantization of the effluent can be finer; yet the differences in temperature are more definite. The head of the effluent was obscured by the cold plate because of a right bank by the aircraft. The result of this obscuration is that the color quantization falsely indicates the location and temperature of the hottest part of the effluent. The main body of the stream has an apparent radiant temperature of 14°C to 14.5°C; whereas, temperatures of 15.5°C to 15.9°C were measured at a cross section of the river. A point-temperature taken by hand thermometer 90 meters below the discharge point (the approximate point of maximum temperature shown on the image) was 16°C, the same as the apparent radiant temperature.

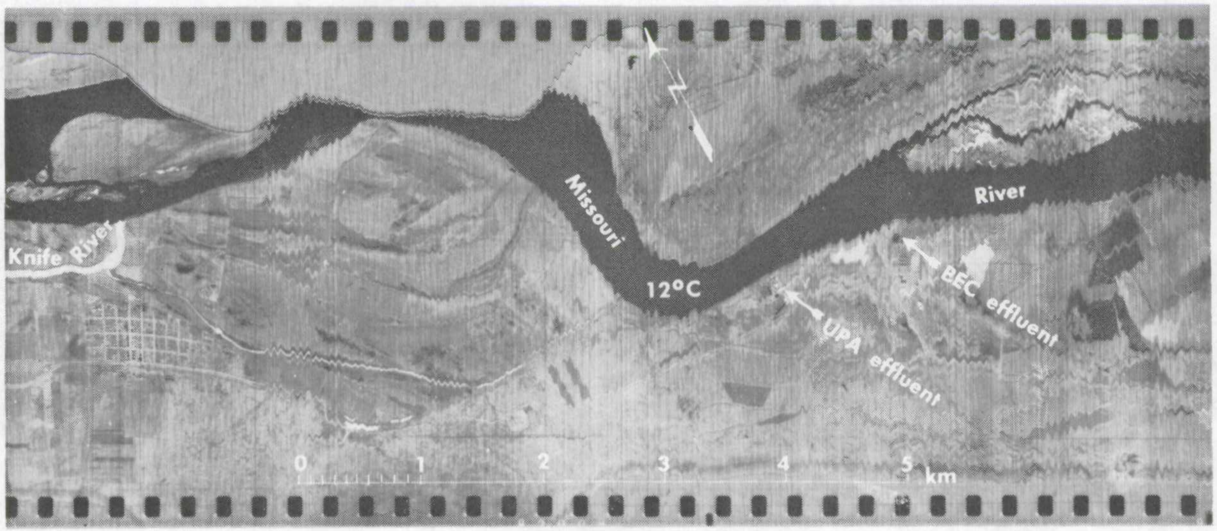
The two parallel lines in cyan extending diagonally across the river (fig. 6c) are at the electric powerlines location. These did not show on the 3.5 to 12.5 μm band (fig. 6b).

United Power Association and Basin Electric Cooperative

The imagery in figure 7 shows the effluent from the United Power Association (UPA; upstream) and Basin Electric Cooperative (BEC; downstream) electric-generating plants, 20 km below Garrison Dam. Both plants are discharging about 5.0 m^3/sec. At the time of the imagery on August 1, 1967 (figs. 7a and 7b), the effluent from UPA was 16.5°C and that from BEC was 18.9°C. The river temperature above the plants was 12°C.

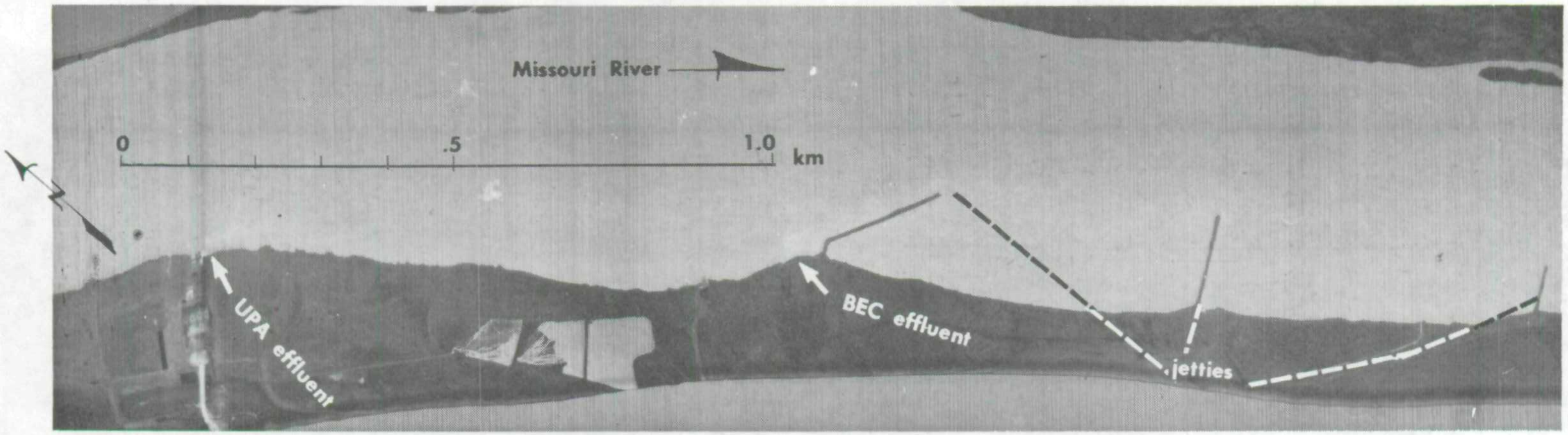


a/ Image in 8 to 14 μm band from 305 meters. 8-1-67

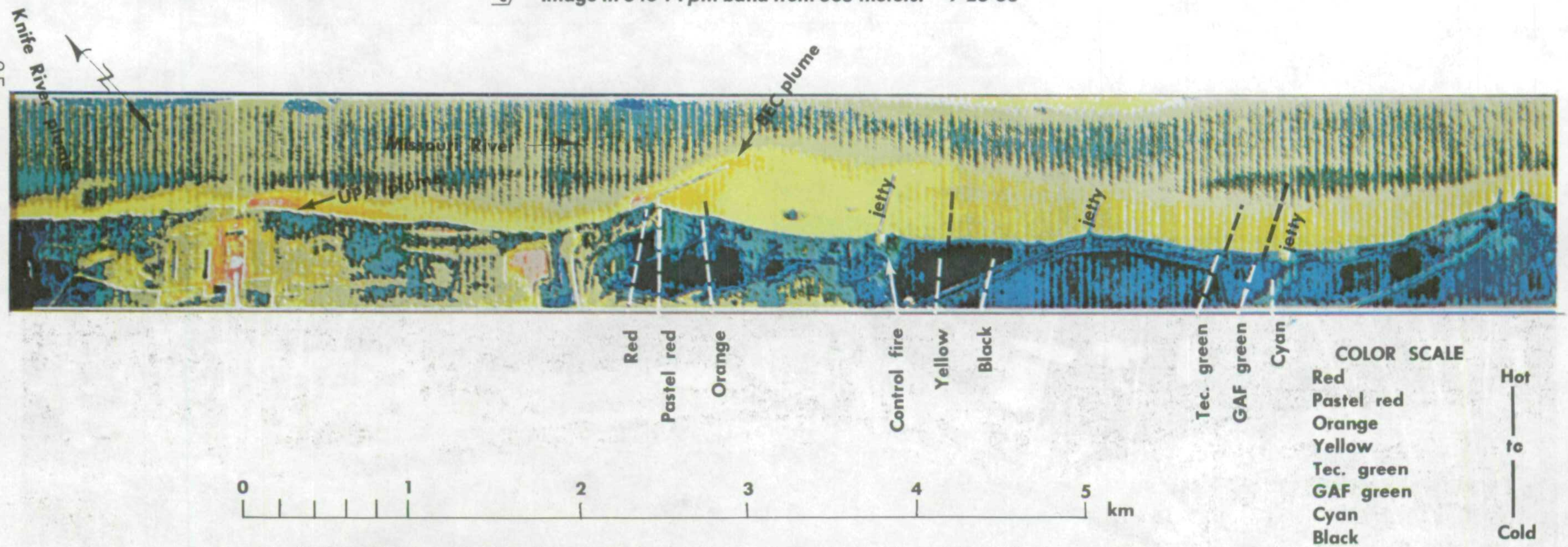


b/ Image in 8 to 14 μm band from 1,524 meters. 8-1-67

Figure 7.—Infrared imagery of the cooling-water effluents from the United Power Association and Basin Electric Cooperative generating plants.

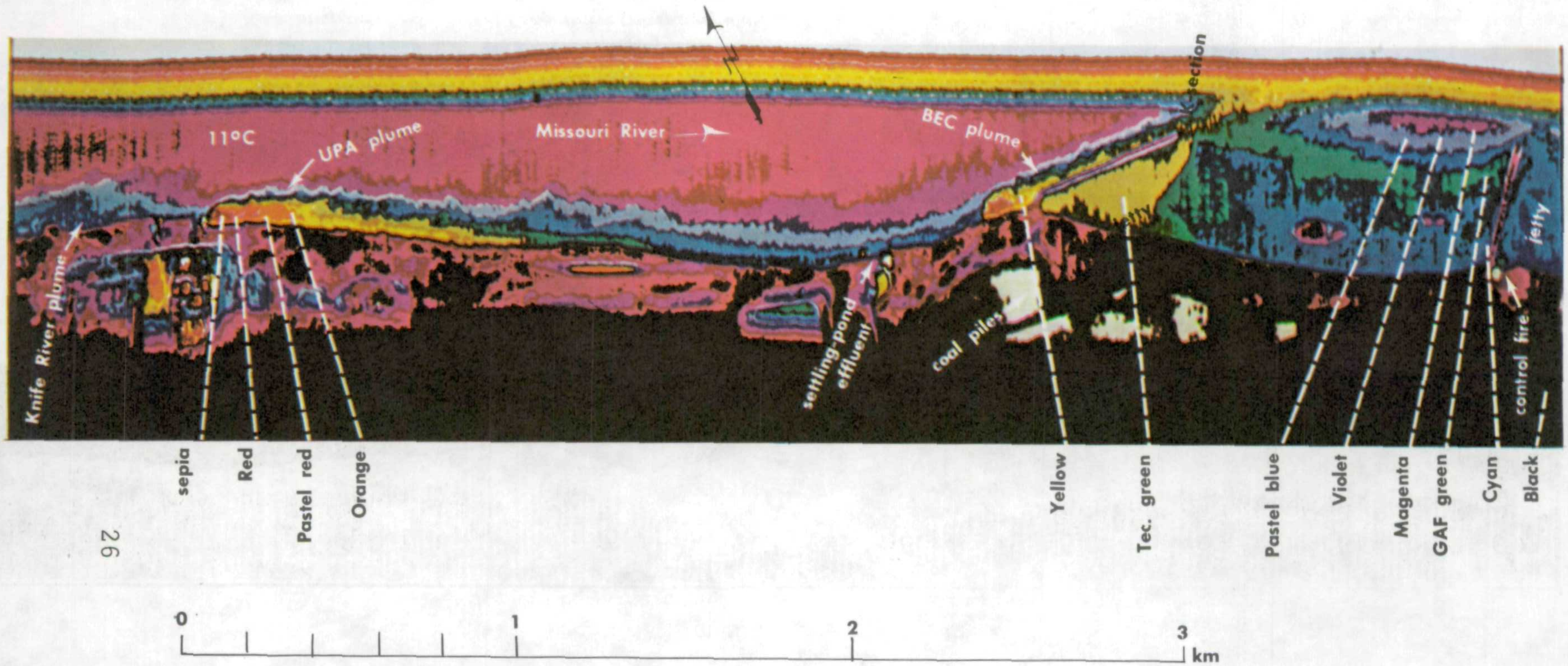


c/ Image in 8 to 14 µm band from 305 meters. 9-26-68



d/ Color-coded quantization of image in 3.5 to 12.5 µm from 305 meters. 7-23-69

Figure 7.—Infrared imagery of the cooling-water effluents from the United Power Association and Basin Electric Cooperative generating plants.



COLOR SCALE

Color	Temperature	Color	Temperature
Sepia	16.4-16.7	GAF green	13.3-13.8
Red	15.6-15.9	Cyan	12.8-13.3
Pastel red	15.0-15.6	Pastel blue	12.3-12.8
Orange	14.5-15.0	Violet	11.8-12.3
Yellow	14.2-14.5	Magenta	11.4-11.8
Tec. green	13.8-14.2	Black	$<$ 11.4

e/ Color-coded quantization of image in 8 to 13.5 μm from 305 meters. 7-23-69

Figure 7.—Infrared imagery of the cooling-water effluents from the United Power Association and Basin Electric Cooperative generating plants.

The figure indicates clearly the pattern of dispersion of the thermal influx. By careful study of the imagery negative, the warmer water from the upper plant could be traced to the far side of the river, and the combined effects of both plants could be traced for about 2.8 km downstream. A small amount of flow (0.05 m^3/sec) from the BEC settling pond discharges above river level and is easily discernible. The top of the jetty just downstream was barely submerged and appears to cause an upsurge of warm water and further diffusion.

The effluents from the generating plants can be detected on the imagery obtained from an altitude of 1,524 meters (fig. 7b), but loss of synchronization between the plane and camera speed resulted in a very ragged image. It is questionable whether the settling-pond effluent would have been detectable from this altitude even with good imagery.

Figure 7c is an example of imagery obtained on the flight of September 26, 1968. Note that there were additional jetties built in this area between the flights of August 1, 1967, and September 26, 1968. The ground temperatures were probably 2°C to 5°C colder than the average river-water temperatures. Though the thermal plumes are detectable, the effect of the colder ground on the automatic gain control of the instrument was to mask out the more subtle differences in the river.

A color-coded quantization of the 3.5 to 12.5 μm imagery obtained July 23, 1969, is shown in figure 7d. The effluent temperatures from UPA and BEC were 27°C and 29°C, respectively, and the temperature of the river above the effluent entry point was 11°C. This quantization is probably about as good as can be obtained from the raw data. In general, the pertinent information about the thermal anomalies--the sizes and shapes of the plumes, and the temperature variations--are evident.

Low-frequency noise in the detector has resulted in a linate intermixture of Technifax green and yellow, and of cyan, GAF green, and Technifax green. Also, the general instrument-effected shift noted in figure 6 is also evident here in the change from Technifax green to GAF green in the main body of the river.

Figure 7e is a color-coded quantization of the 8 to 13.5 μm image and represents the best results obtained. The limited field of view of the scanner resulted in a loss of the thermal pattern below the BEC plant, but if the images in the 3.5 to 12.5 μm and 8 to 13.5 μm bands are used in conjunction, there is adequate definition. The aircraft was banked to the left while flying over this area, as indicated by the hot-plate obscuration. The plate appears in the color image as a series of colored bars.

The temperature plumes from both plants as well as the plume from the Knife River are clearly indicated. The cooling-water intake for BEC is part of the effluent structure and lies in the temperature plume from the UPA effluent and, if surface temperatures are indicative, would mean water about 1°C warmer than the main river was being used by BEC. UPA would be getting about the same effect on their intake from the Knife River, which enters the Missouri River about 3 km upstream. It is probable that more pronounced effects would be evident when low flows prevail in the Missouri River. The warmer water from the plants apparently moves through the jetty 0.3 km downstream from BEC. The jetties are composed of large boulders and figure 7d indicates they have little effect on the temperature plumes other than directing the BEC effluent from shore.

The white patches in the land area (fig. 7e) generally represent the plant buildings and settling ponds that were too hot to be color coded. The spot at the head of the plume of the UPA effluent is probably the concrete structure rather than water and is too hot to code. The warm spot about 50 meters above the BEC intake structure is a discharge of about 0.05 m^3/sec from the UPA settling ponds. The spot on the far right side of the image is a fire used to locate a ground-truth point. At this point a manually read thermometer indicated 14°C for the river at the time of the flight. The apparent temperature from the image if 13°C (cyan). It is believed the GAF green just streamward from the white spots is attributable to the fire.

A temperature cross section of the river taken with an underwater thermometer at the outer end of the first jetty below BEC is shown in figure 8. The cross section was taken about 2 hours after the flight on July 23, 1969, but recording thermographs on both sides of the river indicated no change in the water-surface temperature during this time. The maximum and minimum temperatures found were 15°C and 11°C, respectively. The maximum apparent radiant temperature from the image was 14°C (Technifax green). The minimum apparent radiant temperature could not be checked because of obscuration, but would probably be the same as the main body of the river area shown (11.4°C-11.8°C, magenta). The cross section shows definite vertical mixing and slow lateral movement of the thermal addition.

Lake Sakakawea

The pronounced effect on the river temperature by the impoundment of Lake Sakakawea is shown in figure 9. The

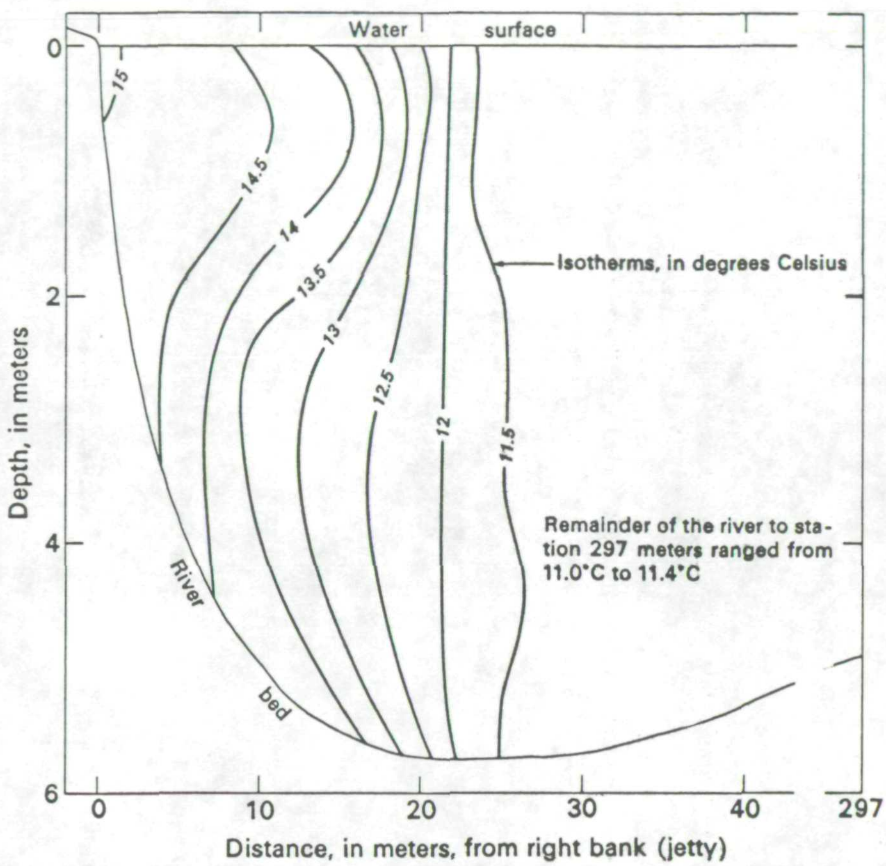
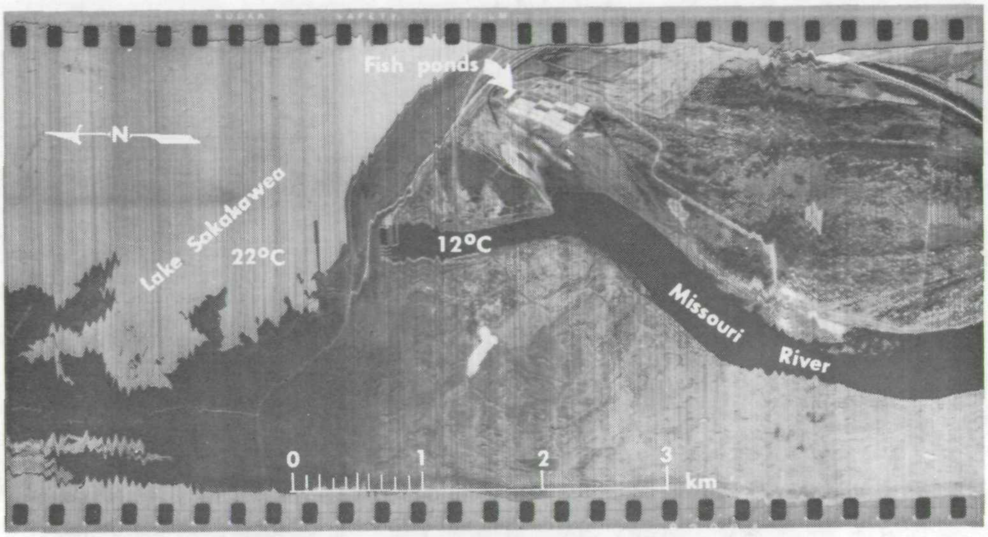
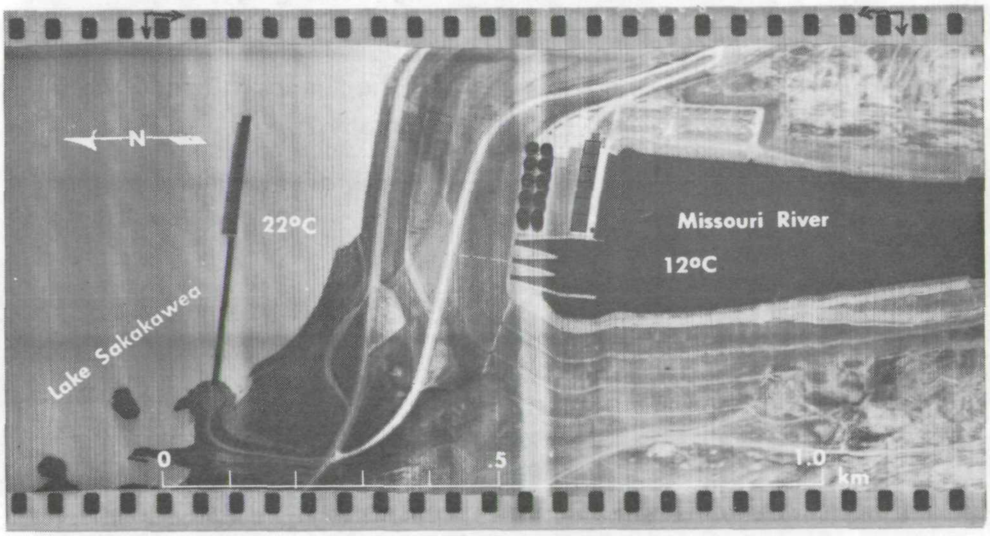


Figure 8.—Temperature cross section of the Missouri River 0.3 km below the Basin Electric Cooperative effluent point.



a/ Imagery from 1,524 meters.



b/ Imagery from 305 meters.

Figure 9.—Infrared imagery (8 to 14 μm band) of Garrison Dam. August 1, 1967.

imagery was obtained August 1, 1967. The surface temperature of the lake was 22°C, while that of the release through the turbines was 12°C. The extreme contrast in tone for the water above and below the dam is readily apparent from 305 meters and 1,524 meters.

Apparent radiant temperatures computed from the imagery of July 23, 1969, found the lake surface at 17.2°C and the water from the turbines at 11.7°C. Temperature checks on site soon after the flight found the lake surface and turbine releases at 17.5°C and 11.5°C, respectively.

RIVER TEMPERATURE PHENOMENA

A comparison of the Missouri River temperatures at Bismarck prior to and after construction of Garrison Dam is shown in figure 10. The river temperature followed quite closely the mean daily air temperature prior to construction--data obtained from manual observations made at USGS gaging stations. The records indicated almost no change in the temperature of the river as it progressed through the State. The mean air temperature shows a drop of about 1°C from the upper to the lower reaches of the river. The effect of Lake Sakakawea has been to hold the river temperatures much lower prior to the period of maximum mean daily air temperatures

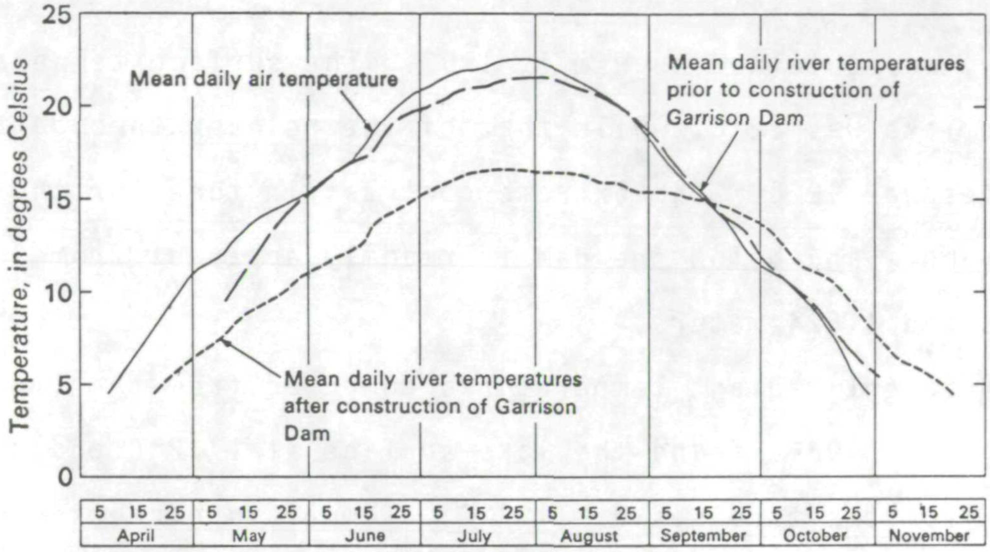


Figure 10.— Relationship between air temperature and Missouri River temperature at Bismarck prior to and after construction of Garrison Dam.

and to maintain higher temperatures as the air cools. In latter July and early August (the present study period), the effect of the lake is to drop the Missouri River temperatures at Garrison Dam from about 22°C to 11°C and at Bismarck from 22°C to 17°C. The surface temperatures of Lake Sakakawea followed quite closely those of the mean daily temperatures at the time of the study. However, owing to the temperature stratification in the lake, much colder water is discharged through the hydroelectric turbines. Figure 11 shows two typical vertical temperature profiles in the lake. On August 24, 1969, temperatures varied from 22°C at the surface to 12°C at the bottom of the lake, with no distinct thermocline. On July 25, 1970, temperatures varied from 19°C at the surface to 9°C at 46 meters (the probe did not reach bottom). Note the abrupt temperature change in the thermocline layer between 33 and 37 meters.

The results of spot thermometer readings, surface-temperature-recorder readings, and apparent radiant temperatures from the infrared imagery are plotted in figure 12 to indicate a temperature profile from Garrison Dam to the headwaters of Oahe Reservoir. It should be emphasized that infrared imagery in any wavelength senses the apparent radiant temperature of the skin surface only. The cross

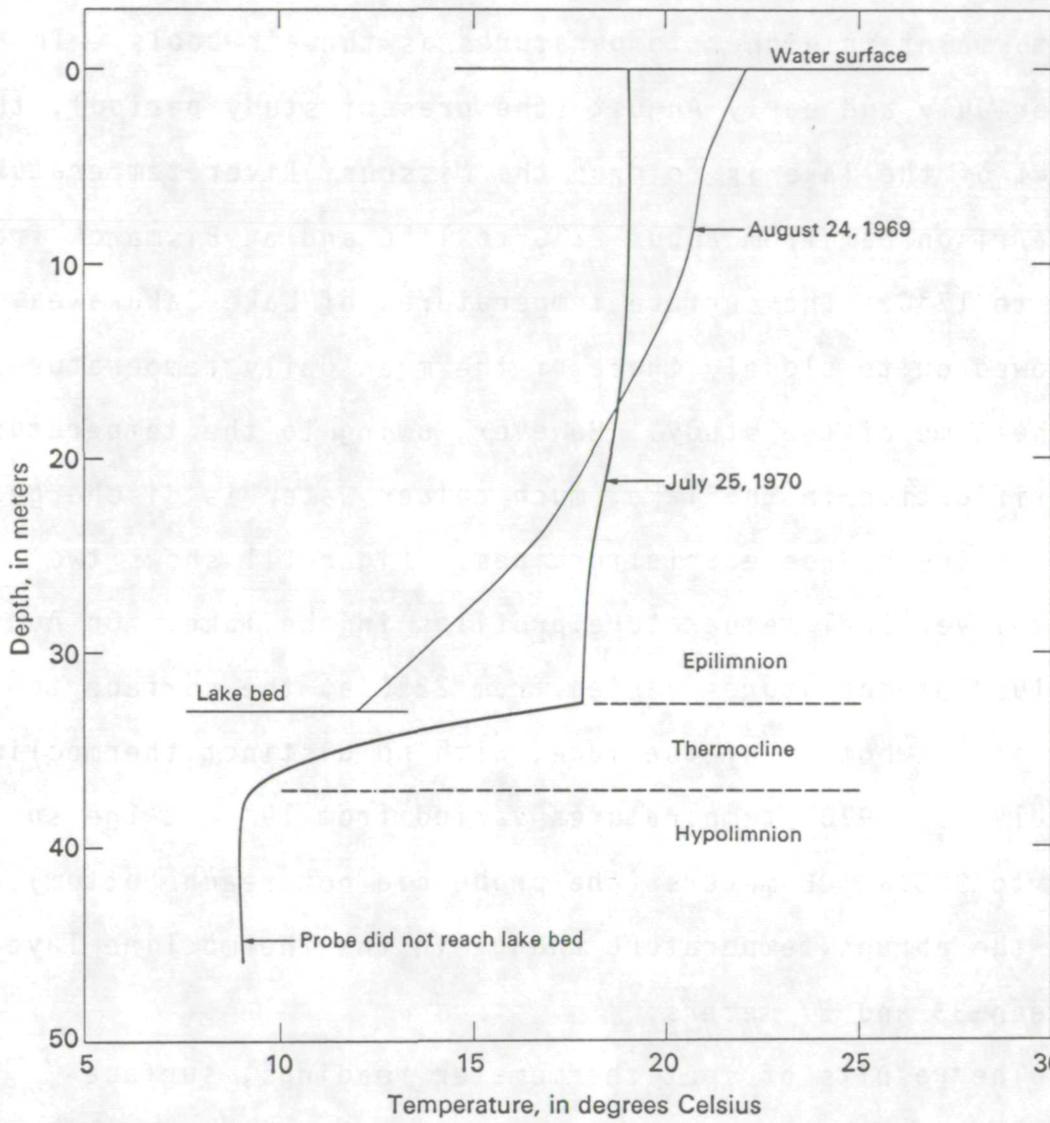


Figure 11.— Vertical temperature profiles taken in Lake Sakakawea.

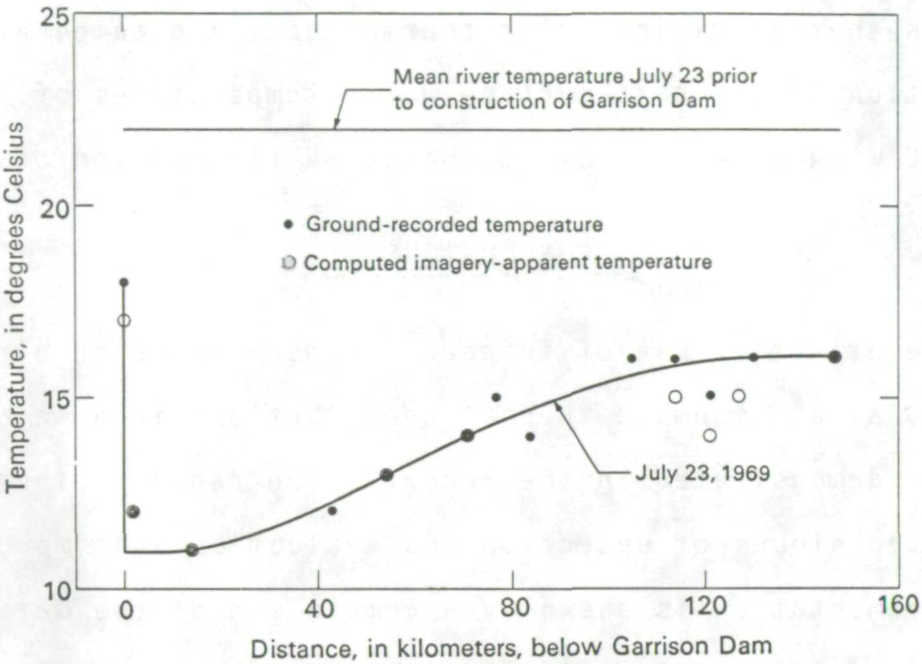


Figure 12.— Mean temperature profiles of the Missouri River.

sections taken in the Missouri River generally indicated a thorough thermal mixing. The thermographs indicated a daily fluctuation of the near-surface water temperatures of 0.5°C to 1.0°C with a 24-hour air temperature fluctuation of 14°C.

CONCLUSIONS

The effective use of infrared imagery in describing both the natural and manmade thermal contributions in a major river is demonstrated in the report. The rapid refinement of the techniques of detection and evaluation and improvement of instrumentation is shown by a comparison of the data obtained August 1, 1967, with that obtained September 23, 1969.

The imagery without thermal reference sources was adequate for qualitative analysis of the geographic locations and geometric patterns of the thermal anomalies.

Thermal reference sources along with manual gain control are necessary to make an adequate quantitative analysis. The study indicated that computed apparent temperatures from low-altitude flights agreed with temperatures from ground-truth-data instruments within 1°C.

The ground resolution obtained with the available instruments was generally adequate to define the thermal anomalies from the 305-meter altitude, but ground resolution and atmospheric attenuation precluded any but the broadest interpretations when obtained from 1,067 meters and above. Ground resolution down to 15 meters appears desirable to define most of the thermal anomalies and would probably be sufficient in choosing optimum locations for electric-generating and industrial plants dependent on the thermal properties of the water.

The impoundment of Lake Sakakawea has resulted in a significant drop in the temperature regimen of the Missouri River between Garrison Dam and the headwaters of Oahe Reservoir. At the time of this study, indications are that tributary inflow and generating-plant effluent do not contribute enough warmer water to cause noticeable changes for more than 2 to 3 km downstream.

The present study should be considered only the first step in monitoring the developments that may change the thermal properties of the Missouri River. The need for such monitoring is indicated by present plans to build or enlarge lignite-fueled thermal-electric plants, and possible construction of nuclear-fueled generating plants along the river.

With the development of a workable combination of ground and spatial thermal resolution, an orbital system might be used to provide long-term repetitive information for evaluation of time-variant thermal phenomena.

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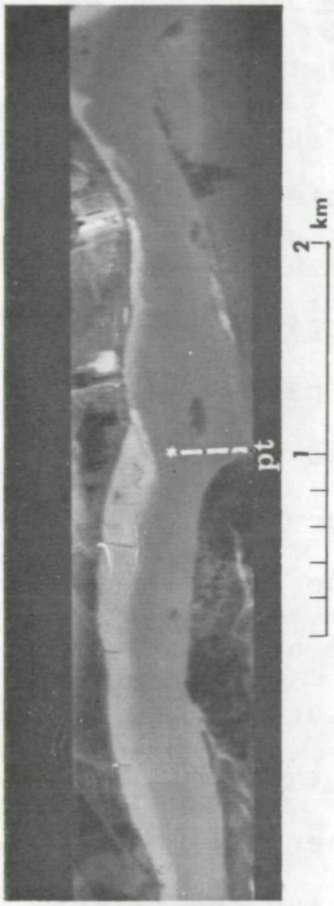
APPENDIX A

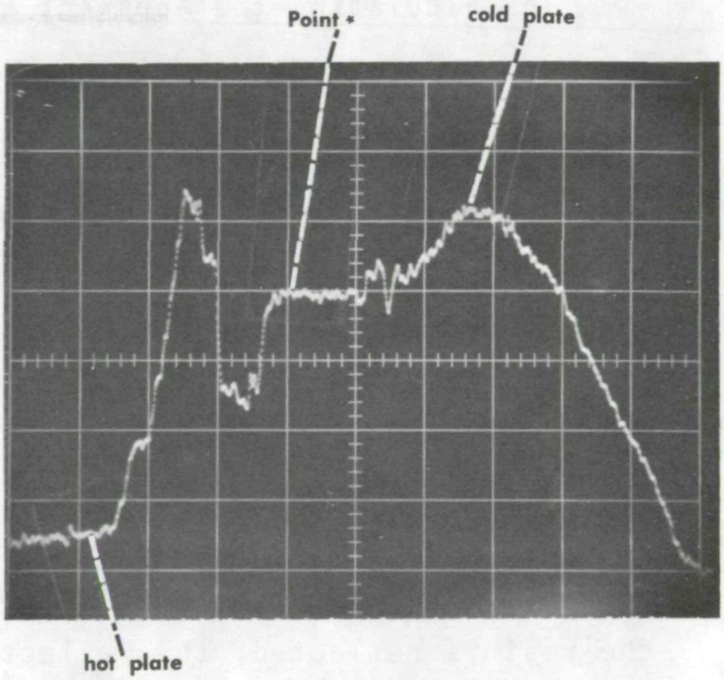
Computation of Apparent Radiant Temperature

In calculating the apparent radiant temperature for a designated point (fig. 13a) the first step was to photograph an amplitude profile of a scanline through the point (fig. 13) including signals from the hot and cold reference plates. The temperatures of these plates were obtained by use of thermistor data, which were recorded at the beginning of each run. Both plates were coated with flat black paint whose emissivity in the 8 to 13.5 μm band is 0.9 (and whose reflectance is 0.1). Part of the radiation received by the scan optics from each plate is emitted from the plate, and the rest is reflected; the reflected radiation originating from the surroundings. The plates and their surroundings have been constructed to allow the assumption that the surroundings are equivalent to a covering hemispherical blackbody radiator at ambient air temperature. During the flight, the hot plate was also allowed to assume ambient air temperature.

By use of the above data and assumptions, the effective radiances of L_h of the hot plate and L_c of the cold plate were calculated as follows:



a/ Contact print
Flight direction ↑
Scan direction →



b/ Amplitude of scanline through point *

Hot plate radiance	4.37	$\mu W \cdot cm^{-2}\ sr^{-1}$
Point * radiance	4.06	"
Cold plate radiance	3.95	"

Apparent temperature of point * is 54° F

Figure 13.—Location and scanline profile used in apparent-temperature conputation.

$$L_h = 0.9\ L^b(T_h) + 0.1\ L^b(T_h) = L^b(T_h)$$

$$L_c = 0.9\ L^b(T_c) + 0.1\ L^b(T_h)$$

where $L^b(T)$ is the radiance in the 8 to 13.5 µm band of a blackbody having the temperature T; T_h is the temperature of the hot plate and surroundings; and T_c is the temperature of the cold plate. These effective radiances were used along with the scanline amplitude profile to calculate the apparent radiant temperature for the point. After studying the amplitude profile of each scanline, and comparing it with the corresponding contact print, one can find the profile of the river and locate the approximate position of the designated point on it. This done, the relative amplitudes (in centimeters, say) of the cold plate, hot plate, and point signals were measured directly from the profile by use of a scale. The apparent radiance L_p of each point was then derived by linear interpolation of the cold- and hot-plate radiances, L_c and L_h, respectively. The interpolation formula is as follows:

$$L_p = \frac{L_h - L_c}{D_h - D_c}(D_p - D_c) + L_c$$

where D_h, D_c, and D_p are vertical distances measured from an arbitrary level on the profile.

Linear interpolation of radiance is justified under the assumption that the spectral responsivity of the detector is nearly flat in the 8 to 13.5 μm band. Manufacturer's performance curves for the Ge:Hg detectors used with scanner 1 validate this assumption. Furthermore, the cold- and hot-plate temperatures, in most cases, closely bracketed the apparent-temperature variations over the surface of the river, a situation which is favorable to linear interpolation.

The apparent radiance of the point thus obtained, the corresponding blackbody temperature was then determined. This temperature was taken to be the apparent temperature of the river at the point; since the emissivity of water in the 8 to 13.5 μm band is 0.99. A further assumption here is that there is no atmospheric absorption or scattering in the band From a practical standpoint, this assumption is substantially correct for the 305-meter data. However, some significant error because of atmospheric effects may be introduced by this assumption for the 1,067-meter data. Computations of the 1,067-meter atmospheric path absorption and radiance would be inordinately costly and may not be highly reliable. An indication of the differences between the apparent radiant and recorded temperatures can be obtained from figure 12.

The precision of the calculation procedure is ±0.1°C. However, because of electronic noise and other random variations in system response, the precision of the apparent radiant temperatures should not be considered better than ±0.5°C.

APPENDIX B

Color-Coded Quantization

The first data-processing operation in producing a color-coded quantization is voltage-level slicing. For each slice, the magnetic tape containing the data is replayed, and the signals are fed to the slicing unit. The response between two preset levels is recorded in image form on a film strip in opaque black, the remainder of the film being left transparent. The film-strip segment resulting from each slice, called a contour negative, is used to produce a single color transparency, one of the colors appearing in the final quantization. The transparencies are then overlaid to produce a multicolored sandwich, which is then photographed to produce the final color negative and positive transparencies. The choice of the size and number of slices must take into consideration the amplitude of river signals, the relative noise level, the number of colors available, and the limitations of the slicing unit. Noise effects, which may be hardly noticed in the black and white imagery, tend to become pronounced in the color-coded quantized imagery. Because much of the data are characterized by relatively large amplitude noise and (or) low-amplitude river signals, it was decided to use a graded sequence of colors, wherein each color is not far different from the adjacent ones. With this scheme, interspeckled colors because of noise are not as confusing as with a contrasting color sequence.

THERMAL STUDY OF THE MISSOURI RIVER IN NORTH DAKOTA USING INFRARED IMAGERY BY ORLO A. CROSBY