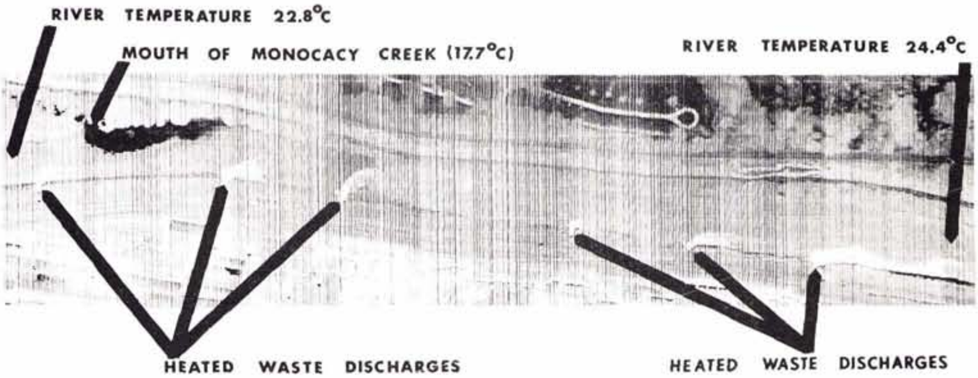

FRONTISPIECE. Predawn infrared image of the Lehigh River at Bethlehem, Pa. August 1, 1968.

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Ground-Water Flow

Previously unlocated discharges along the banks of the Lehigh River, Pennsylvania, were detected with thermal IR in the 8–14 micron range.

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INTRODUCTION

THIS STUDY IS a part of a U. S. Geological Survey—National Aeronautics and Space Administration (NASA) cooperative program to develop remote-sensor technology useful in the solution of water-resources problems. Specific objectives of this study include locating points of ground-water discharge to the Lehigh River (Figure 1) and points of industrial and domestic-waste discharge. Although the data used in this study were aquired from aircraft, the usefulness of similar data from an orbital satellite was considered.

The hypothesis being tested is that thermal infrared imagery, which displays temperature differences, can be used to identify ground-water discharge. Much ground water with a nearly constant temperature of about 12° C is discharged from a limestone aquifer to the Lehigh River throughout the year. However, the river temperature varies seasonally, being much warmer in the summer and cooler in the winter than the nearly constant ground-water temperature. Because of the thermal contrast and because the river is shallow and turbulent, infrared imagery was expected to pinpoint the location of both cool ground-water and heated-waste discharge. Ektachrome color and Ektachrome color-infrared photographs may show differences in visual properties (perhaps related to differences in aquatic vegetation) between areas in the river that receive water from different sources.

DATA ACQUISITION

Three sets of predawn and one set of midday infrared imagery have been taken of the Lehigh River from its mouth, at Easton, to a point about one mile north of Cementon (Figure 2), a reach of about 23 miles. Surface-water temperatures were measured at about 25 sites during each of the flights to provide ground truth (water temperature) data. Ektachrome color and color-infrared photographs were also taken during the midday flight. Features observed on the infrared images and the photographs were examined in the field. Soil and water temperatures were

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ABSTRACT: *Previously unlocated ground-water discharges along the banks of the Lehigh River, Pennsylvania, were detected by a Reconofax IV infrared imager which senses in the 8–14-micrometer bandwidth. Springs with flows of as little as one gallon per minute were detected on predawn imagery. The cold areas on the infrared image did not indicate the quantity of water being discharged.*

measured to distinguish thermal anomolies in the river from those on the banks. The hardness and conductance of the river, springs, and other discharges were measured to identify the source of each discharge to the river.

The first set of predawn infrared imagery was obtained by the U. S. Geological Survey in April 1967, using a Reconofax IV infrared imager which senses in the 8–14 μm bandwidth. The river surface appeared as a uniform white tone on a film-positive image, probably because of the response of the automatic gain control to the large cool land surface and the relatively narrow warm water surface. The automatic gain control adjusts to the average of the total signal received on each scan, and for this imagery, the average signal was essentially that of the large land area. The signal received from the water, which was much warmer than the land, exceeded the dynamic range of the film, causing the film positive to show a uniform white tone for water.

The second set of predawn imagery was obtained in July 1967 by the NASA Electra NP3A, using an RS7 infrared imager (8–14 μm). This imagery showed land features in excellent detail, but the water again appeared as a nearly uniform white tone on a film-positive image, although a few areas of seeps and springs along the banks of the river were barely discernible. Again, the quality of the imagery was not adequate for hydrologic interpretation and analysis.

The midday imagery was taken on July 31, 1968, from the NASA Convair 240A, using a Reconofax IV infrared imager (8–14 μm). The land was much warmer than the water at this time, and the river appeared almost uniformly black on a film positive; so, thermal differences could not be discerned. The difficulty was the reverse of that on the previous predawn imagery and was also believed to be caused by the automatic gain control.

The third set of predawn infrared imagery, the best that has been obtained for this site, was taken on August 1, 1968, by NASA with the Reconofax IV mounted in the Convair 240A. The imagery was taken after 6 days of no precipitation and after a month that had a total of only 1.60 inches of precipitation at Allentown. The flow of the river was 532 cfs (cubic feet per second) at Walnutport, near the upstream limit of the study reach; 750 cfs at Bethlehem, just downstream from the mouth of Monocacy Creek; and 932 cfs at Glendon, 2 miles upstream from the mouth of the river. These flows are equaled or exceeded about 80 percent of the time. Very few thermal features within the river could be detected on the imagery, but numerous springs and seeps could be clearly seen along

FIG. 1. Location of the Lehigh River basin.

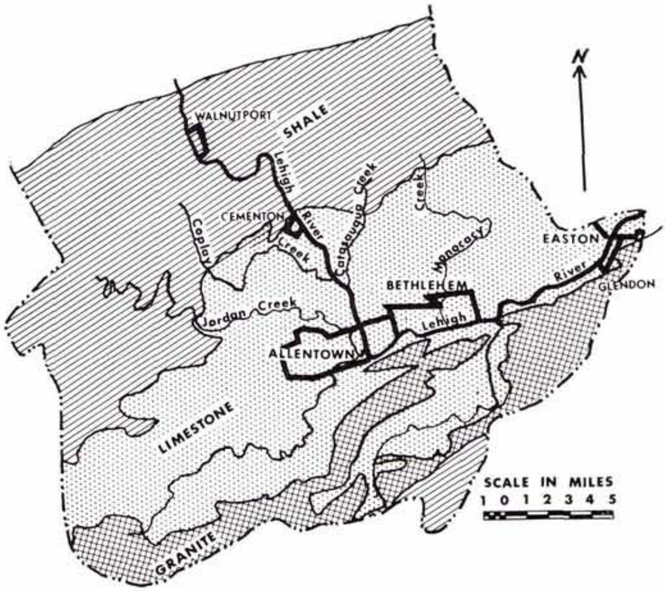

FIG. 2. Geologic map of the lower Lehigh River basin.

the banks. The river and land temperatures were very similar (22° to 26° C) when this imagery was taken. As a result, the cooler springs (10° to 15° C) along the banks of the river stood out clearly on the imagery.

On July 31, 1968, Ektachrome color and Ektachrome color-infrared photographs were taken from an altitude of 2,000 feet (RC-8 camera). Except where cloud cover was excessive, the photographs were of excellent quality.

DATA REDUCTION AND INTERPRETATION

The imagery obtained by NASA on August 1, 1968, was carefully examined to identify thermal anomalies along the river. Nearly all of the anomalies were located and examined in the field in September 1968. These field investigations indicated that there was no relation between the size of the cold (dark) areas on the imagery and the magnitude of the ground-water discharge.

The color and color-infrared photographs yielded considerable information of hydrologic interest, but no visible manifestations of the thermal features were detected on the imagery. Among the features that could be seen on the photographs were areas of dead vegetation, emergent and submerged rooted aquatic plants, oil floating on the river, structure in the bedrock at the bottom of the river, and bottom sediments (including deposits indicative of eddies and unidentified long narrow grooves or ridges). The color and color-infrared photographs were useful in locating and (in some instances) identifying the features seen on the infrared imagery. Some hydrologic features were more apparent on the color-infrared than on the Ektachrome color, although using both enhanced the possibility for meaningful interpretation. Stereo viewing was not essential for interpretation, but the 60 percent overlap of the photographic frames compensated for loss of image quality caused by surface-wave glitter patterns and other reflections from the water surface.

INTERPRETATIVE RESULTS

APPLICABILITY TO WATER-RESOURCE PROBLEMS

The Lehigh River was chosen as a test site because it is known that significant quantities of ground water discharge directly to the Lehigh River from limestone aquifers. The geologic map (Figure 2) of the lower Lehigh River basin shows the area underlain by limestone. Figure 3 shows water-level contours in part of the limestone aquifer during a period of relatively low water levels in October 1968. This map shows a gently sloping water-table trough that parallels Jordan Creek to about the 280-foot (above mean sea level) contour, then trends northeastward, under Coplay Creek, to the Lehigh River. Stream-gaging stations on Jordan and Coplay Creeks indicate that about 27 mgd (million

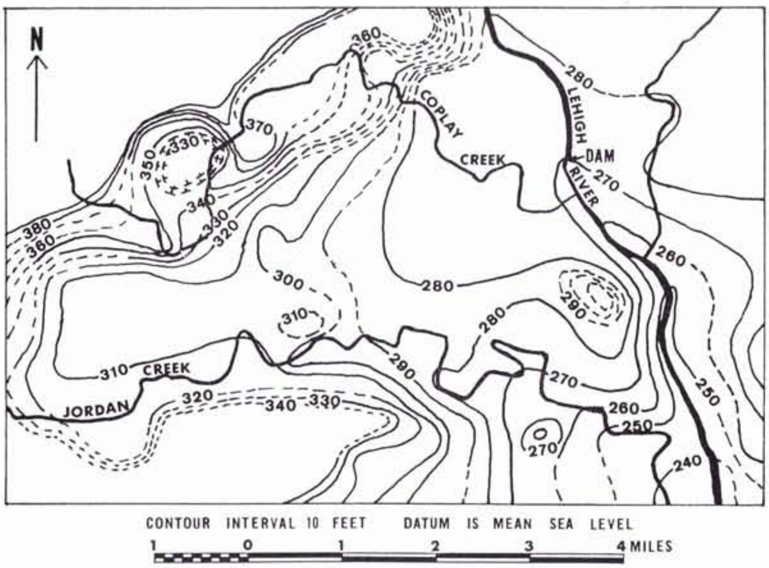

FIG. 3. Water-level contour map, mid-October 1968.

gallons per day) discharges from those streams to the limestone aquifer; some of this water is eventually discharged from springs directly to the Lehigh River.

Numerous springs and seeps on the banks of the Lehigh River can be seen on the imagery (Figure 4) covering the center of the ground-water trough that is indicated in Figure 3. Field estimates of discharge indicate that the total flow of all the springs shown in Figure 4 is less than 10 percent of the estimated ground-water inflow (27 mgd) to this reach. Therefore, most of the ground-water inflow must occur through the river bed and was not detected by the scanner. Apparently, the denser, colder ground water issues from many small openings in the river bed, flows along the bottom of the river, and is admixed by the turbulent river water.

The reach shown in Figure 4 lies in a ground-water trough (Figure 3) and should receive a substantial quantity of ground-water discharge. However, no springs or seeps could be seen upstream from the dam (Figure 4), probably because the higher head behind the dam reduced ground-water discharge to the pool. The reach of river downstream from the dam (Figure 4) received the largest quantity of ground-water discharge that could be located in the entire test site.

The size of a cold area, as shown on the imagery, depends more on the depth and

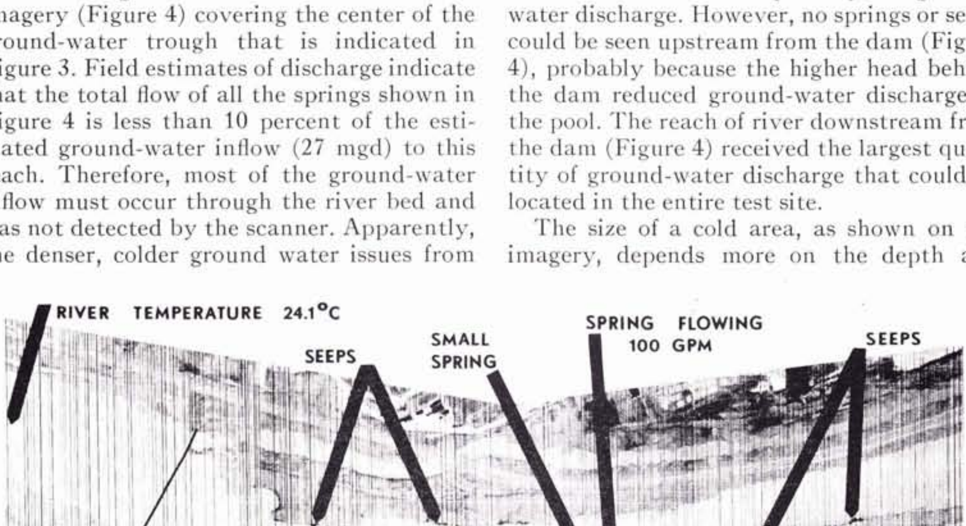

FIG. 4. Predawn infrared image of the Lehigh River at North Catasauqua, Pa., August 1, 1968.

velocity of the river than on the quantity of water discharged from seeps and springs. Where the river has high velocities, water from small springs is quickly mixed with river water and removed from the vicinity of the spring. For example, the area labeled *spring flowing 300 gpm* on Figure 4, which was the largest spring found during this investigation, discharges into swiftly flowing water and produces a relatively small cold area on the imagery. In contrast, the area labeled *many seeps* on Figure 5 has a total flow of only a few gallons per minute, but it discharges into slow moving water in an area of shallows and produces a large cold area on the imagery.

Most of the cold (dark) areas that are identified in Figures 4 and 5 are due to water-temperature river anomalies that result from cold ground-water discharges from seeps and springs. However, because many of the discharges were located a few feet back from the edge of the water when the imagery as taken, some of these cold areas included part of the bank. For example, at one of the small seeps just downstream from the mouth of Coplay Creek (Figure 4), no thermal anomalies could be detected in the river during the field investigation, but the temperature of the land surface around the seep (18° C) was 3.2° C less than the temperature of the river (21.2° C) and several degrees less than the surrounding land surface.

Very few springs and seeps are present in the reach (the Frontispiece), although a few heated-waste discharges at Bethlehem, Pa. (light areas) can be seen on the figure. In fact, very few springs of any size can be found from Allentown to the mouth of the Lehigh River. The main ground-water movement occurs in an east-west direction parallel to the strike of the limestone beds. Relatively small amounts of ground water flow southward across the bedding into the Lehigh River.

APPLICABILITY TO SPACE SENSING

Remote sensing of the Lehigh River has indicated that springs with flows of about one gallon per minute can be detected by aircraft-mounted infrared scanners. This would suggest that it may be possible to detect some large springs from spacecraft equipped with a very high thermal and spatial resolution imaging system. Except where large quantities of water are involved, however, it would seem that aircraft will be more effective than spacecraft in using remote sensing techniques to locate ground-water discharges.

CONCLUSIONS AND BENEFITS

Remote sensing can provide unique data needed for hydrologic understanding essential to successful development and management of water resources. In this study previously unlocated ground-water and heated-waste discharges were detected by an infrared imager. By using infrared imagery in conjunction with other hydrologic data, this investigation has provided data on the specific areas of discharge (Figure 4) from Jordan Creek through the limestone aquifer to the Lehigh River. This information is necessary to design and operate properly a proposed dam in the headwaters of Jordan Creek.

A possible benefit of widespread use of infrared imagery is the detection of large springs that may be suitable for industrial or public-supply use. Although no such large springs were found in the test site, the study did demonstrate the feasibility of using infrared imagery to locate ground-water discharge

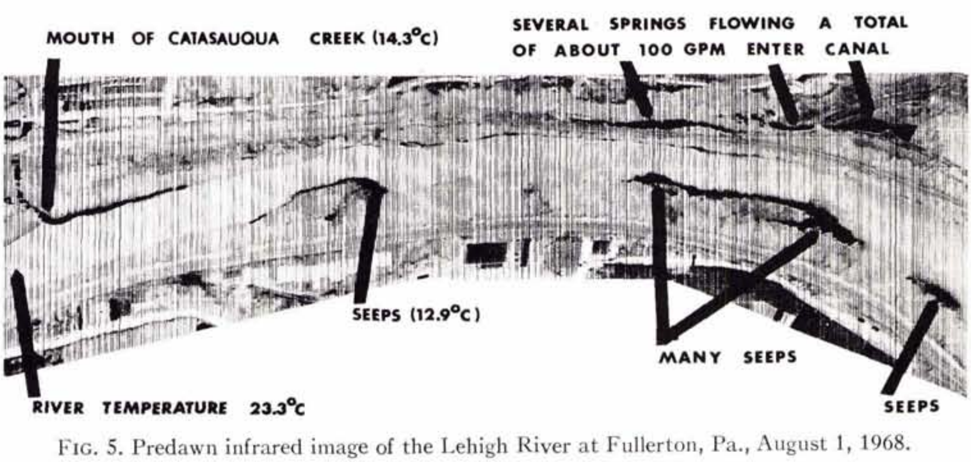

FIG. 5. Predawn infrared image of the Lehigh River at Fullerton, Pa., August 1, 1968.

along the banks of the river. In the test site, it has been possible to locate seeps and springs which could not have been found readily from the ground because the river banks are steep and overgrown, the river cannot be easily waded or navigated with small boats, and the seeps are often very small. Precisely defining the location of ground-water discharge will aid in understanding the mechanics of ground-water flow in other areas.

Ground-water discharges near the banks are best detected by infrared imagery taken when the land and water masses are at nearly the same temperature and the discharges are at a significantly higher or lower temperature. The best infrared imagery (8–14 μm) for this site was obtained during the predawn hours. However, the time of day the imagery is taken is probably not as important as the relative temperatures of the land and water.

Future Mission Requirements

This study has proven the capability of infrared imagery, taken at low altitudes, to locate very small seeps and springs along the banks of rivers. At least two questions would warrant further investigation which is beyond the scope of this study. Can seeps and springs be detected from higher altitudes? Can ground-water discharge through the river bed be detected under optimal conditions of temperature and flow?

Answering the first question would require collection and interpretation of additional imagery taken with various scanners at high altitudes. Answering the second question, that of locating discharges that enter the river away from the banks, would require scheduling of flights with only a few hours notice, as very specific conditions of temperature and flow in the Lehigh River are required. Probably the most favorable condition occurs in the winter, when the river temperature is about 4° C and about the same as the land temperature, and ground-water discharges are relatively warm (10° to 15° C). In addition, low-flow conditions must prevail, as the springs will be obscured by high flows.