REMOTE SENSING FOR DEFINING AQUIFERS IN GLACIAL DRIFT

By

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INTRODUCTION

The economy of much of the glaciated portion of the middle western states is greatly influenced by the availability of ground water. Shallow aquifers, which contain extensive ground-water reserves and are continually replenished to some degree, occur throughout the region.

The bottom of many shallow aquifers in glacial drift is less than 100 feet (30.5 meters) below the surface. Thickness of these outwash sands and gravels may vary from only a few feet to as much as 80 feet (24 meters) or more. Quality of water is generally good. Present plans for mapping these aquifers extend many years into the future because of tedious standard investigation procedures. Remote sensing may provide part of the information required to speed up these ground-water surveys.

Aquifers can seldom be detected directly by using remote sensing, but there are certain properties of aquifers, and a number of associated features and conditions which influence reflected and emitted radiant energy. Features that appear on imagery that aid in identifying aquifers are land forms, glacial outwash patterns, stream patterns, vegetative type and condition, soil moisture, and snow melt patterns. Also, thermodynamic considerations show that a shallow aquifer might form a heat sink that influences and modifies the temperature effects of heat originating at the land surface and within the crust [2] [3].

The objectives of this study are to determine the properties of shallow aquifers and related features that influence electromagnetic energy, to determine how these properties can be detected remotely, and to establish remote sensing procedures for aiding in ground-water mapping.

This research effort is underway in areas of South Dakota where intensive geology and water resources investigations have been conducted. Thus a great deal of data are readily available for correlation with remote sensing imagery. Upon successful completion of the studies in areas of known aquifers, the effort will be expanded to a pilot study in an area where a ground-water investigation is in its early stages. Procedures developed under the known conditions will be used to predict the occurrence of aquifers.

This progress report deals specifically with the thermal infrared phase of aquifer mapping; in particular the direct influence of aquifer characteristics on surface thermal contrasts. The related photographic and thermal studies involving soil moisture and other conditions and features as they relate to the occurrence of aquifers are still underway.

The research work reported in part herein is expected to yield ground-water maps of shallow aquifers in glacial drift. The maps should be useful in detailed investigations for determining the location for drilling explorations. It is expected that detailed explorations can be made faster and at a reduced cost with the availability of aquifer maps produced from remote sensing imagery.

The project is jointly supported by the U. S. Geological Survey and the National Aeronautics and Space Administration. The District Office of USGS at Huron, South Dakota, the South Dakota State Geological Survey, and the U. S. Bureau of Reclamation furnished the well logs and historical information used in the studies and gave valuable advice in setting up the studies. Dr. Fred Schmer of RSI was helpful in providing advice and consultation. Dr. Fred Waltz and Mrs. Josephine Parikh of RSI conducted the statistical studies.

DESCRIPTION AND LOCATION OF STUDY AREA

The geology and hydrology of Beadle County, South Dakota, where these studies were conducted, were investigated and reported by Hedges [5] and by Howells and Stephens [6]. Brief sections from those reports are reproduced here to give the reader an insight into the ground water potential and investigation problems.

"Most surficial deposits in Beadle County are the result of glaciation and collectively are called drift. Along water courses and in sloughs and lakes the drift is covered by deposits of alluvium; locally the drift is covered by windblown sand and silt. Alluvium in the county consists of poorly sorted, poorly stratified, thin, discontinuous layers of material that range in grain size from clay to boulders.

"Drift in Beadle County can be divided into two major types, till and outwash. Till, which was deposited directly from or by glacial ice, is a heterogeneous mixture of silt, sand, gravel, and boulders in a matrix of clay. It is the most abundant glacial deposit in the county. Outwash, which was deposited from or by meltwater streams beyond the margin of active glacial ice, consists primarily of layers of clayey or silty sand and sandy gravel interbedded with layers of sandy and gravelly silt or clay. Beds of well-sorted sand and gravel are contained in the outwash but generally are small or discontinuous.

"About 62 percent of the area of Beadle County is underlain by 10 feet (3.05 meters) or more of aquifer material in surficial deposits. Water levels in the aquifers fluctuate in response to recharge and discharge; in Beadle County, average water levels generally have been stable or rising slightly during the past 10 years, indicating that recharge is equal to or slightly in excess of discharge.

"More than 5 million acre-feet of water (616×10^7 cubic meters) is stored in three aquifers in surficial deposits in Beadle County. The greatest potential for development of high-capacity wells is in areas where the major aquifers are more than 25 feet (7.6 meters) thick. The aquifers are recharged by infiltration of precipitation in Beadle County and by underflow from adjacent areas."

Two areas are being studied having contrasting aquifer conditions. Shallow aquifers in the James River Basin are intermittent with intermingled layering of sands and gravels and finer materials. The aquifers in the Sioux River Basin, on the other hand, consist of fairly coarse, unconsolidated materials in well-defined layers. This report is concerned only with investigations in Beadle County in the James Basin. A later report will deal with the Sioux Basin.

PROCEDURE

Flight lines labeled as J-J' and H-H' in Figure 1, were located to provide maximum data relative to diverse aquifer conditions, and number of well logs.

Aircraft missions which provided data reported in this study were flown by the South Dakota State University (SDSU) RC45J Remote Sensing Institute (RSI) aircraft. Ideal conditions for conducting predawn flights to obtain thermal imagery for identifying aquifers are rare in areas away from arid deserts, and cannot be predicted more than a few hours prior to flight time. It is thus desirable to have an aircraft available on a basis of "quick alert" to obtain a successful predawn mission.

Photographic imagery was taken by the NASA RB-57F aircraft at an altitude of 60,000 feet (18,300 meters) on November 9, 1970. The high altitude imagery covered an extensive area, including Beadle County, and will be useful in this study as an aid in ground-water mapping by evaluating surface conditions related to the occurrence of aquifers.

Remote sensing instrumentation aboard the RSI aircraft includes the following:

1. Four 70mm format Hasselblad 500 EL cameras, 50mm focal length for multispectral photography.
2. Framing cameras, 9 1/2-inch (24.1cm) film format, 6-inch (15.2cm) and 12-inch (30.4cm) focal lengths (used alternately with the Hasselblad cameras).
3. Thermal infrared scanner with sensitivity in the 4.5 to 5.5 μm wavelength band.
4. Precision radiometer, PRT-5, 2° field of view, for calibration of thermal scanner data.
5. Sol-a-Meters -- one on top of the aircraft with 180° field of view to measure incoming radiation and three on the bottom of the aircraft to measure reflected radiation. Purpose of the Sol-a-Meters is to provide continuous data for correction of imagery adversely affected by attenuation of the solar beam.

The PRT-5 radiometer is used as a basic sensor for thermal infrared mapping flights. The radiometric data are used to calibrate the infrared scanner imagery when the instruments are both used. When the PRT is used alone, the tracking data, plotted on a strip chart recorder, are related to known ground conditions. Several predawn missions were flown with the PRT providing the only temperature record, during periods when the scanner was not available.

Three cameras in the multispectral array were provided with film-filter combinations to correspond as closely as possible to the bandwidths in the ERTS-A spacecraft.

All processing of imagery from the RSI aircraft is done in the RSI laboratory for purposes of achieving quality control. Local processing also provides rapid turn-around for quick checking against field conditions. A color-encoding television densitometer was used in this study for producing color maps that separate the range of optical densities into narrow density bands. If appropriate, boundaries of areas representing real conditions can be closely approximated or inferred by visually manipulating the color slices to create the desired density contrasts.

Missions were flown diurnally and seasonally to take advantage of time-dependent phenomena that may help define aquifer and related soil moisture conditions. Flights were timed to assess theoretical considerations concerning maximum temperature gradients between the land surface and aquifers. Since heat is conducted from warm to cool materials, the direction of heat transfer at various times of the year can be inferred. In the spring and fall, the orientation of isotherms is nearly vertical, which means that the vertical heat movement is reduced to nearly zero. The steepest temperature gradients occur during the warmest and coldest parts of the year.

Summer missions, with multispectral cameras and thermal scanner, were flown to test the heat exchange hypothesis where little or no vegetation existed, and where plant cover was profuse, to indirectly measure soil moisture by plant temperature sensing. Plants without adequate soil moisture are warmer since their transpirational cooling mechanism is inhibited.

Diurnal flights were made at three times [7]; (1) predawn for soil moisture and thermal characteristics of aquifers and recharge areas, (2) after sundown for shallow subsoil thermal characteristics, and (3) between the hours of 2-4 pm during periods of maximum transpiration, for thermal characteristics of plants and ground water conditions.

Flight lines were generally laid out for convenience in gathering ground truth so that their centers coincided with roads. Also, exploration wells are most frequently drilled along roadways. However, actual flights must pass about 1/8 mile (0.20 kilometer) on either side of the centerline road so that radiance detected by the calibration PRT-5 can be associated with uniform soil and vegetation conditions that are identifiable on the thermal imagery.

To aid in nighttime navigation, rotating beacons were laid out along flight lines. Under clear conditions it was found that beacons placed 5 to 8 miles (8 to 13 kilometers) apart were adequate.

By far, the most valuable ground truth data available were the published results of geology and water resources investigations, along with profile data contained in well logs. Ground truth data gathered at the time of overflights included the following: temperature and depth to water table in selected observation wells, vegetation and soil type and condition, soil moisture, soil temperature, snow depth and water content, and climatological information. Detailed descriptions of procedures used in gathering ground truth are included for only those measurements used in this report.

A temperature log has been recorded monthly by USGS District Office Personnel in a 500-foot (155 meters) depth artesian well near the center of flight line H-H'. The temperature profile measurement is made to monitor changes in water temperature with depth, as the season changes. Since the well remains capped between measurements, it is likely that water profile temperatures are very close to soil profile temperatures. The artesian well flows very slowly, when uncapped, during periods of measurement.

A substantial number of remote sensing aircraft missions have been flown for this project to determine the optimum conditions for conducting such missions, to obtain good data. Careful recording of meteorological data related to successful missions has resulted in the accumulation of recommended conditions for conducting such missions. Optimum daytime flight conditions are not difficult to determine. On the other hand, predawn flight conditions for assessing aquifers are very difficult to determine.

Data from a predawn mission flown August 5, 1970 were used in the studies reported here. The locations of logged exploration wells were plotted on thermal imagery and optical densities (D) measured at the plotted points with a Macbeth spot densitometer. Values of optical density were then statistically correlated with data taken from the well logs. Simple linear correlation techniques were used to determine the degree of dependence of surface temperature on the independent variables. The dependent variable used in this analysis was optical density (D) of the thermal film. [optical density (D) was used instead of temperature (T) of the ground since there is a linear relationship between (D) and (T)]. The independent variables used in the analyses are:

X_2 - Depth to water table
X_3 - Depth to top of aquifer
X_4 - Thickness of aquifer
X_5 - Estimated thermal diffusivity coefficient
X_6 - Topography (departure from average surface elevation in area)
X_7 - Depth to bedrock
X_8 - Type of bedrock material.

An explanation of the variables listed is given below.

The depth to water table was recorded in more recent logs but was not recorded in most earlier logs. Shallow aquifers in the area are usually saturated; however, water tables fluctuate seasonally, and with years depending on recharge. Where no figure appeared in the well log, the depth to top of shallowest aquifer was used. This may be inaccurate since artesian pressures in the area frequently result in a water table above the shallowest aquifer.

Depth to top of aquifer was considered to be the depth to the shallowest water-bearing material.

Aquifer thickness was the sum of the thicknesses of all material with water-bearing capabilities.

Estimated thermal diffusivity was based on published values for saturated aquifer materials [1] [2].

Depth to bedrock was the figure recorded in the well logs. Data were recorded as missing where the well did not extend to bedrock.

Topography was recorded as the positive or negative departure of ground surface from average surface elevation in the near vicinity of the well.

Type of bedrock material was recorded in the well logs where the well extended to bedrock.

RESULTS AND DISCUSSION

The area in which these studies were conducted, and the specific flightlines for the predawn August 5, 1970 flight are shown in Figure 1. The three sections of thermal imagery that appear in Figure 2 are referenced for location in Figure 1.

Three sections of thermal imagery from along flightlines J-J' and H-H' are shown in Figure 2. Circled numbers on the imagery refer to apparent or proven locations of shallow aquifers. Imagery described as Sections A and B covers all portions of flightline J-J' from which well log data were used. Section C imagery covers only the part of the total H-H' flight line for which well log data are available, but is typical of the entire flightline.

The following discussions of numbered locations pertain to the numbers that appear on the three sections of imagery in Figure 2.

Location 1 is a highly-explored aquifer with 16 vertical profile logs available. Averaging the log data for the 16 holes shows an average depth to aquifer of 28 feet (8.5 meters) and an average aquifer thickness of 73 feet (22 meters).

Location 2 indicates a possible aquifer of limited thickness, suggested by the cooler surface temperature in the general area. The water resources map of Figure 1 does not show there being an aquifer in this immediate area.

Location 3, with very cool surface temperatures, indicates a possible aquifer for considerable thickness. No well logs are available, except for one slightly beyond the periphery of the area. Figure 1 does not show there being an aquifer in this area.

Location 4 lies in an area which is a part of a major aquifer, shown in Figure 1, and is indicated by the triangular shaped cool area in Figure 2. Most of the logs available in this area are from a location off the lower edge of the imagery. However, they do verify the existence of the aquifer.

Location 5 is in an area of a proven water-bearing aquifer. It coincides with the location of an extensive aquifer shown in Figure 1. Sixteen well logs in the immediate area show an average depth to aquifer of 34 feet (10.4 meters) and an average aquifer thickness of 55 feet (16.7 meters).

Location 6 has the appearance of an area underlain by a shallow aquifer. Five well logs show an average depth to aquifer of 36 feet (11 meters) and an average aquifer thickness of 50 feet (15.2 meters).

The area in Section C, represented by two numerals 7, is a broad, flat glacial outwash plain with shallow water-bearing materials under the entire area. Twenty-one well logs represented by Section C, and in the remainder of J-J' to the south, show an average depth to aquifer of 28 feet (8.5 meters) and an average aquifer thickness of 30 feet (9.2 meters).

With reference to the thermal infrared imagery shown in Figure 2, dark areas on the imagery are coolest, and light areas are warmest. Theoretical considerations indicate that the darker or cool areas that appear on predawn imagery flown during summer months are associated with shallow aquifers. Optical densities, D, of thermal film were used for correlations rather than ground temperatures, T. Densities are easier to obtain and their use avoids the extra step of relating D to T. The relation between D and T for a particular flightline is likely to be different for each mission.

Simple correlation coefficients were computed to relate the seven independent variables shown in the procedure section to optical density, D, of the negative thermal film. It must be remembered that optical density of the negative film yields values that are low for cool areas and high for warm areas. Some of the data were missing from well logs which resulted in unequal numbers of paired calculations. The numbers of observations for each variable are given as follows:

Variable	No. of Observations
X_2	50
X_3	45
X_4	47
X_5	44
X_6	50
X_7	35
X_8	33

Standard methods for testing the significance of correlation coefficients were used [4]. Table I shows the results of the statistical correlations.

Variable X_4, thickness of aquifer, is the best index of soil surface temperature for the conditions of this mission. Factors which tend to reduce the statistical correlation are, (1) aquifers frequently extend to depths beyond which the annual cycle of heat exchange is completely damped out, (2) shallow aquifers are not necessarily continuous with depth, and (3) aquifers occur at varying depths below the surface. The depth of the stratum of constant temperature is deeper in higher latitudes. Although the depth of damping has not yet been determined for conditions in the study area, methods are being devised for computing it.

Variable X_3, depth to aquifer, is not significant in the analyses involving both flightlines. X_3 was significant when computed for line J-J' only, where there was a considerable variation in depths to aquifers. The range of X_3 data for line H-H' was less which would tend to lower the correlation coefficient in this case.

Variable X_2, depth to water table, is not significant. However, as pointed out earlier, many of the well logs did not have depth to water table recorded. Where X_2 data were not available, a figure was used equal to X_3. In most cases where an X_2 figure appeared in a well log, it indicated a water table above the aquifer. It is known that artesian conditions exist in the area, and that water tables are generally above the top of the water-bearing formation. In calculation of X_3 and X_2 coefficients for line J-J' alone, X_3 was significant but X_2 was not, suggesting that aquifer depth has a greater influence on surface temperature than does the depth to water table.

Variable X_5 is highly significant. Establishing a measure of validity for estimated thermal diffusivity coefficients will be useful in later heat flux computations.

Variable X_6, topography, is not significant. In connection with predawn flights, the assumption could be made that cold air drainage into low areas could result in cooling the ground surface. Since exploration wells were drilled in high, low, and level areas, the fact that X_6 lacks significance is strong evidence that air drainage was not a factor for this particular mission.

Variable X_7, depth to bedrock, is highly significantly correlated with density of the film. It is likely that the correlation results from the association of thicker aquifers with greater depth to bedrock. Since aquifer thickness is highly correlated with surface temperature, so is depth to bedrock, since they increase and decrease somewhat in unison.

Figure 3 is an enlargement of a thermogram of the area shown as 1 in section A of Figure 2. The imagery in Figure 3 was obtained on a north-south flightline about one hour later than when J-J' was flown.

Figure 4 is a color-encoded map of the thermogram shown in Figure 3. It was produced with the color-encoding equipment described earlier. The potential of the color-encoding system is obvious when one considers that it offers a means for automatic delineation of classes of information related to optical density. In this case the stratifications are aquifer thickness.

The maximum and minimum temperatures measured by the PRT radiometer in the airplane during this mission were 14.2° C and 17.8° C, respectively. The radiometer has a 2° field of view and integrates an area about 175 feet (53.4 meters) in diameter at an altitude of 5,000 feet (1525 meters).

Information derived from well logs for correlating with surface temperatures has certain deficiencies which is not surprising in view of the fact that the explorations extended over a period of more than 30 years, involving a number of individuals and several organizations. Also, the data were not gathered with remote sensing studies in mind.

The timing of flights, the antecedent weather conditions, and those occurring during the mission are critical factors. The optimum timing and conditions are:

1. A flight date in late winter or early spring for maximum upward, and late summer or early fall for maximum downward temperature gradients.

2. A period of low temperatures in winter and high temperatures in summer for several days, with minimum cloud cover, prior to and during the mission to create larger temperature gradients, and greater surface contrasts.

3. Clear weather with low humidity, and a minimum of haze, aerosols, etc. When the sky is cloudy the amount of solar radiation is sharply reduced. Thus there is less energy available to heat the soil during the day. The base of a cloud radiates with nearly black-body intensity for its temperature. During the night hours, this return flux from the cloud reduces to almost zero the net radiation loss from the ground surface and thus reduces the fall of air and soil temperature below that expected on a clear night.

4. Very little or no snow cover over aquifers. Snow, because of its low heat conductivity, acts as an insulator and reduces to almost zero the amplitude of the temperature fluctuations in the soil. During periods of extremely cold air temperatures, the soil is kept much warmer than it would otherwise be by this insulating blanket. When the air temperature is at or above the melting point of ice, much of the heat energy of the air and radiant energy of sun and sky are used to melt and evaporate the snow, and thus are unavailable to warm and thaw the upper soil layers [1].

5. Very little antecedent rainfall. Rain can be expected to reduce or completely obliterate temperature anomalies produced by shallow aquifers. The downward movement of water of uniform temperature will erase the anomaly temporarily, or reduce it to a size that is almost indistinguishable. Generally, the more permeable the soil, the more easily the anomaly is lost by infiltration of rain water, and the less precipitation necessary to erase the anomaly.

6. Surface wind velocity of less than 5 to 7 knots if possible. Temperature anomalies associated with shallow aquifers are of the order of no

more than 2 or 3° C. Convection and conductance of heat caused by air turbulence can be expected to eliminate temperature anomalies of that magnitude.

7. A difference of more than 3 or 4° C between ambient temperature and dew point temperature at flight time, to avoid the possibility of dew, frost or fog.

The many important factors to consider in scheduling remote sensing aircraft to obtain usable data for this particular remote sensing application are obvious from the foregoing.

SUMMARY

This continuing remote sensing study of shallow aquifers leads to these conclusions for late summer, predawn missions.

1. Dynamic thermal changes near the earths surface can be used for thermal infrared sensing for detection of shallow aquifers in glacial drift.

2. Surface soil temperatures along the flightlines varied between 14.2° C to 17.8° C, on the August 5, predawn flight. Cooler temperatures were associated with the occurrence of shallow aquifers. Statistical studies indicated, under favorable conditions, that surface temperatures may be used to predict certain features related to the occurrence of shallow aquifers. They were aquifer thickness, thermal diffusivity coefficient, and depth to bedrock.

3. The timing of remote sensing missions -- diurnally and seasonally -- and the optimum meteorological conditions occurring prior to and during the mission, are critical insofar as night thermal missions are concerned. Optimum conditions for daytime missions, though important, are not so stringent.

4. Numerous aircraft missions conducted in connection with this study have demonstrated that repetitive flights made under variable conditions of time of day, seasons, and soil and vegetation, produce

additional evidence to verify the occurrence of shallow aquifers.

5. Imagery from this study, along with ERTS-simulated imagery, indicates the feasibility of applying ERTS A and B data to reconnaisance studies for detection of shallow aquifers.

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TABLE I

Simple correlation coefficients used to relate variables X_2, X_3, X_4, X_5, X_6, X_7, and X_8 to optical density, D, of negative thermal film. Data from predawn flight on August 5, 1970.

X_2, depth to water table	0.074
X_3, depth to top of aquifer	0.094
X_4, thickness of aquifer	-0.721**
X_5, estimated thermal diffusivity coefficient	-0.554**
X_6, topography	N.S.
X_7, depth to bedrock	-0.595**
X_8, type of bedrock material	0.142

**correlation coefficients significant at the one percent level.

N.S. - not significant

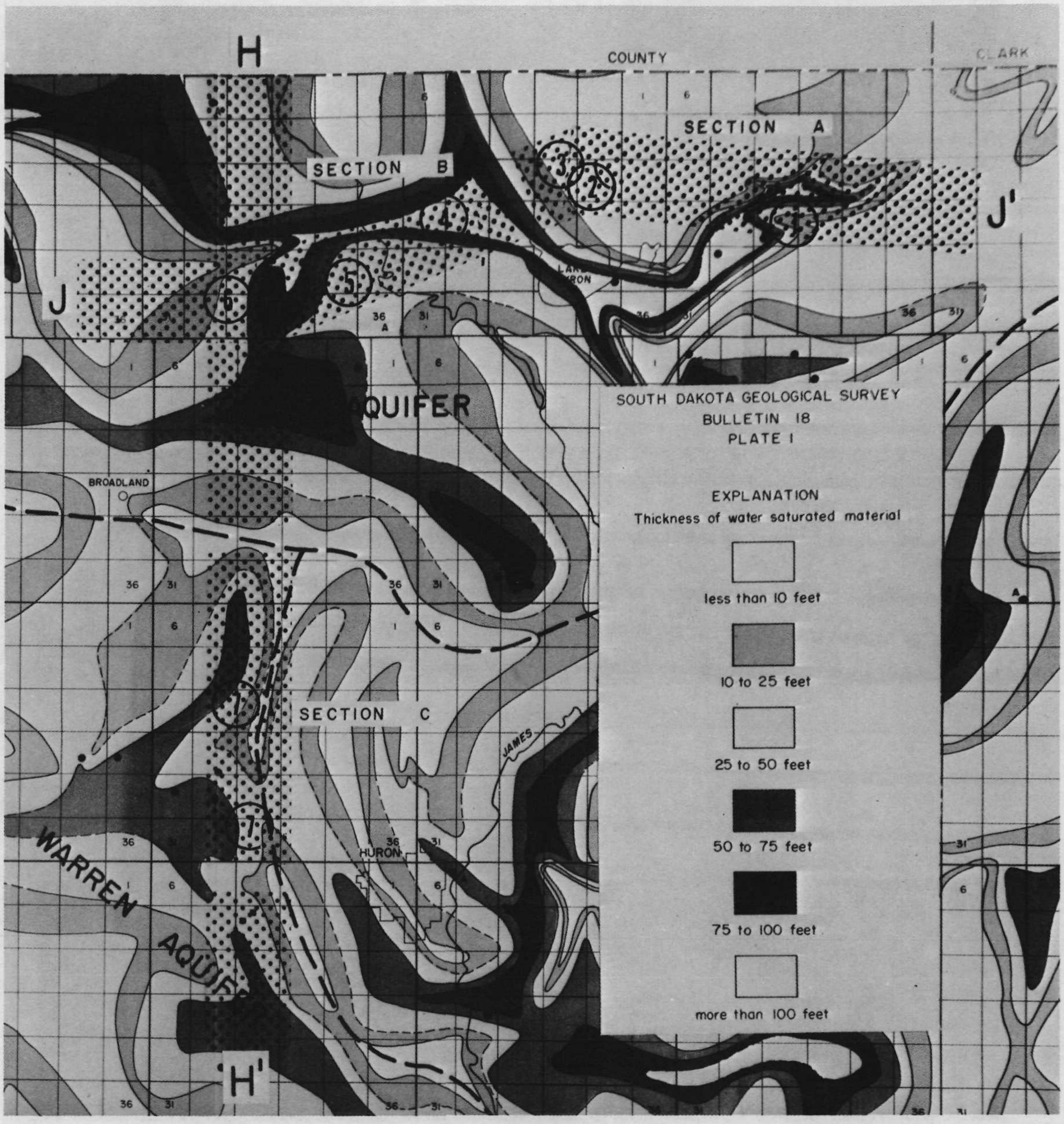
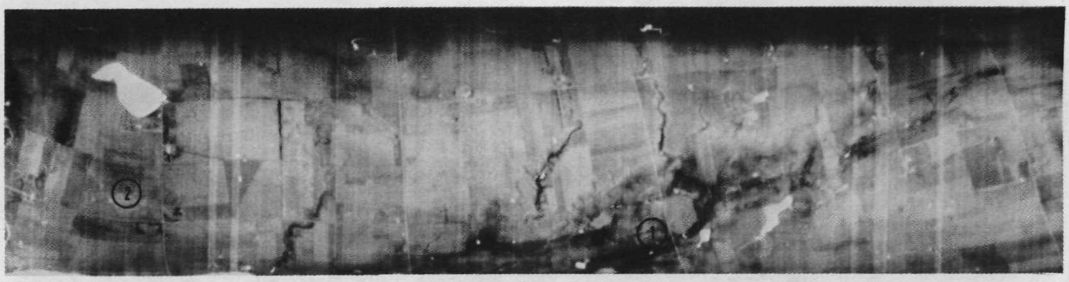
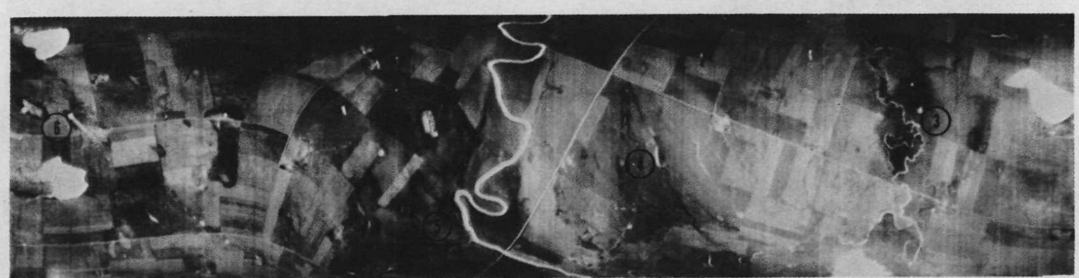


Figure 1. Portion of Beadle County South Dakota showing thickness of water-saturated material in surficial deposits and location of predawn flightlines on August 5, 1970.



SECTION A



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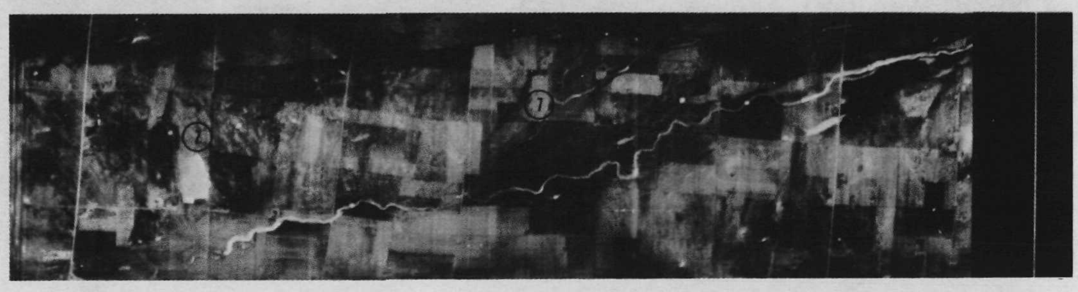

SECTION C

Figure 2. Thermograms of sections of flightlines J-J' and H-H', shown in Fig. 1. Dark areas indicate location of possible shallow aquifers (4.5 to 5.5mμ).

Figure 3. Enlarged thermogram of area shown as ① in Section A of Fig. 2. Obtained on a N-S flightline slightly later than when J-J' was flown.

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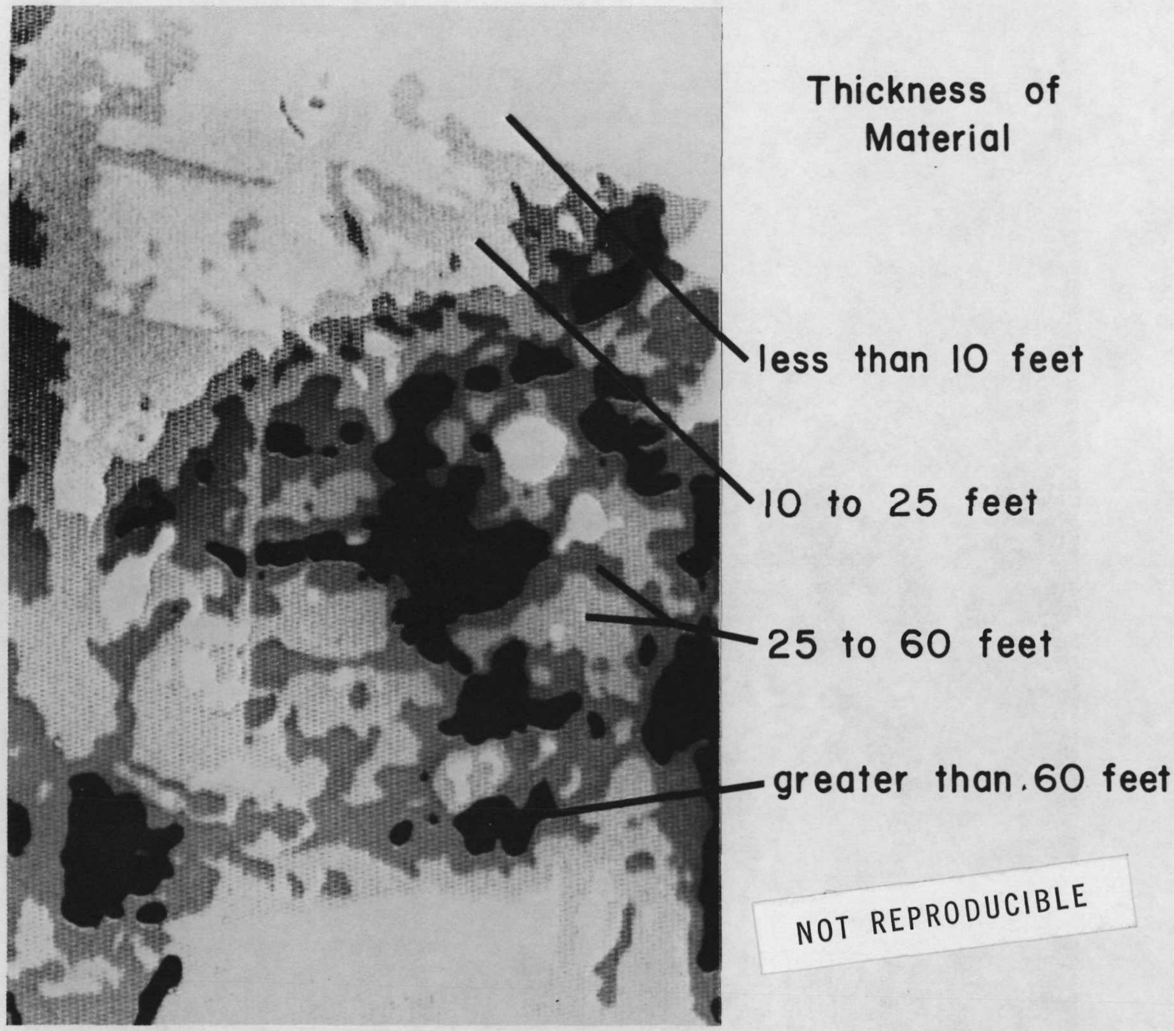

Figure 4. Color encoded map of Fig. 3. Areas with different colors represent various thicknesses of saturated buried aquifer material.