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AIRBORNE THERMAL MAPPING OF A "FLOW-THROUGH" LAKE IN THE NEBRASKA SANDHILLS[1]

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ABSTRACT: The Sandhills region represents a tremendous water resource for the State of Nebraska. Small shallow lakes, marshes, and subirrigated meadows are abundant due to interactions between ground water and surface water. One theory relating ground water to lake-flow systems in the Sandhills has been termed the "flow-through" concept. Thermal-infrared remotely acquired images document the flow-through model for a test site in Western Nebraska.

(KEY TERMS: remote sensing; ground water; thermal-infrared; discharge zones.)

INTRODUCTION

The Sandhills region of Nebraska accounts for nearly one-fourth (or 57,000 km^2) of the state's total area and represents the largest sand sea in the western hemisphere (Smith, 1965). This unique region consists of stabilized sand dunes modified by deflation hollows ("blowouts"), large interdunal wet meadows, and numerous natural lakes.

Recent studies by Ahlbrandt and Fryberger (1980) and Ahlbrandt, *et al.* (1983), indicate that the eolian deposits of the Sandhills occur as relatively thick sands composed of complex Holocene dune and discontinuous, diachronous interdune deposits unconformably overlying the Plio-Pleistocene fluviolacustrine sediments, which subsequently overlay the Tertiary Ogallala Formation. Typically, 6 to 21 meters of fine to medium uniform sand covers the surface, making it very difficult to distinguish the eolian-alluvial sand boundary. The result is a unique hydrologic setting where the geologic medium is essentially homogeneous.

While the unusual landscape of the Sandhills is both intellectually stimulating and aesthetically pleasing, the outstanding resource of the area today is, without question, its tremendous ground water reserves, a fact which can only be described as a paradox in light of the region's semiarid climate. The average annual precipitation for the Sandhills ranges from 63.5 centimeters in the east to 40 centimeters in the west, very little of which results in surface runoff due to the sandy soil. The region recharges the underlying Ogallala Group, a tremendous ground water reserve amounting to approximately 9.3 x 10^5 cubic meters of water (Reed, 1966). Small shallow lakes, marshes, and subirrigated meadows are abundant where the water table intersects the land surface or is close to it in many interdunal valleys.

Despite the prodigious ground water reserves of the Sandhills, little is documented concerning ground-water/surface-water interactions. Keech and Bentall (1978 reprint) speculated about the hydraulic connection of Sandhills lakes with the water table, concluding that some bodies of water fluctuate in unison with the rise and fall of the water table while others, particularly in the western Sandhills, are sealed off from the zone of saturation and thus manifest no ground-water/surface water interaction. The latter group of lakes tends to have high levels of alkalinity. Buckwalter (1983) concluded that Sandhills lakes reflect considerable diversity in seasonal and annual fluctuations in areal extent, including the degree to which they mirror water table variation.

In the case of the Sandhills, one of the most frequently mentioned concepts regarding ground-water/lake-water interrelation is the "flow-through" lake concept (e.g., Hall, 1976). A flow-through lake is essentially a topographic depression that extends below a water table and, due to the slope of that saturated surface, the ground water flows in from the upgradient end of the lake and discharges from the downgradient end.

Of course, the pattern of flow into and within a given lake may be variable from a temporal viewpoint. For example, a lake's "normal" summer flow direction might actually be reversed during winter due to two natural influences – the precipitation of water into the lake and the freezing of the ground; thus, no ground water recharge occurs (Ginsberg, 1984).

The concept of a "flow-through" lake is no doubt extremely simple. In fact, given a certain topographic and hydrogeologic setting, one would expect such a pattern of ground water flow. However, postulating about the existence of flow-through circulation patterns in lakes and documenting

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them are two very different matters. We suggest that: 1) the flow-through model, however simple, is a valid tool for interpreting Sandhills hydrogeology; and 2) imagery acquired by thermal-infrared remote sensing can be used in lieu of intensive field programs for identifying lakes which manifest flow-through characteristics.

OBJECTIVE

The intention of this paper is to present evidence, in the form of an airborne thermal scan, that indicates a flow-through regime for a large Sandhills lake. Thermal regimes of two other nearby lakes are compared. Findings are predicated upon image analysis and geologic/topographic justification.

STUDY AREA

The specific geographic area chosen for the purpose of addressing our objective is the southwestern Sandhills, in particular Crescent, Blue, and Hackberry Lakes in and around the Crescent Lake National Wildlife Refuge located in Garden County (Figure 1). The lakes in this portion of the Sandhills tend to be quite numerous, shallow, somewhat ephemeral, and alkaline. There is usually no surface water inflow or outflow in connection with these lakes and, therefore, are often referred to as "water table" lakes. Crescent Lake contains 397 surface hectares of water, Blue has 117 hectares, and Hackberry is 178 hectares in size (McCarraher, 1977).

THERMAL SCANNING FOR HYDROGEOLOGIC INVESTIGATION

The methodologies and technologies of aircraft and satellite remote sensing have been previously applied to the Sandhills and directed toward a variety of natural-resource problems such as range fires, soils classification, wind erosion, surface-water fluctuations, and wetlands (Seevers, *et al.*, 1973; Lewis, *et al.*, 1975; Seevers, *et al.*, 1975; Buckwalter, 1983; Rundquist, 1983). However, apart from the use of Landsat data for mapping the lakes and wetlands of the region, virtually no previous remote-sensing work has addressed the hydrologic and hydrogeologic character of the Sandhills.

One particular remote-sensing methodology, thermal-infrared scanning, seems to hold promise for analyzing certain aspects of Sandhills hydrogeology. Thermal-infrared remote sensing involves recording infrared energy as it is emitted from the surface of objects. This procedure allows the acquisition of temperature data for specific terrestrial targets by means of airborne instrument packages. While the human eye is sensitive to energy with wavelengths between 0.4 and 0.7 microns, thermal scanners generally operate in the longer-wavelength 8-to-14 micron region of the electromagnetic spectrum; energy which is not visible to humans. The 8-14 micron region constitutes an atmospheric "window" or a wavelength range where the atmosphere neither limits severely nor prevents totally the transmission of thermal energy from the ground to the airborne sensor system. For our application, thermal imagery was used only to distinguish relative temperature differences of the lake water. The basic assumption is that ground water is significantly cooler than lake water in the summer and therefore will produce distinguishable thermal signatures.

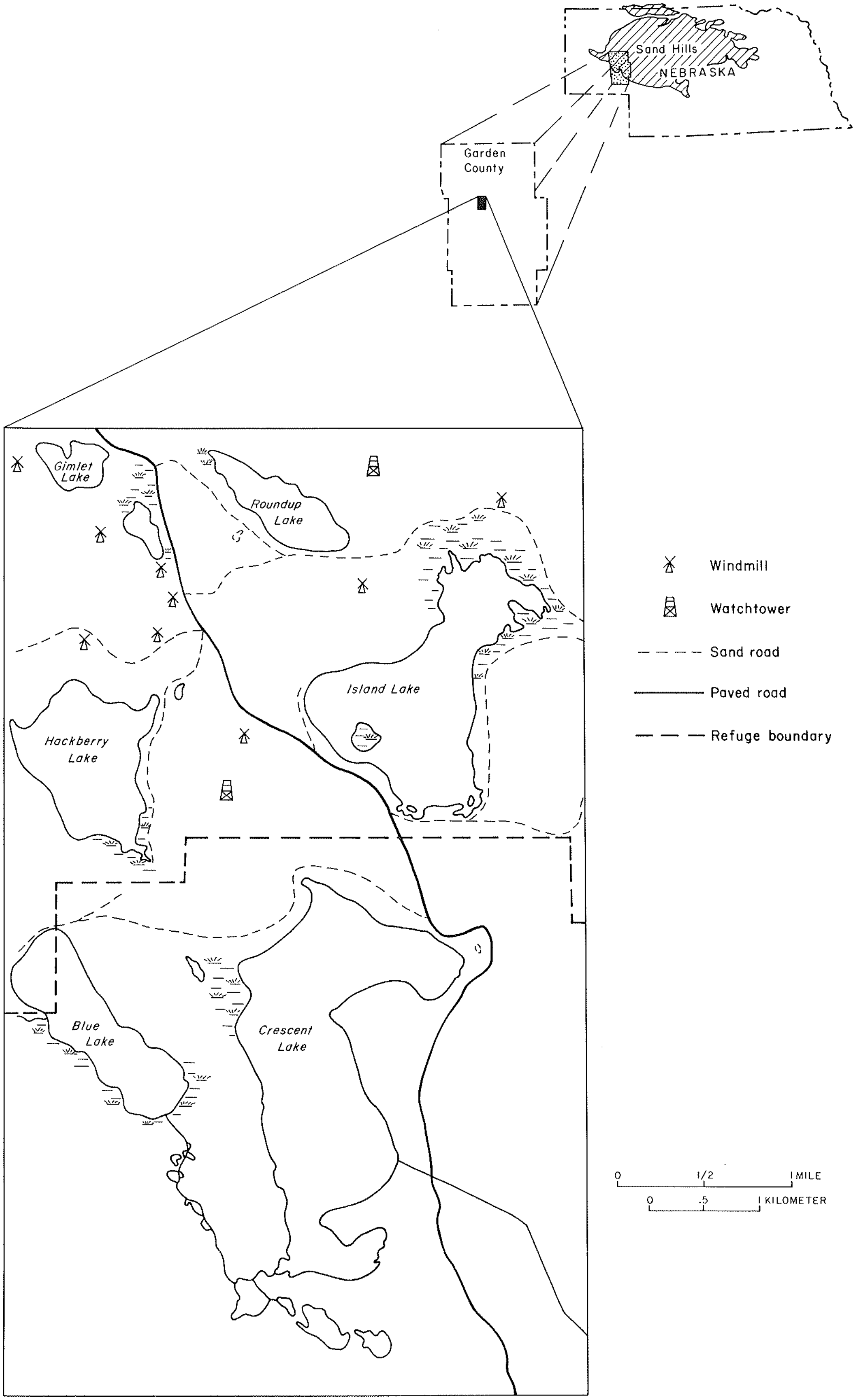
The particular airborne instrument used to collect the data analyzed as part of the present research is referred to as "TIMS" (Thermal Infrared Multispectral Scanner). As the name implies, TIMS is a multichannel thermal device. The six TIMS channels, ranging in electromagnetic sensitivity from 8.2 to 12.2 microns, were designed for the spectral differentiation of certain surface mineralogies (Kahle and Goetz, 1983); however, the TIMS system has recently been employed for other types of remote-sensing research (e.g., Queen, *et al.*, 1984; Inglis and Budge, 1984). For the purpose of our investigations in the Nebraska Sandhills, TIMS Channel-1 (8.2-8.6 microns) was arbitrarily chosen for use since thermal-wavelength selectivity is of little advantage in interpreting the surface temperatures of bodies of water.

The collection of thermal-emittance data from the ground surface by the TIMS system is based on 8 bits per ground-resolution element ("pixel"); i.e., the system records the terrestrial response for each pixel as a number ranging from zero to 255 ($2^8 = 256$). A low emittance or low digital number for a given pixel is indicative of a cool ground temperature while a high digital number corresponds to a warm surface. When the digital data are processed (for example, by means of a film-write system used for converting the numbers to a photographic product), the cool surfaces are imaged on the "photograph" (e.g., Figure 2) in dark tones and the warm surfaces are light in tone. It is important to note that the sensor records only "skin temperature" (about 50 microns deep); *it does not penetrate the surface.*

DATA

The data analyzed for the research are the result of a TIMS overflight in the late afternoon of August 13, 1983, an extremely hot day with the ambient air temperature near 100 degrees F. The mission, along a corridor 4.8 kilometers wide, resulted in a digital data matrix of 3,906 rows by 642 columns, or a total of 2,507,652 pixels, each representing a ground area of 10x10 meters. The array subset corresponding to our specific study area was approximately 500 rows by 600 columns (300,000 pixels).

Figure 2, the principal graphic in this report, is the result of a digital contrast stretch employed to utilize the full display range of the storage medium (in this case, photographic paper), thereby accentuating subtle variations within the lakes themselves. With this quantitative manipulation, the water and wetlands surfaces, which contained original digital numbers between 50 and 80, were expanded such that the 50-60 range was stretched to 0-240 and 61-80 became 240-255



A portion of the Crescent Lake National Wildlife Refuge

Figure 1. A Map Showing Location of the Study Area Within the Context of the Sandhills Physiographic Region and State of Nebraska.

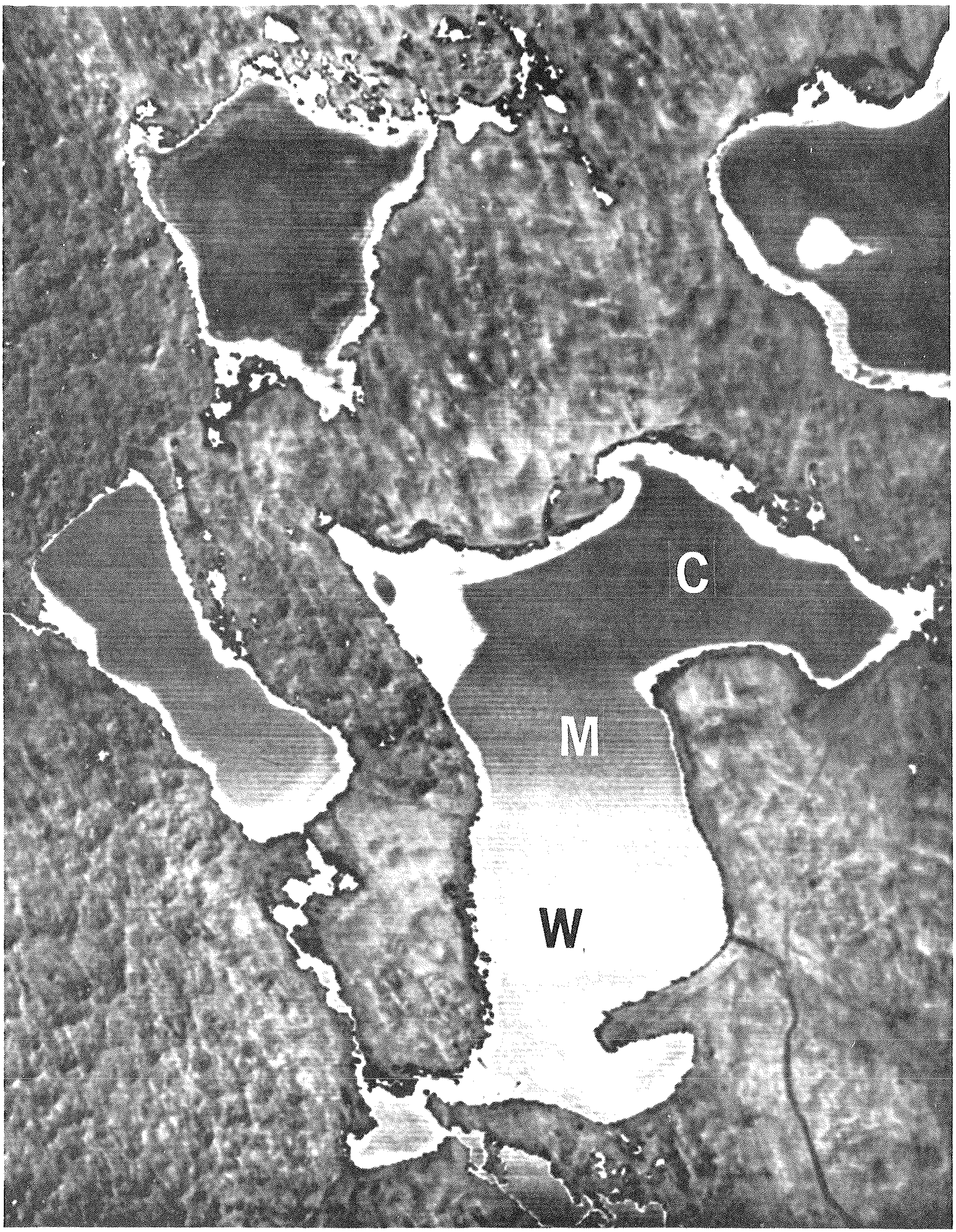


Figure 2. Digitally Enhanced Daytime Thermal-Infrared Image of Study Area. Dark tones indicate cool surface; light tones indicate warm. Area C – cold groundwater inflow; M = mixing zone; W = warm water.

(see, for example, Sabins, 1978). Some of the character of the land surface is also preserved in this enhancement by means of separate numerical manipulation of the non-water pixels before final photographic printing.

Notice from Figure 2 that the digital contrast stretch and film-write system has yielded a positive photographic TIMS image which reveals a striking temperature pattern for Crescent Lake (this contrast stretching routine also causes the lake-marginal zone of vegetation to be shown in white). The image suggests that cold water inflow (zone "C") occurs at the north end of the lake, the central portion of the lake shows evidence of mixing or slight warming (zone "M"), and the warmest water (zone "W") is in the southern portion of the lake (perhaps indicating exit from this particular lacustrine system).

In an effort to extract detailed information concerning the thermal regime of Crescent Lake (on August 13, 1983), three 5 x 5 pixel arrays (one for each of the three "zones" identified above) were selected and digital numbers for each were averaged. The resulting average digital number for each zone was converted to temperature expressed in degrees Centigrade using established procedures (Short and Stuart, 1982).

Temperature conversions for zones "C," "M," and "W" as shown on the image (Figure 2) substantiate inferences expressed earlier. Apparent temperatures in zone "C" averaged 17.6° Centigrade, and in zone "W" temperatures averaged 19.8° Centigrade; a range in apparent water surface temperature of 2.2° Centigrade.

Figure 3, intended to provide both a generalized cross-section of Sandhills geology and a topographic/geologic rationale for the flow-through thermal character of Crescent Lake, extends from the look out tower north of the lake to a point on the spring-fed Blue Creek to the south (refer to Figure 1). This diagram suggests a higher water table elevation north of Crescent Lake with subsequent sloping downward to the south; in fact, flowing springs have been reported at the north end of the lake (Brennan, *et al.*, personal communication, 1984). Because of the high head north of the lake and the perennially flowing creek to the South, we conclude that the flow-through pattern suggested by the TIMS image is indeed feasible and acceptable.

Blue Lake, located immediately west of Crescent Lake (refer to Figures 1 and 2), is the deepest lake in the entire Nebraska Sandhills (McCarraher, 1977), with depths reaching 5.5 meters (Brennan, *et al.,* personal communication, 1984) and, like Crescent, it exhibits a flow-through thermal signature. However, the thermal contrast and resulting pattern for Blue Lake is not as distinct as it is for Crescent Lake, perhaps because the much greater depth (and volume) of the former tends to moderate the temperature extremes which one would expect in a very shallow lake such as Crescent (maximum depth is about 1 meter). The bottom of Blue Lake drops off rapidly to 5.5 meters along the eastern shore (Brennan, *et al.,* personal communication, 1984), but there is no apparent evidence of such depth illustrated in the thermal image (Figure 2), a fact which effectively removed bottom configuration from consideration during our image interpretation (as noted earlier, TIMS records "skin" temperature).

Although Hackberry Lake is located in close proximity to Crescent and Blue (refer to Figures 1 and 2), the thermal regime appears quite different in the imagery (Figure 2); it clearly is not a flow-through lake even though it has no surface outlet. Notice that Hackberry (mean depth of 1 meter)

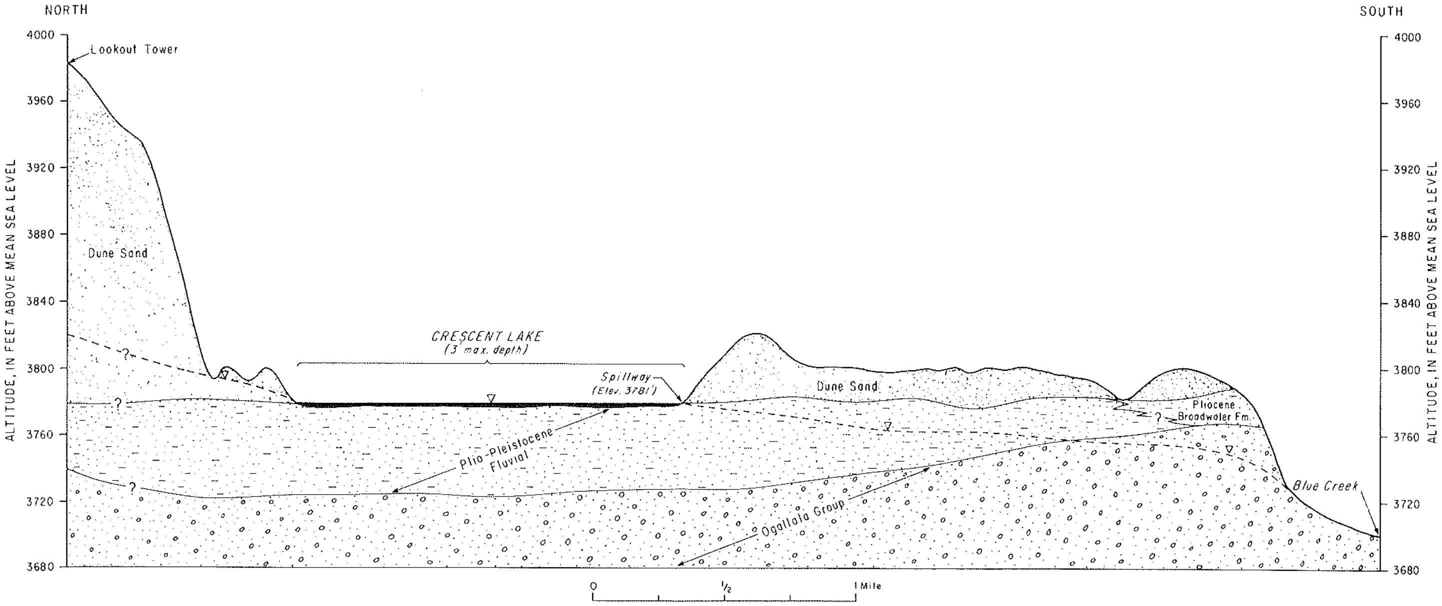


Figure 3. A Topographic/Geologic Cross-Section from the Lookout Tower North of Crescent Lake (refer to Figure 1) Through the Lake Itself to Blue Creek (south of Crescent Lake; not shown in Figure 1).

contains scattered warm and cool zones, none of which are distinct. We suspect that water enters and exits via discrete points, either at lake margin or lake bottom.

CONCLUSIONS AND IMPLICATIONS

We believe that our study illustrates how the timely acquisition of thermal-infrared remotely sensed data can contribute to increased scientific understanding of hydrologic processes in Sandhills lakes. The work provides evidence that Crescent and Blue Lakes "behave," at least part of the time, according to flow-through principles while Hackberry possesses a more complex system of ground-water/surface-water interaction. Note that all three lakes are in close geographic proximity.

The implications of our research are measurable on at least two scales; site-specific and regional. Our current work focused on the former – attempting to understand how individual lakes behave – but perhaps the real potential of such research can only be realized with regional integration of results. For example, it is now possible to classify lakes according to thermal patterns over a wide area of the Sandhills, at different points in time, thus contributing to regional hydrologic models of ground-water/surface-water interactions. In addition, the economy of the Sandhills is tied to cattle and associated hay production; therefore, we must acquire knowledge about the ways in which ground water affects the subirrigated meadows where hay is produced. Finally, because some of the wet meadows in the Sandhills have been converted to cropland agriculture which is irrigated and "chemigated" by center-pivot systems, research such as ours should contribute to a better understanding of water-quality problems, both real and potential, in the Sandhills.

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