E. Karl Sauer
Department of Civil Engineering
University of Saskatchewan
Saskatoon, Saskatchewan S7N 0W0, Canada

Hydrogeology of Glacial Deposits from Aerial Photographs

Geological processes interpreted from aerial photographs define ground-water systems and boundary conditions in glaciated terrain.

Abstract: *Aerial photographs provide useful qualitative evidence of ground-water discharge, recharge, and storage in glaciated terrain. Landforms indicate geological processes and boundaries of the hydrologic system. Ground-water discharge is readily identifiable. Storage and recharge can be evaluated from indirect evidence such as topographic form, surface drainage, and glacial stratigraphy. Temporal relationships shown by seasonal and annual changes in ground moisture aid in this interpretation.*

Landforms shown to be significant include low-relief non-patterned moraines, low relief ridged moraines, high relief hummocky moraines, glacio-fluvial outwash plains, proglacial valleys, and ice-contact valleys.

Air photo patterns related to the flow phenomena are shown as (1) springs and natural piping; (2) tones of gray and tone patterns; (3) vegetation and plant communities; (4) soil salinity and salt accumulation; (5) slope instability; (6) flood plain anomalies related to piping and discharge; and (7) land-use activities such as mining, irrigation, and forest cutting.

Introduction

Aerial photographs present a unique vertical perspective of certain landscape features that exist as expressions of the hydrogeology of an area. The evidence provided by these surface expressions is particularly useful for ground-water engineering in glacial deposits. There are two reasons for this. First, phenomena related to the flow system such as ground-water recharge and discharge exhibit characteristic patterns on the photographic image. Second, glacial processes creating the natural boundary conditions of the hydrologic model are confined to a relatively shallow surface zone of the terrain; the interpretation of aerial photographs is most effective in this shallow surface zone. The elements of hydrogeology are the flow and storage of ground water within a framework of natural terrain boundaries. Therefore, even though the interpretation of aerial photographs is essentially surface exploration technique, it has an effective capability for establishing a reasonable first approximation of the hydrogeology of glacial deposits.

Terrain evaluation from aerial photographs has been developed successfully for ground-water studies in the glaciated terrain of southern Saskatchewan (Figure 1). The methodology has evolved through experience (Mollard, 1979) gained over the last two decades in this area. The effectiveness of air-photo interpretation for this purpose has been greatly enhanced through research in defining the glacial stratigraphy (Christiansen, 1968; Whitaker and Christiansen, 1972) and history of deglaciation (Christiansen, 1979) of the region.

Theoretical Concepts

Principles of Photo Interpretation

All photographic images have certain elements in common. These include size and shape of objects, shadows, tones (or colors) or tone patterns, and the association of objects. Belcher *et al.* (1943) and Belcher (1943, 1946, 1948) translated these elements into landscape terms such as landform, soil type, erosion form, drainage, vegetation, and land use. If landscape features can be identified

Photogrammetric Engineering and Remote Sensing,
Vol. 47, No. 6, June 1981, pp. 811-822.

on a photograph and related to ground conditions or geological processes, they provide a basis for evaluation of the physical environment.

This approach is a refinement of the concepts encompassed within the study of geomorphology where geologic structure, processes, and time are interrelated and form the landscape as we see it today. Thus, landforms are the basic framework for the interpreter of aerial photographs.

Hydrogeology involves a more specific and refined application of this interpretation concept. Recharge infiltration potential can be interpreted by relating the processes of deposition indicated by landform types to the physical properties of their component sediments. This interpretation then can be extended by relating the sequence of geologic events that landforms represent to the creation of hydrologic boundary conditions.

The ultimate objective in ground-water engineering is to determine the storage and flow system within the framework of the terrain model. Storage may be interpreted through estimates of infiltration capability or porosity of surface sediments, and evidence of ground-water discharge is the most obvious indicator of the flow system on aerial photograph.

Temporal relationships shown by seasonal and annual changes in ground moisture and vegetation aid the interpretation of some of the more subtle indicators of ground-water storage and discharge on aerial photographs. Certain forms of evidence are more apparent in dry conditions or late fall, whereas others show better in mid-summer or during wet climatic intervals. Thus, the time of year or the particular year the aerial photographs were taken can be critical. In nearly all studies, a comparison of a sequence of aerial photographs covering a range of environmental conditions at the same location is useful in ground-water studies.

HYDROGEOLOGY

The ground water system can be shown as an equation to account for factors in the hydrologic cycle with effect flow and storage of ground water over short periods of time, i.e.,

Change in Storage = Recharge − Discharge.

On a long term basis discharge (outflow) will equal recharge (inflow) and storage will be constant. For example, most ground water below a stream is in permanent storage when the stream elevation represents the water table. This simple concept represents a mathematical model of a natural process. This process expresses itself in the landscape in a variety of ways related to climate, topography, geology, vegetation, and land use. The surface expressions that result from this process provide observational evidence that can be synthesized to form a working model of the ground-water systems under consideration.

Glacial terrains contain (a) permeable layers providing storage and the capacity for flow and (b) nonpermeable layers, forming three-dimensional boundaries containing the flow system. The spatial arrangement of these two components constitutes the physical dimensions of the terrain model, or hydrologic boundary conditions. Storage is dependent upon porosity; flow rate is dependent upon permeability and hydraulic gradient. Boundary conditions are created by changes in relative permeability, keeping in mind that very few sediments are impervious in the strictest sense of the word. This is important in evaluating the effects of ground water on terrain stability, because unstable conditions can result from water in sediments that have very low permeability.

In glacial deposits a great variation in permeability may be expected.

GLACIAL PROCESSES AND BOUNDARY CONDITIONS

Initially, two basic processes were involved in the creation of the components of the glaciated terrain, flowing ice, and melt-water from the ice. Well-sorted, permeable strata are created by meltwater, and poorly sorted less permeable boundary layers are deposited by glacier ice. These sediments are referred to as stratified drift and till, respectively. All types of glacial sediments are referred to collectively as drift.

After the ice disappeared, during post glacial time, the terrain was modified by wind and water. For example, wind formed sand dunes and loess deposits, where water created floodplains and alluvial fans. These features are found superimposed on glacial landscapes.

The division of glacial sediments into two general categories, while useful, is an oversimplification. Ice and meltwater may act as independent processes or as complexly interrelated processes. Thus, the drift created by glaciers may be expected to range from extensive layers, to a uniform mass, to a spatially complex intermingling of lithologies.

Stratigraphy. The stratigraphy of a glaciated terrain has been affected by both a complex array of processes and a fluctuating advance-retreat-readvance phenomenon. It is generally accepted that there were four major ice-ages in North America, but Christiansen (1968) has separated till deposits in Saskatchewan into stratigraphic units which represent only two, or possibly three, major glacier advances. Tills generally are used as definitive stratigraphic units because tills have distinctive physical features and are more or less continuous throughout the region. Stratified drift or loess deposits do not exhibit these characteristics. Sand and gravel layers between these till-stratigraphic units are some of the major aquifers in this region.

Landforms. The preglacial terrain of southern

Saskatchewan was a sedimentary plain composed essentially of thick layers of Upper Cretaceous clays and sands (Figure 1). The landforms that evolved from continental glaciation of sedimentary plains do not generally possess large integrated drainage systems. As a result, they retain a large part of the precipitation which recharges the groundwater system. The rate of recharge may vary significantly because of the difference in permeability between till and stratified drift.

Landforms can be easily delineated on aerial photographs. When landforms are produced by repeated glaciation, predictable sequences of till and stratified drift layers occur. For example, till usually underlies surface stratified drift; also, springs along a valley slope may indicate a stratified drift between a surface till and another till layer below the seepage zone.

Moraines, although composed almost entirely of till, can be regional recharge areas because of their large number of water-filled lakes and ponds. Moraines occur in three forms:

- Low relief, non-patterned moraines (Figure 2);
- Low relief, ridged moraines (Figure 3); and
- High relief, hummocky moraines (Figure 4).

There is very little reliable quantitative data on the permeability of tills. The older weathered tills in Saskatchewan are extensively fractured (Christiansen, 1968; MacDonald and Sauer, 1970). Studies by Grissak and Cherry (1974) have shown that the fracture permeability of the older tills is two or three orders of magnitude greater than the intergranular permeability.

Observations in Saskatchewan (Sauer, 1978) have shown that the relative relief on moraines is correlated with the average thickness of the till deposited by the last or youngest glacier. The

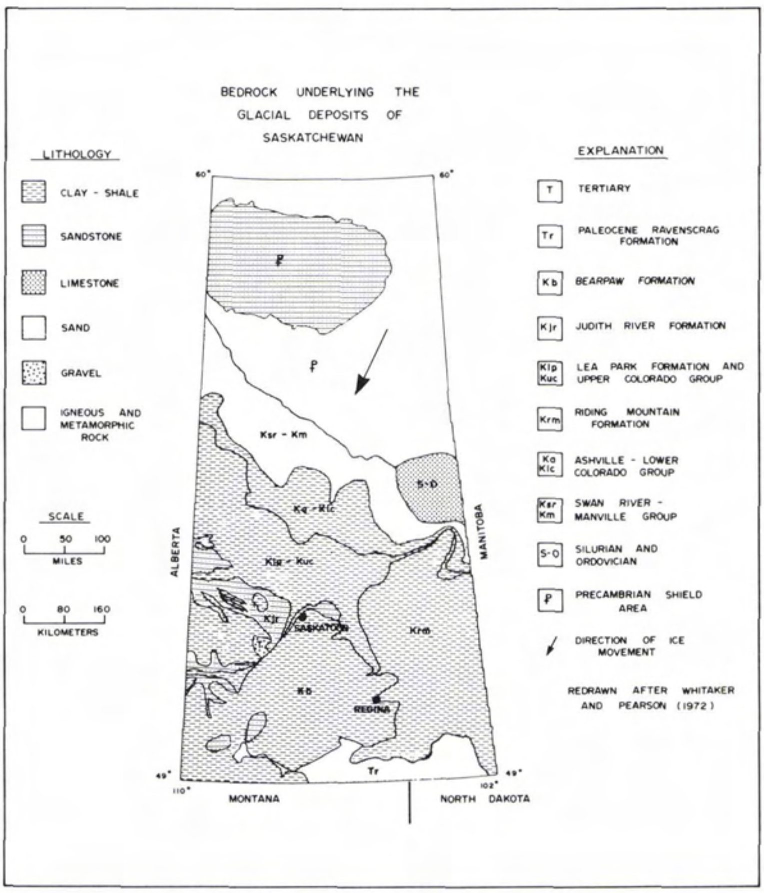

FIG. 1. Map of Saskatchewan showing direction of ice movement and preglacial geology. Tills in the southern region are composed mainly of clay from the Cretaceous Bear-paw, Judith River, Lea Park, and Riding Mountain Formations. Sands and gravels originate mainly from Swan River-Manville sands, Silurian and Ordivician carbonates, and Precambrian igneous and metamorphic rocks.

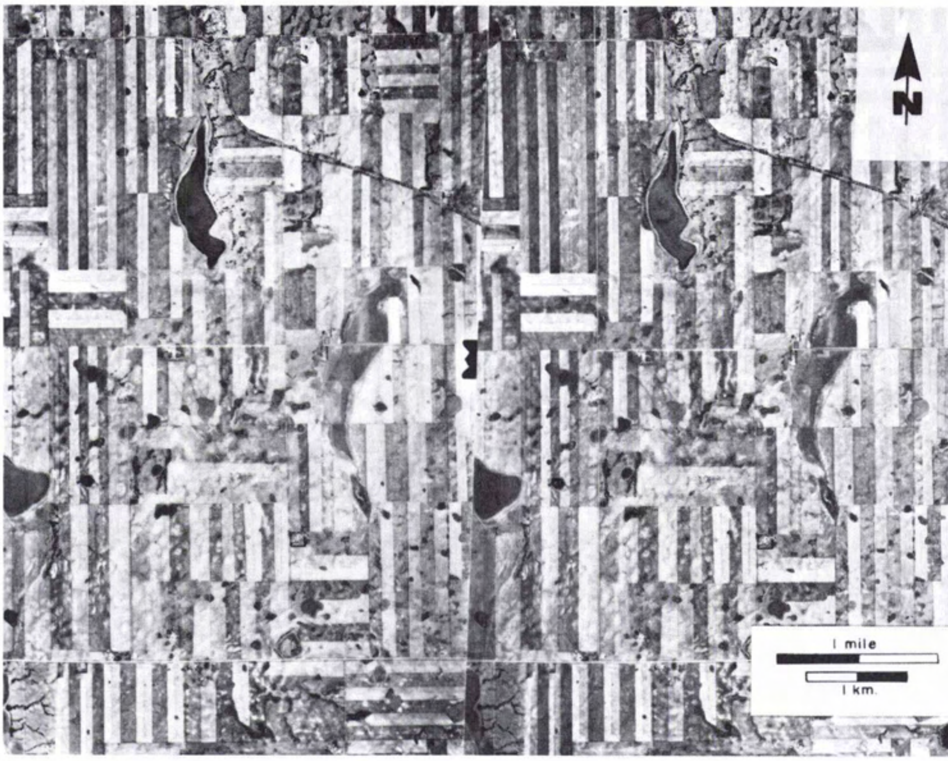

FIG. 2. A stereogram of low relief (5 to 10 m) ground moraine composed mainly of a thin layer (2 to 10 m) of clay rich till. Surface storage area is small and infiltration rates are low because the till has low permeability. Photos courtesy Canada National Air Photo Library.

FIG. 3. A stereogram of a low relief (5 to 10 m) ridged moraine composed mainly of a thin (2 to 10 m) layer of clay rich till. Surface storage capacity is fairly large so recharge is significant even though the permeability of the till is low. The thin surface layer of till allows relatively efficient recharge of underlying sands or gravel. Photos courtesy Canada National Air Photo Library.

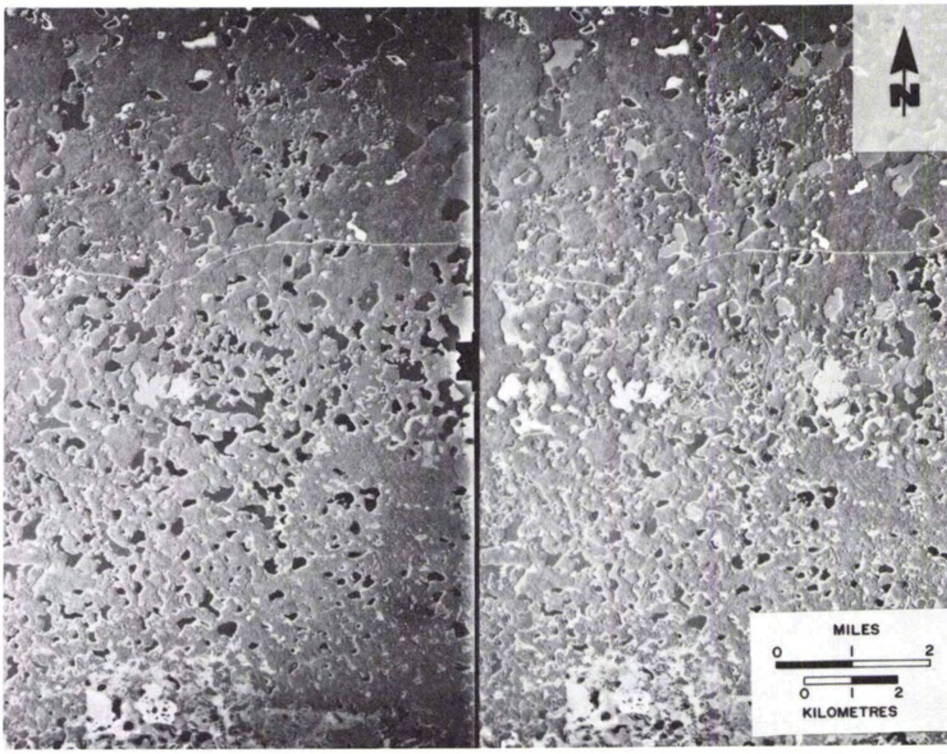

FIG. 4. A stereogram of a high relief (10 to 15 m) ground moraine composed of thicker (30 to 80 m) layer of clay rich till. Surface storage capacity is large. Photos courtesy Canada National Air Photo Library.

surface tills are usually massive even when weathered, whereas the underlying weathered tills created by earlier glacial advances are highly fractured. The resulting change in permeability can be a significant boundary condition in the ground-water flow system.

Glacio-fluvial outwash plains (Figure 5) are usually flat with very little surface storage capacity. The sand and gravel layers have a high permeability so that outwash plains are almost always major recharge areas.

Ice contact stratified drift landforms such as eskers and kames usually are not significant ground-water storage systems because they represent small high areas and are well-drained. The permeability and infiltration rates are, however, very high.

Glacial and proglacial valleys have been excavated into the drift and commonly cross stratigraphic boundaries. These landforms can have significant effects on recharge and discharge. The valleys are generally of two forms: (a) those formed in tunnels (ice-contact valleys) within melting stagnant ice and (b) those created from erosion by proglacial meltwater.

Ice contact valleys (Figure 6) usually are partly filled with collapsed drift but retain some of the hillslope relief of the buried valley. They are often characterized by a chain of lakes or ponds. Flowing streams are rare in the valleys. The role of any part of the valley in terms of recharge, discharge, or storage is indicated by surface ponding, the presence of springs along slopes or at the valley base, and indications of soil salinity caused by ground water seepage and evaporation.

Valleys formed by proglacial meltwater (Figure 7) were originally eroded to grade in the hydraulic sense and subsequently back-filled and, thus, are usually occupied by an underfit stream instead of a series of segmented lakes.

Proglacial channels are commonly joined by a few tributary channels and receive some surface runoff from a limited catchment area. Where surface runoff into the valley is significant, the valley is usually occupied by meandering underfit streams. Normal runoff is not sufficient to maintain flow in these streams for prolonged periods. When flow in the streams continues for weeks or months the flow is usually sustained by ground water.

AIR PHOTO PATTERNS RELATED TO FLOW PHENOMENA

Springs and Natural Piping Phenomenon. Where ground water outcrops, a flow velocity may

FIG. 5. A large outwash plain (OW) along the flank of a deeply incised meltwater channel. The sand and gravel layer is about 5 m thick and is an unconfined aquifer. Springs (S) can be seen on the valley slope where sand overlies till. Photo courtesy Canada National Air Photo Library.

be maintained by seepage pressure, resulting in erosion. This form of erosion by ground water is called piping (Casagrande, 1940) and is a primary cause of failure in earth dams and hydraulic structures.

Natural piping usually appears on hillside

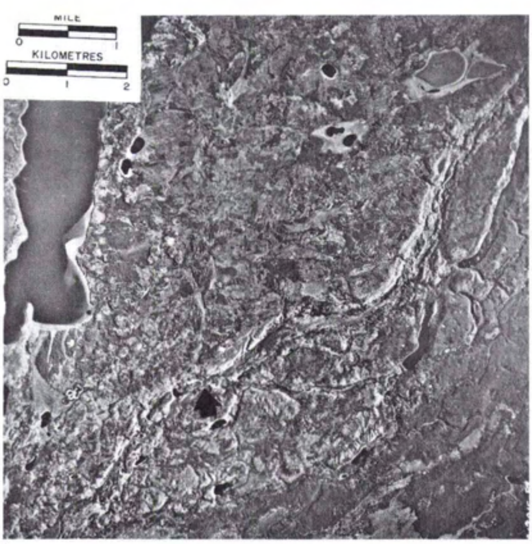

FIG. 6. An ice-contact valley apparently formed by melt-water sorting and deposition in a stagnant ice sheet. Numerous eskers and kames can be seen within the valley. The small lakes and ponds may act as recharge basins for the gravel deposits in the valley. Photo courtesy Canada National Air Photo Library.

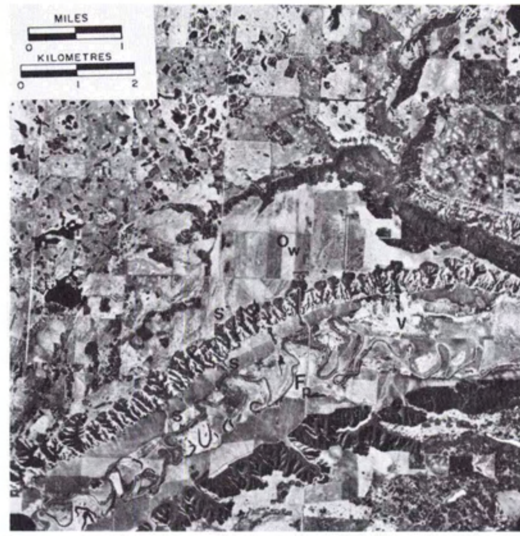

FIG. 7. A deep proglacial valley and the floodplain of an underfit stream (F_p). The valley fill is about 35 m thick and thus may be an important aquifer. Discharge can be observed by numerous springs (S) at the valley base and the white pattern of aquatic vegetation (V). Springs (S) can also be seen where water is discharging from sand and gravel outwash (OW) above the valley. Photo courtesy Canada National Air Photo Library.

FIG. 8. Springs (arrows) formed by natural piping and erosion along the contact between a surface sand outwash (OW) and underlying till. Where the water table is high surface erosion is minimal. Where the water table is low the sand has been formed into dunes (D). Photo courtesy Canada National Air Photo Library.

slopes as small craters at the seepage line (Figure 8). The volumes of soil eroded may be small if soils are stabilized by lush vegetation and by the natural resistance to erosion of the water bearing strata. Where clay underlies the saturated sand layer, slumping may be associated with the seepage (Figure 9). Small springs or ground-water outcrops can be readily detected on aerial photographs (Figures 5, 7, and 8). Under certain conditions, when combined with surface runoff, large excavations may develop (Figure 10).

Tones of Gray and Tone Patterns. The water content of a sediment reduces its spectral reflectance (Condit, 1970). This reduction is greatest for sandy deposits (Figure 11) in the range of visible red light (0.6 to 0.7 μm) and in the non-visible near-infrared range (0.7 to 1.0 μm). In clay deposits the reduction extends over a greater range (0.4 to 1.0 μm). Both black-and-white infrared and color infrared films are sometimes used for surface drainage studies because they exhibit the greatest contrast.

Vegetation. Plants have been used as indicators of ground-water occurrence for many years. Meinzer (1927) studied plants in the desert envi-

FIG. 10. A very large depression formed by ground water discharge. The large flat-bottom gully is filled with aquatic vegetation as is typical. Ground-water discharges from a glacial gravel (likely outwash or delta) covered by loess. Photograph courtesy Canada National Air Photo Library.

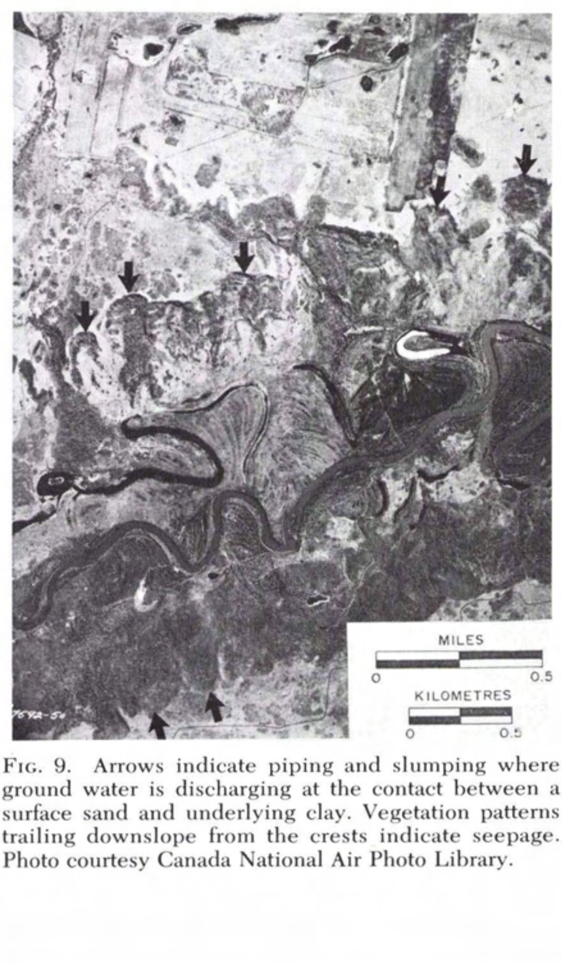

FIG. 9. Arrows indicate piping and slumping where ground water is discharging at the contact between a surface sand and underlying clay. Vegetation patterns trailing downslope from the crests indicate seepage. Photo courtesy Canada National Air Photo Library.

FIG. 11. Sharp changes in reflectance in sand caused by changes in water content are indicated by white and dark patterns. Thin arrows indicate dry soils and thick arrows indicate wet soils. The heavy vegetation is developed in shallow bog where the water table is at the surface. Photograph courtesy Canada National Air Photo Library.

ronment of the western United States and found some useful correlations between ground water and plant species. White (1932) investigated the use of plant characteristics in estimating ground water supplies in similar terrain. Ground-water effects on plant communities were examined in Saskatchewan by Meyboom (1966) and Meyboom *et al.* (1966) and plants around the prairie potholes of North Dakota were studied by Stewart and Kantrud (1972). Cannon (1971) extended plant indicator concepts to geological mapping and mineral prospecting in Texas. Richardson and Sauer (1975) used plant indicators on aerial photographs, among other forms of evidence, for the engineering evaluation of terrain in the Arctic environment of the Yukon.

Sauer and Wilson (1977) examined the use of plant indicators for engineering studies in the prairie environment of Saskatchewan and found that, although edaphic factors (soil type) were significant in supplying nutrients for some plant species, the availability of ground water seemed to be the most critical factor. Boundary conditions for ground water are often determined by stratigraphy. Thus, a concentration of water-loving plants along a topographic contour serves as an indicator of stratigraphy.

Plant communities may also indicate ground-water storage. For example, heavy tree growth on dune fields (Figure 8) indicates a high water table.

Meyboom (1966) and Sauer and Wilson (1977) found that recharge and discharge could significantly affect soil chemistry. Soil chemistry, in turn, plays an important role in plant selection. They demonstrated that plant species or the structure of vegetation communities can be used to differentiate zones of recharge from zones of discharge, both on a local and regional scale.

Plant indicators are most useful in severe environments because competition for survival is more intense. Thus, plants with low ecological amplitudes (which, in turn, are better indicators) tend to dominate arid or cold environments where fewer species survive. In tropical areas vegetation development is so massive that local changes in ecologic or environmental factors may be completely obscured. In dry climates lush vegetation tends to occur only along saturated permeable strata (Figure 8).

There are, however, some practical constraints in using vegetation as a diagnostic element in the photo-interpretation process. These are

- Photographic scales most commonly in use are too small for identification of individual plant species. This constraint is partly offset by the observation of Sauer and Wilson (1977) that plant communities are often better indicators of the physical environment than individual plant species.
- In forested regions the frequency or fires can be an important factor in the interpretation of plant development. After fires have occurred, a natural, complex succession of plant species evolves over time (Johnson and Rowe, 1975). Plants are subject to a selective process controlled by the changing environment: re-establishment of plant growth, and competition amongst plants for nutrients and competition for insolation. Thus, some caution must be exercised by the interpreter in correctly evaluating the significance of plant communities.

  Satellite imagery can be useful in establishing a fire history (since 1972) in forested areas. Landsat images provide a synoptic view of the total landscape. Burned areas exhibit a unique color which becomes more subdued with time. Color composite images using spectral bands 4(green), 5(red), and 7(near infrared) show the most promise in this connection.

Johnson and Rowe (1975) found that landform and geology influence plant succession. For example, on sandy, well drained sites, plant sequences change and differ from those on till deposits. Thus, the succession pattern can be an indicator of the terrain. Man-made disturbances may change conditions from the ecological setting seen on aerial photographs to those observed on the ground at a different time. The successions or re-establishment of vegetation may be quite different than those occurring after natural disturbances.

Salinity. Cole (1926) related the origin of sodium sulphate deposits in saline lakes to ground-water discharge. Cole presented evidence to show that, when water discharging from springs is saturated with sulphates, evaporation produces the large salt flats (locally called alkali flats) common to the prairie region. Meyboom (1966) observed that both regional and local flows of water through the glacial drift in Saskatchewan resulted in salt accumulations even though the ground water was not saturated with salts (Figure 12). Sauer (1974) found that the highly unstable foundation conditions (Figure 13) in salt flats were attributable to upward flows of water in the salty sediments. It has also been observed that salinity problems on cultivated fields (Figure 14) correlate with climatic variations, and a rising water table tends to increase the extent of salt accumulation. In dry years, salt accumulation shows a marked decrease and many saline patches in fields disappear. Thus, there is considerable evidence to support the theory that saline conditions in this region are directly related to ground-water discharge followed by evaporation into the atmosphere.

Certain plants (halophytes) are more tolerant to saline ground water than others. This tolerance restricts the development of vegetation near saline areas to be limited to a few plant species. Thus, the diversity of species is an indirect indicator of ground-water salinity and of discharge or recharge areas. Saline plant communities can be differentiated from communities associated with fresh ground water at normal photographic scales.

The spectral reflectance of salt is relatively high.

FIG. 12. A high relief ground moraine (A) is functioning as a ground-water recharge area. The area in the upper right half of the photograph is sloping away from the moraine and ground water is discharging at the base of the slope as indicated by saline patterns at D and the vegetation pattern at V.

FIG. 14. Salt accumulation on a cultivated field. The land-owner (on the right) stated that it was impossible to drive his farm machinery through the salt patch when a large pond at the top of the hill behind the automobiles was full of water. A recharge, flow, and discharge sequence is indicated.

However, the distribution of salt on the surface varies in thickness and concentration. The variety of patterns at the surface reflect the amount and distribution of salt and the patterns of surface flow in the discharge area (Figure 15). Salt accumulations occur most commonly in areas where ground water is partly ponded and not free to run off.

Slope Instability. Certain sediments are more susceptible to instability than others. For example, the Upper Cretaceous clays in the prairie region are notoriously unstable (Peterson, 1945) whereas glacial till has a very steep angle of repose. Where seepage takes place very large landslides can develop on tills (Sauer, 1979). Slope stability or instability thus depends on the geology of the deposits, their water content, and on ground-water flow rates. Some general observations on slope instability are

- Most slopes will fail under some conditions. Under very dry conditions, however, failures are infrequent and usually restricted to small block glides or debris falls. Massive slumping occurs under extreme conditions of water saturation or in continuous outcrops of thick clay deposits, which have very low shear strength. Very steep slopes usually indicate dry conditions and rock types that are relatively stable.
- Slumping may indicate either outcrops of low strength clays or high rates of seepage or both.

FIG. 13. A highway foundation failure in a saline lake basin where ground water is discharging and is creating a "quick" condition. The white patches beside the roadway are salt-saturated sediments pushed upward to the surface by foundation displacement and exposed by evaporation.

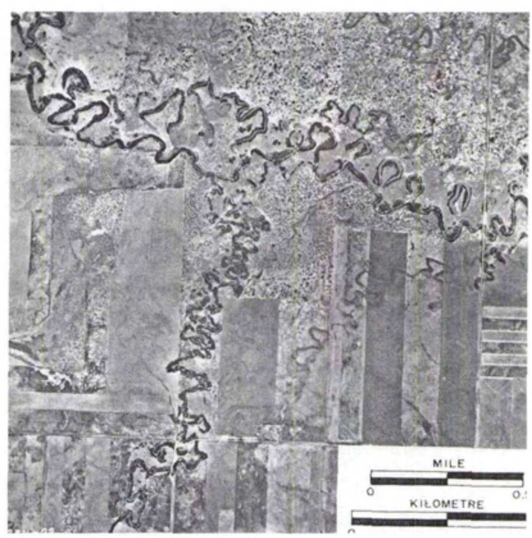

FIG. 15. The speckled pattern is characteristic of saline soils developed by ground-water discharge. Photograph courtesy Canada National Air Photo Library.

Slumping almost always indicates clay deposits (Figure 16) but some ground water is commonly present. The presence of water may not be obvious but it is nevertheless almost certain to be a contributor to the instability.

- Slumping may also be related to a lithologic boundary or structural discontinuity and, therefore, may be indicative of hydrologic boundary conditions. Evidence of this situation can be seen along ravines where slope morphology changes with increasing depth of erosion (Figure 16).

Stream Flow Characteristics and Floodplain Features. Stream flow and floodplain morphology are often affected by ground-water discharge or recharge. This is particularly true along the underfit streams flowing in a glacial meltwater channels. During most of the year a large part of the flow in these streams originates from ground water.

Meyboom (1966) described ground-water flow into river valleys of former glacial meltwater channels. He found that salinity increased toward the center of the valley; this effect was clearly indicated by a zonation of plant communities.

Valley morphology can be strongly influenced by lithologic changes and strata that discharge significant amounts of ground water. For example, discharge from an intertill sand or silt may result in piping which accelerates lateral erosion and forms deep incised meanders on a very small floodplain (Figure 17). The beginning and end of this incised meander pattern marks the boundaries of this zone, vertically, horizontally, or both. When seepage rates are large with high exit gradients the stream channel develops a flat base with spoon shaped, serrated banks (Figure 18). This form is similar to the gullies produced by outcrops shown in Figure 8. The mechanics are similar.

Land-Use Activities of Man. Obvious indications of man's activities are gravel or rock quarries, and mining activities of various kinds. However, land-use effects on ground water involve alterations to the natural environment and affect recharge, discharge, and to some extent storage.

The most obvious activities affecting ground water are drainage systems which reduce storage and irrigation systems which increase storage, recharge, and in some cases discharge (Figure 19).

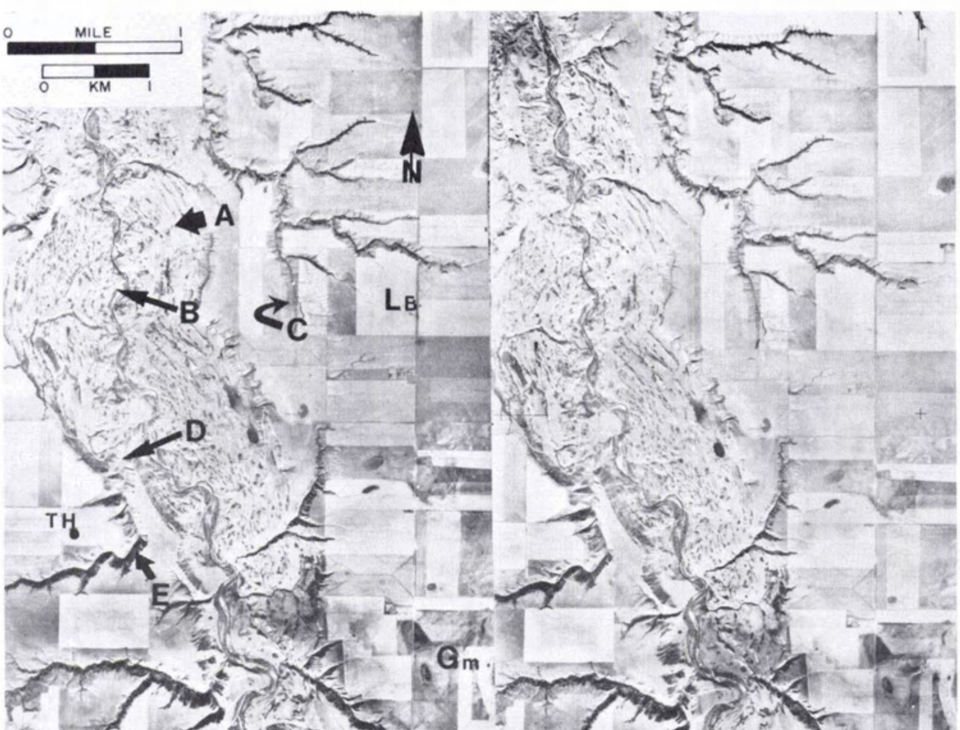

FIG. 16. Continuous retrogressive failure in soft clay shale can be seen in this stereogram at A and B. The elevation of the contact between the till and the shale can be seen at D. A lake basin clay at the surface is indicated by the gullies and tone patterns at C. The lake basin clay overlies till of a ground moraine exposed at Gm. Some seepage is evident at A. Photographs courtesy Canada National Air Photo Library.

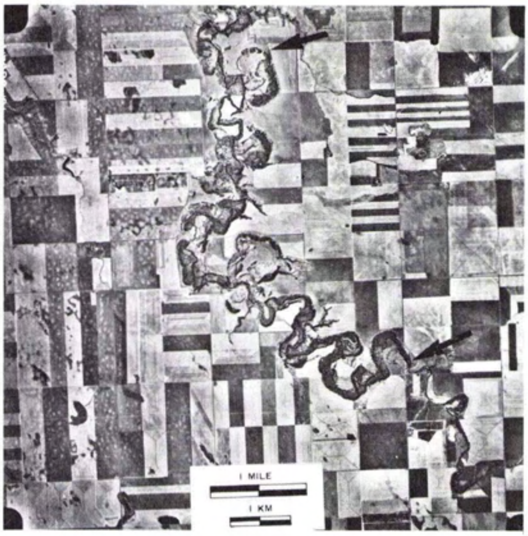

FIG. 17. Deeply incised meanders on the stream between the two arrows suggest a zone where the creek has eroded through an intertill sand. Vegetation patterns along the slopes indicate seepage or ground-water discharge and confirm the tentative interpretation. Photograph courtesy Canada National Air Photo Library.

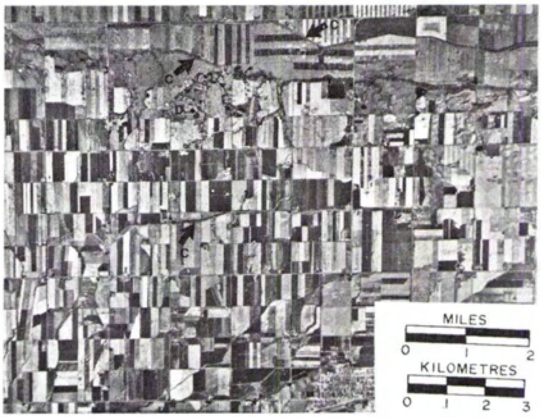

FIG. 19. Springs have developed at D from the recharge by Irrigation canals at C. Photograph courtesy Canada National Air Photo Library.

Side effects, such as slope instability (Figure 20) and salty soils, often can be observed in irrigated areas or near canal systems where subsurface flow and ground-water discharge have increased. Drainage and irrigation by canal systems are easily identified on aerial photographs because of their linear trend (Figures 19 and 20).

Urbanization has profound effects on the ground-water regime. Invariably, dramatic increases in water-table elevations take place soon after urban development. The water input for this change comes from irrigation of lawns and gardens, leakage from water mains and sewers, and a reduction in evaporation from the ground surface which has been covered by pavement and buildings. Some striking examples were cited by Hamilton and Tao (1977) in which the water table rose as much as 25 feet (8.3 m) after building development. These changes in the ground-water regime can create soil instability because of water saturation.

Forest cutting may also cause significant changes in ground-water conditions. Clearing accelerates runoff, especially from snow melt. On the other hand, transpiration, which often is the greater consumer of water, is reduced or almost eliminated. For example, it has been observed that

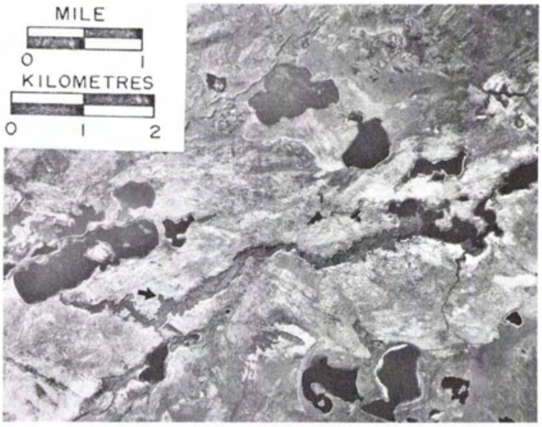

FIG. 18. A stream valley with a wide flat bottom covered by aquatic plants. The serrated spoon-shaped valley walls, the general morphology, and the vegetation patterns indicate ground-water discharge along valley slopes. The sediment adjacent to the valley is a deep, uniform, fine sand. Photograph courtesy Canada National Air Photo Library.

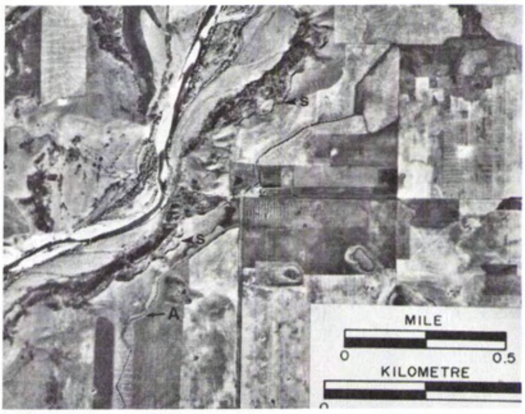

FIG. 20. The linear alignment of an irrigation canal is seen at A. Active slope instability can be seen at points marked S where the canal parallels the river valley. The river is not actively undercutting the slope at these points. It can be concluded that seepage from the canal is the main cause of this instability. Photograph courtesy Canada National Air Photo Library.

in forested regions the water table rises significantly after fire and remains at a high level until vegetation is re-established. The net effect of these events on shallow aquifers is difficult to evaluate unless some form of historical record is available through a sequence of photographs taken over a period of several years.

Summary

Geological processes interpreted from aerial photographs define ground-water systems and boundary conditions in glaciated terrain. The ground-water flow system within this framework is indicated on black-and-white photographs by springs, tone patterns, vegetation indicators, salinity of surface soils, slope instability, and apparent anomalies in streams and floodplains. Direct and indirect evidence of recharge and storage is often evident because of these landscape features. Discharge phenomena tend to be the most apparent, however.

References

Belcher, D. J., 1943. The Engineering Significance of Soil Patterns, *Proceedings 23rd Annual Meeting of the Highway Research Board,* November, 1943, pp. 569-598.

———, 1946. Engineering Application of Aerial Reconnaisance, Geological Society of America, Bulletin, Vol. 57, pp. 727-734.

———, 1948. The Engineering Significance of Landforms, *Highway Research Board Bull. 13,* pp. 9-28.

Belcher, D. J., L. E. Gregg, and K. B. Woods, 1943. *The Formation Distribution and Engineering Characteristics of Soils,* Engineering Bulletin, Purdue University Res., Serial No. 87.

Cannon, H. L., 1971. The Use of Plant Indicators in Ground Water Surveys, *Geologic Mapping and Mining Prospecting,* Taxon, Vol. 20, pp. 227-256.

Casagrande, Arthur, 1940. Seepage Through Dams, *Contributions to Soil Mechanics,* Boston Society of Civil Engineers, pp. 295-236.

Christiansen, E. A., 1968. Pleistocene Stratigraphy of the Saskatoon Area, Saskatchewan, Canada, *Canadian Journal of Earth Sciences,* Vol. 5, pp. 1167-1173.

———, 1979. The Wisconsinan Deglaciation of Southern Saskatchewan and Adjacent Areas, *Canadian Journal of Earth Sciences,* Vol. 16, pp. 913-938.

Cole, L. H., 1926. *Sodium Sulphate of Western Canada,* Canadian Dept. Mines, Ottawa, Canada, Mines Branch, 646 p.

Condit, H. R., 1970. The Spectral Reflectance of American Soils, *Photogrammetric Engineering,* Vol. 36, pp. 955-966.

Grisak, G. E., and J. A. Cherry, 1975. Hydrologic Characteristics and Response of Fractured Till and Clay Confining a Shallow Aquifer, *Canadian Geotechnical Journal,* Vol. 12, pp. 23-43.

Hamilton, J. J., and S. S. Tao, 1977. Impact of Urban Development on Groundwater in Glacial Deposits, *Proceedings 30th Annual Canadian Geotechnical Conference,* Saskatoon, pp. 11-12-11-35.

Johnson, E. A., and J. S. Rowe, 1975. *Fire and Vegetation Change in the Western Subarctic,* Canada, Indian Affairs and Northern Development, ALOR 75-76-61, 58 p.

MacDonald, A. B., and E. K. Sauer, 1970. The Engineering Significance of Pleistocene Stratigraphy in the Saskatoon Area, Saskatchewan, Canada, *Canadian Geotechnical Journal,* Vol. 7, pp. 116-126.

Meinzer, O. E., 1927. *Plants as Indicators of Ground Water,* United States Geological Survey, Water Supply Paper, 577, 95 p.

Meyboom, Peter, 1966. *Ground Water Studies in the Assiniboine River Drainage Basin; Part I; The Evaluation of a Flow System in South Central Saskatchewan,* Geological Survey of Canada, Bulletin 139.

Meyboom, Peter, Van Everdingen, and R. A. Freeze, 1966. *Patterns of Ground Water Flow in Seven Discharge Areas in Saskatchewan and Manitoba,* Geological Survey of Canada, Bulletin 147, 57 p.

Mollard, J. D., 1970. Photo Interpretation Studies in the Location of Prairie Ground Water Supplies, *Canadian Geotechnical Journal,* Vol. 7, pp. 127-135.

Peterson, R., 1954. Studies of the Bearpaw Shale at a Damsite in Saskatchewan, *Proceedings American Society of Civil Engineers,* Soil Mechanics and Foundation Division, Vol. 80, Separate 476, 28 p.

Richardson, N. W., and E. K. Sauer, 1975. Terrain Evaluation of the Dempster Highway across the Eagle Plain and along the Richardson Mountains, Yukon Territory, *Canadian Geotechnical Journal,* Vol. 12, pp. 296-319.

Sauer, E. Karl, 1974. Geotechnical Implications of Pleistocene Deposits in Southern Saskatchewan, *Canadian Geotechnical Journal,* Vol. 11, pp. 359-373.

———, 1978. *Some Geotechnical Implications of Glacial Tills in Southern Saskatchewan, Canada,* University of Saskatchewan, Dept. of Civil Engineering, Research Report 10, 34 p.

———, 1979. A Slope Failure in Till at Lebret, Saskatchewan, Canada. *Canadian Geotechnical Journal,* Vol. 16, pp. 242-250.

Sauer, E. Karl, and E. A. Wilson, 1977. Vegetation Indicators for Terrain Evaluation in a Prairie Environment, *Canadian Geotechnical Journal,* Vol. 14, pp. 445-465.

Stewart, R. E., and H. A. Kantrud, 1972. *Vegetation of Prairie Potholes in North Dakota, in Relation to Quality of Water and Other Environmental Factors,* United States Geological Survey Professional Paper 585-D, 36 p.

Whitaker, S. H., and E. A. Christiansen, 1972. The Empress Group in Southern Saskatchewan, *Canadian Journal of Earth Science,* Vol. 9, pp. 353-360.

Whitaker, S. H., and D. E. Pearson, 1972. *Geological Map of Saskatchewan,* Saskatchewan Research Council and Department of Mineral Resources.

White, W. N., 1932. *A Method of Estimating Ground Water Supplies Based on Discharge by Plants and Evaporation from Soil,* United States Geological Survey Water Supply Paper 659-A, 105 p.

(Received 14 May 1980; revised and accepted 23 December 1980)