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DEPARTMENT OF MINES AND TECHNICAL SURVEYS

BULLETIN 147

PATTERNS OF GROUNDWATER FLOW IN SEVEN DISCHARGE AREAS IN SASKATCHEWAN AND MANITOBA

Peter Meyboom, R. O. van Everdingen, and R. A. Freeze

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By
Peter Meyboom,
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PREFACE

In 1960 the Geological Survey of Canada started three major groundwater investigations in western Canada. Although the investigations were carried out with different objectives, they had in common a novel approach to hydrogeology by which emphasis was placed on the dynamic character of groundwater.

This report contains well-documented results of extensive piezometer measurements related to groundwater flow-systems in typical prairie environments. The authors describe the interrelation between groundwater and surface water, and they derive certain empirical rules to describe the nature of discharge areas in deep river valleys.

J. M. HARRISON,
Director, Geological Survey of Canada

OTTAWA, April 22, 1964

BULLETIN 147 — Typische Beispiele für Grundwasserströmungssysteme in sieben Abflussgebieten in Saskatchewan und Manitoba.

Von P. Meyboom, R. O. van Everdingen und R. A. Freeze

Dieser Bericht beschreibt die Fortschritte, die im Laufe von drei grösseren Grundwasserstudien in sieben Abflussgebieten in den Präriegebieten des westlichen Kanada erzielt wurden. Die Untersuchungen haben gezeigt, dass der Grundwasserablauf auf Talsohlen beschränkt ist.

БЮЛЛЕТЕНЬ 147 — Закономерности истечения подземных вод в семи дебитных районах Саскачевани и Манитобы.

П. Мейбум, Р. О. ван Эвердинген и Р. А. Фризе

Отчет дает описание результатов достигнутых по сие время тремя главными программами исследований подземных вод в семи дебитных районах внутренних равнин Западной Канады. Эти исследования показали что исток подземных вод ограничен дном долин.

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PATTERNS OF GROUNDWATER FLOW IN SEVEN DISCHARGE AREAS IN SASKATCHEWAN AND MANITOBA

Abstract

Theories that describe the extent of the zone of groundwater discharge require testing in the field by the installation of piezometers. Four types of piezometers were installed in selected areas on the Prairies. The areas selected for study are drained or bisected by deeply incised rivers or valleys, whose flanks are five to fifteen times steeper than the regional slope between the water divide and the edge of the valley.

Measurements carried out during 18 months show that groundwater discharge is limited to the valley bottom. The boundary between downward flow and lateral or upward flow may lie anywhere between one fifth and one third of the way up the valley flank.

It is not always possible to describe all discharge phenomena in one vertical cross-section. The flow resultant in a vertical cross-section through an area of predominantly downward flow may be a good approximation of the total-flow vector, but the discrepancy between the total-flow vector and the flow resultant increases towards the centre of the discharge area, owing to the increasing magnitude of the longitudinal component of flow.

Résumé

Les théories sur l'étendue des aires de décharge des eaux souterraines doivent être vérifiées sur le terrain à l'aide de piézomètres. On a utilisé quatre genres de piézomètres à des endroits déterminés dans les Prairies. Les aires choisies pour ces travaux sont drainées ou coupées par des rivières ou des vallées profondes dont les flancs sont de cinq à quinze fois plus raides que la pente régionale entre la ligne de partage des eaux et le rebord de la vallée.

Les mesures prises pendant 18 mois indiquent que la décharge des eaux souterraines se limite au fond de la vallée. La limite entre l'écoulement vers le bas et l'écoulement latéral ou vers le haut peut se trouver n'importe où entre le cinquième ou le tiers du flanc de la vallée vers le haut.

Il n'est pas toujours possible de décrire tous les phénomènes de la décharge des eaux pour une coupe verticale donnée. La résultante de l'écoulement dans une coupe verticale à travers une aire où l'écoulement se fait en prédominance vers le bas peut donner une bonne idée du vecteur d'écoulement total. Toutefois, l'écart entre le vecteur d'écoulement total et l'écoulement résultant augmente vers le centre de l'aire de décharge du fait de l'importance croissante de la composante longitudinale de l'écoulement.

INTRODUCTION

Now that drainage basins have been accepted as suitable basis for quantitative groundwater studies, the question arises as to what parts of such basins can be measured most conveniently for the purpose of water-balance studies: the recharge area or the discharge area. Theories on groundwater motion offer two answers to this question. According to Hubbert (1940, p. 928) "discharge is limited to the bottoms of the valleys containing streams." From this, the simple inference may be drawn that by measuring groundwater contribution to stream flow, the total groundwater discharge out of a basin will be known. Toth (1963), on the other hand, concluded that if a flow system is developed in permeable material overlying poorly permeable materials "the bulk of the discharge will take place between the midline and the valley bottom," where the midline is defined as "the line located on the surface midway between and parallel to the valley bottom and the water divide." This would imply that—at least in the ideal case—unspecified measurements have to be carried out in fifty per cent of the drainage basin at either side of the boundary between recharge area and discharge area.

Neither theory has been presented with sufficient field evidence to arrive at a simple scheme of measurements that leads to a first approximation of a groundwater balance. Thus it still remains to be determined in the field at what place in the flow system meaningful measurements can be carried out and how these measurements are to be taken.

This report describes the present progress of three major groundwater investigations in the Interior Plains of western Canada. Each one of the investigators experimented with measurements that would yield sufficient information on patterns of groundwater flow to determine the best location of future instrumentation or to relate certain surface phenomena to groundwater flow in a more qualitative way. Meyboom constructed the flow patterns in the willow ring and those along Cypress, Pembina, Assiniboine, and Arm Rivers; van Everdingen carried out the investigation along South Saskatchewan River; and Freeze studied the groundwater flow underneath the glacial spillway near Readlyn.

All examples deal with discharge phenomena in conspicuous topographic lows. It seemed natural to start the investigations in such areas, for they are the common denominator of the aforementioned theories. To what extent the conclusions from either theory can be adapted as working hypotheses for field studies is examined in the following paragraphs.

Acknowledgments

The authors thank A. Treichel who supervised the installation of all piezometers in Manitoba, and E. Shwedyk, who supervised and surveyed the Arm River installation. Thanks are also due to A. Dudgeon for taking weekly measurements of the Manitoba piezometers, and to A. Mattick of the Water Resources Branch of the Department of Northern Affairs and National Resources in Winnipeg, for providing provisional stream flow data on Cypress and Pembina Rivers.

The excellent cooperation with Olson Drilling Co. (Moose Jaw, Saskatchewan) and Hall Drilling Company (Calgary, Alberta) contributed greatly to the successful completion of the projects.

MEASUREMENT OF GROUNDWATER POTENTIAL

Definition of Terms

The *groundwater flow field* is a three-dimensional field that occupies all space beneath the air-water interface to the depth where groundwater flow becomes impossible. The *groundwater potential* at any point in this field can be expressed in terms of *total head*, defined by Hubbert (1953) as the sum of pressure head and elevation head at that point. By restricting our attention to an arbitrary plane through the flow field we eliminate one dimension of space. Many details of the flow can be depicted adequately on a two-dimensional flat surface. In general, we are dealing either with maps (horizontal plane through the flow field) or with sections across a divide or river (vertical planes through the flow field).

The terminology to be used for the components of the total-flow vector on maps or in cross-sections is illustrated in Figure 1. The flow component in the horizontal plane will be called the *horizontal component* ('H' in Fig. 1). This horizontal component can be resolved into a *longitudinal component* parallel to a river or divide ('1' in Fig. 1), and a *lateral component* perpendicular to a river or divide ('2' in Fig. 1). Thus the orientation of these flow components is determined by the orientation of a river or a divide, whereas the direction of the component is determined by the direction of flow. The third component of the total-flow vector is the *vertical component* ('V' in Fig. 1).

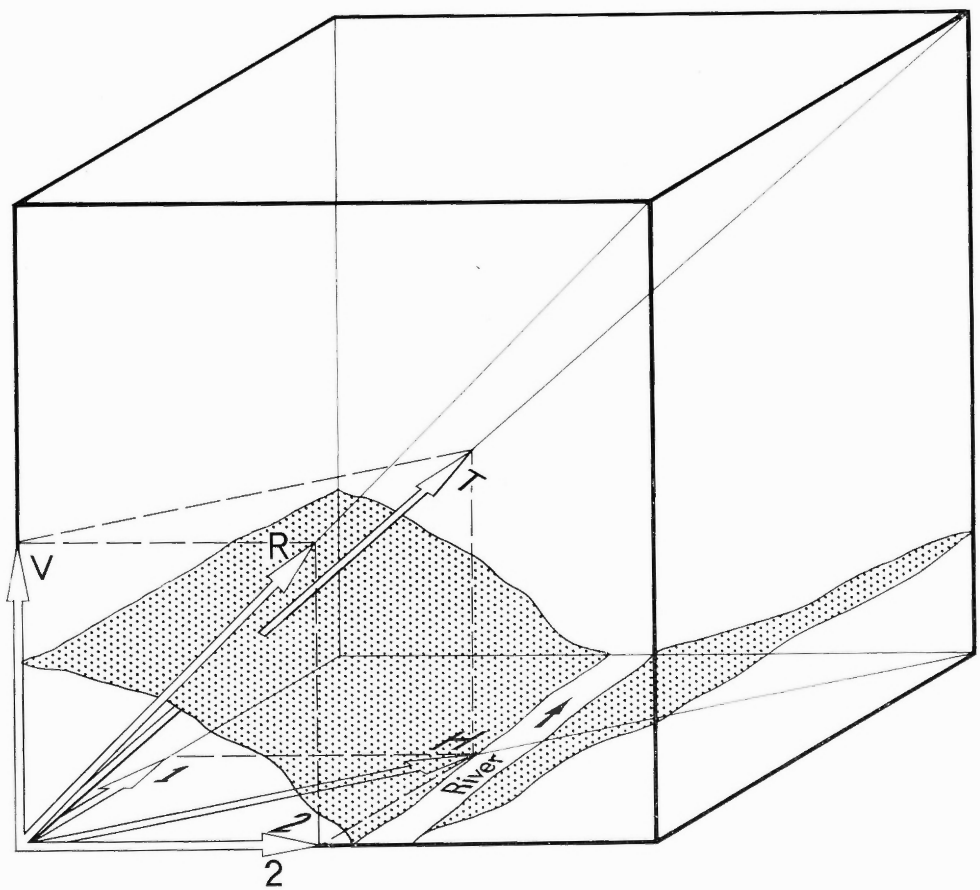
The horizontal, longitudinal, and lateral components of flow can be shown on a map, the lateral and vertical components of flow will show in a section. The sum of the last two will be called the *flow resultant* ('R' in Fig. 1), for each specific point within the section.

The most common ways of depicting a flow field two-dimensionally are water-table maps and maps of the piezometric surface, both of which are generally constructed on the assumption that the horizontal component of flow represents essentially the total-flow vector. However, in those instances where the flow resultant R (Fig. 1) may be a better approximation of the total-flow vector than the horizontal component H, the groundwater flow has to be depicted in a vertical cross-section rather than on a map.

Previous investigators (Ernst, 1954; Toth, 1963) reasoned that in dealing with vertical cross-sections along the predominant topographic gradient, the longitudinal component of groundwater flow would be of no significance as compared to the lateral component, and the flow resultant R would indeed be a good approximation of the total-flow vector.

In order to construct the flow resultant R one requires potential measurements at various depths in one vertical plane. These measurements are obtained by means of open manometer tubes, commonly called piezometers.

A *piezometer* is a small-diameter pipe, which is placed in the ground in such a way that the water level in the pipe represents the total head at the very point in the flow field where the piezometer terminates. Three or four piezometers terminating at different depths at one location form a piezometer nest, whereas a line of piezometer



1. *Longitudinal component*
2. *Lateral component*
V. *Vertical component*
R. *Flow resultant*
H. *Horizontal component*
T. *Total flow vector*

GSC

FIGURE 1. Terminology of flow components

nests constitutes a piezometer cross-section. As each piezometer records the value of total head at the piezometer end, a piezometer cross-section yields a series of potential values in a vertical plane through the flow field.

Constructing a flow pattern is a simple matter now. Lines of equal head can be drawn between the observed values, and flow lines are everywhere normal to the lines of equal head. It should be kept in mind that the hydraulic gradient as indicated on the cross-section is only the true gradient if the plane of cross-section is selected to coincide with the direction of flow. Otherwise, a gradient shown on the cross-section is merely the component of the true gradient along the plane of the section.

The principal interpolation rules that have to be adhered to in constructing these flow diagrams are:

1. When groundwater flow crosses a plane interface between rocks of different permeability, the flow lines and lines of equal head refract by the tangent law (Hubbert, 1940, p. 943). Therefore, flow that is oblique to the bedding planes of strata of varying permeability traverses the more permeable strata nearly parallel with the bedding and the poorly permeable strata more nearly at right angles.

2. Lines of equal head terminate perpendicularly upon impermeable boundaries of the flow field.

3. If the flow pattern is depicted in a vertically exaggerated cross-section the flow lines may no longer be drawn perpendicularly to the lines of equal head, but have to be constructed according to the rules laid down by van Everdingen (1963). By knowing the exaggeration factor and the angle between the horizontal and the equipotential line in the exaggerated section, it is possible to determine from van Everdingen's monograph (op.cit., Fig. 2) the angle between equipotential line and flow line that should be used in the exaggerated section. All flow resultants in the accompanying flow diagrams have been constructed according to this rule.

Piezometer cross-sections can be used to reveal the depth of a flow system or the groundwater flow patterns that underlie certain discharge phenomena. For example, some of the piezometer cross-sections that are reported here have shown more precisely the nature of groundwater flow adjacent to groundwater outcrops. However, before the results of the measurements are discussed, it is necessary to describe the methods of piezometer construction.

Construction and Arrangement of Piezometer Nests

The first investigator who used piezometers for determining flow patterns adjacent to a stream was Pennink (1905), who commented that "groundwater studies have fewer means to safeguard us from mistakes than virtually any other field in the realm of applied sciences." Pennink used closed manometers for his experiments, but as these were felt to be too vulnerable for operation in remote areas under severe climatic conditions, the Geological Survey of Canada decided to install the simpler open piezometers such as were described by Christiansen (1943). In these the water level

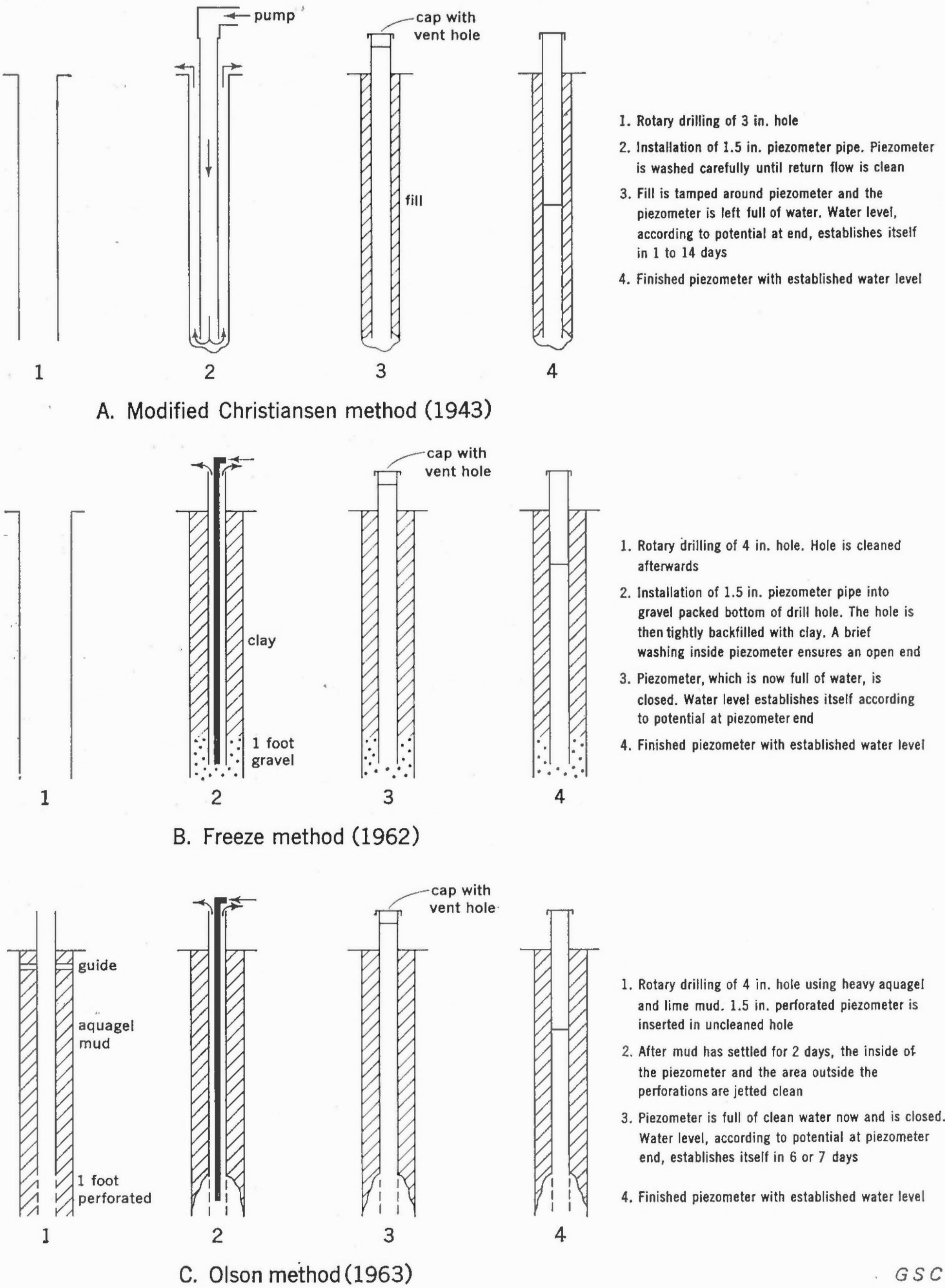
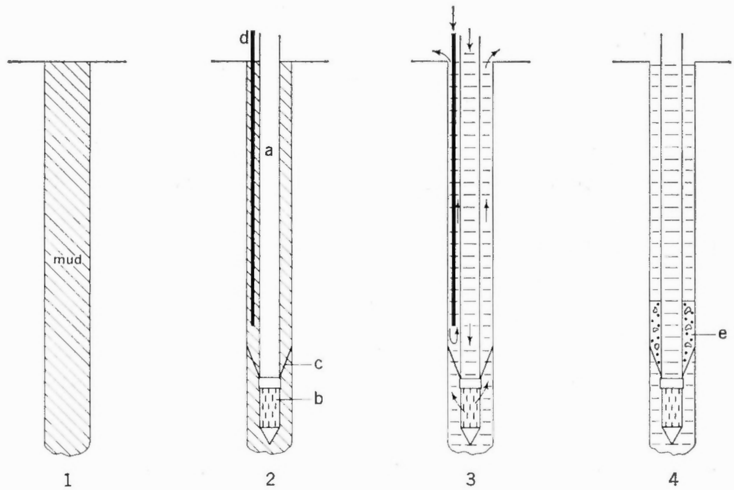
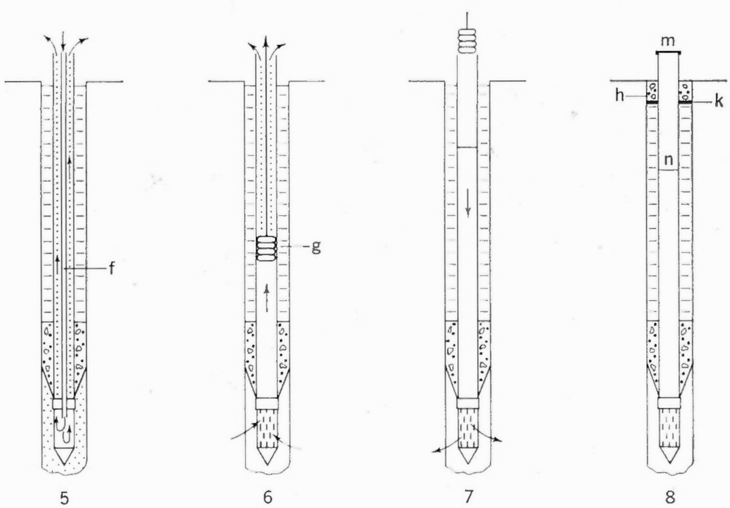


FIGURE 2. Three construction methods for shallow (10 feet) to medium-deep (200 feet) piezometers



1. Rotary drilling of 4.5 in. hole using natural mud (from shale) and in some cases, aquagel
2. Installation of 2 in. piezometer casing (a), with 3 ft. long, 2 in. No. 10 sandpoint (b), Baker's metal petal basket (c), and 1 in. cementing hose (d) outside the casing
3. Washing of hole and casing through the cementing hose and casing. Hole now filled with partly muddy circulation water
4. Cement plug (e) placed above basket, cementing hose removed



5. Wash hose (f) inserted in casing for washing of casing and sandpoint. Casing now filled with clear circulation water
6. After 1 to 2 hrs. swabbing with 2 in. swabbing tool (g), circulation water is swabbed out. Formation water is pulled into screen and casing
7. Swabbing tool is removed, raised formation water plunges back. Stages 6 and 7 provide plunging action to develop the piezometer
8. Cement plug (h) resting on cement bags (k) is placed at top. Well is capped (m). Water level (n) establishes itself, generally, within one day.

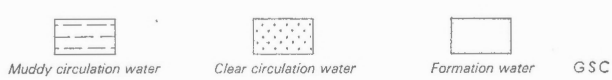


FIGURE 3. Construction method for deep piezometers (Hall, 1963)

has to be measured with a tape or similar device. The materials in which the piezometers are installed are unconsolidated and partly consolidated clays, sands, and silts, in which drilling is easy.

The first series of piezometer sections (at selected crossings of Cypress, Pembina, and Assiniboine Rivers) were all installed by the Christiansen method (Fig. 2A), which was modified to the extent that the piezometers were placed in a drilled hole rather than being driven into the ground. The filling of the annulus[1] was difficult, and there was a danger of filling the cavity and therefore sealing the bottom end of the piezometer. Freeze changed the method (Fig. 2B) by filling the point of measurement with gravel and by flushing the piezometer after, rather than before, backfilling had taken place. This method was employed successfully at the Readlyn site.

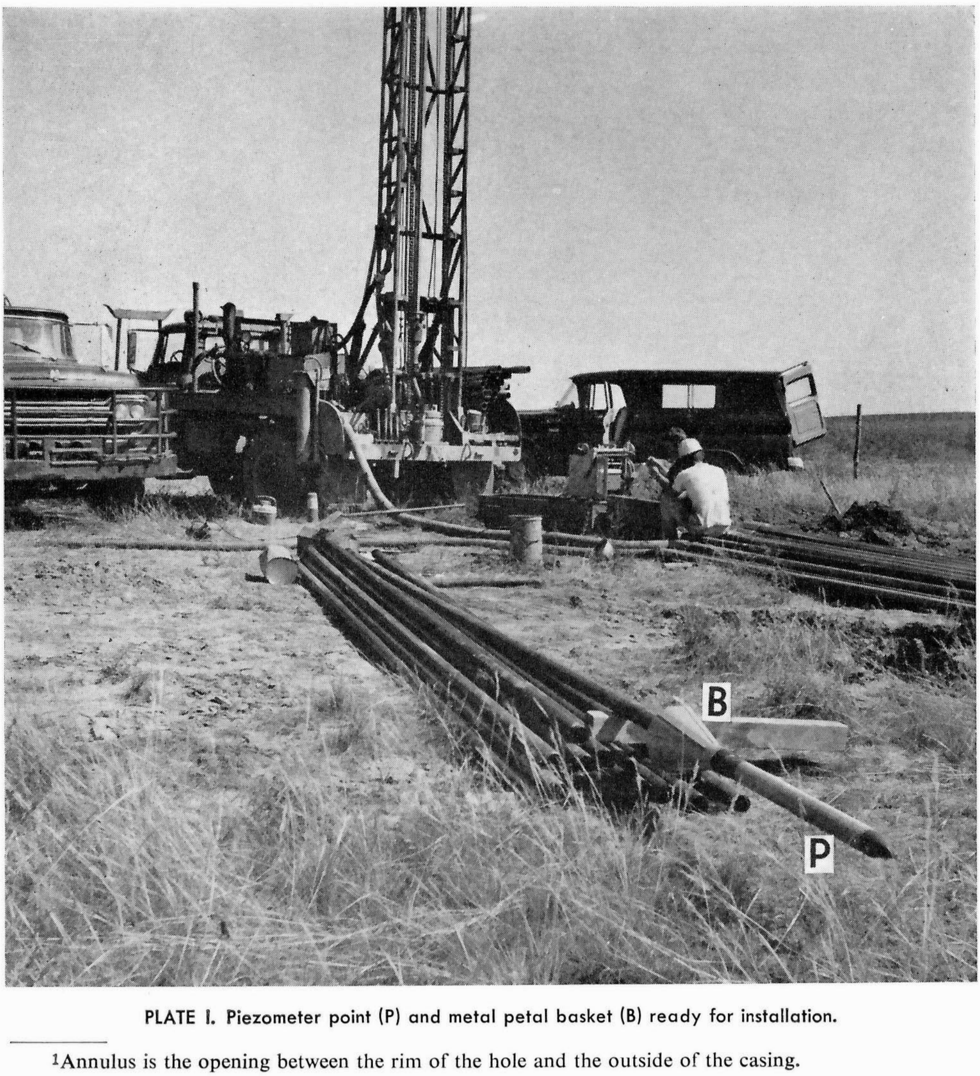


PLATE I. Piezometer point (P) and metal petal basket (B) ready for installation.

[1]Annulus is the opening between the rim of the hole and the outside of the casing.

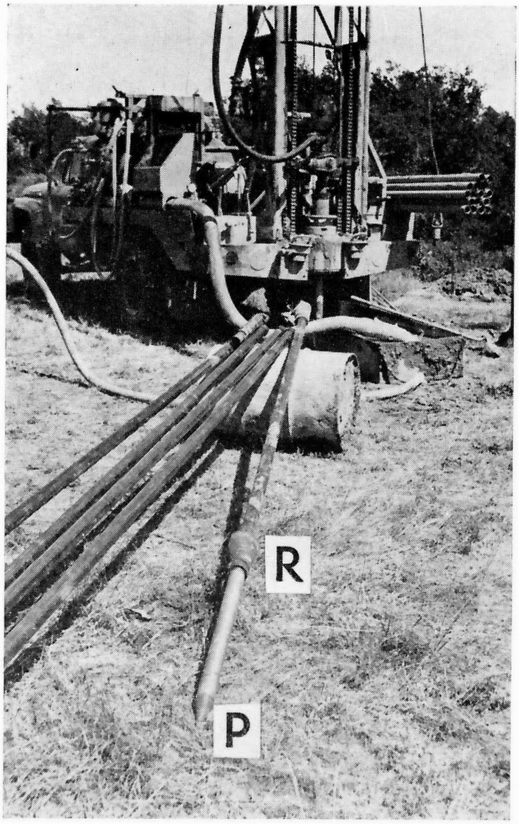


PLATE II. Piezometer point (P) and rubber basket (R) ready for installation. The rubber basket is made on the spot from a 2-foot section of used truck tire, held in place by a stainless steel hose-clamp.

Backfilling the annulus remained troublesome in the deeper piezometers and for the Arm River installation Olson devised a method (Fig. 2C) of installing the piezometers in a heavy mud slurry, made up of lime and aquagel. After the mud had formed an efficient seal, the inside of the piezometer and consequently the area around the perforations were jetted clean. Piezometers installed in this manner functioned perfectly, although the flowing piezometer in the Ardkenneth Member of the Upper Cretaceous Bearpaw Formation had to be cemented completely to prevent leakage during pressure tests.

The Freeze method has proved suitable for relatively shallow piezometers (less than 60 feet) whereas the Olson method affords a means of installing piezometers up to 200 feet deep. Both methods require a homogeneous poorly permeable section. Neither clay nor aquagel will give sufficient seals if high artesian heads are to be measured or if the geological section consists of alternating permeable and poorly permeable strata of considerable thickness, such as in the Riverhurst section. For those conditions the method illustrated in Figure 3 had to be employed.

This method differs from the previous methods in that a sandpoint, fitted with a metal basket (Pl. I) or rubber basket (Pl. II) is installed at the depth where the head has to be determined. A cement plug on the basket prevents interference of heads between the point of measurement and aquifers higher in the section. The Olson method augmented with either type of basket may be the best tool for very deep piezometers in a homogeneous shale section.

The sensitivity of open piezometers depends on the relation between permeability of the material in which they are placed and the diameter of the pipe. Inside a 2-inch piezometer fluctuations of the water level of the order of 1 foot are accompanied by groundwater flow of the order of 0.15 gallon. Thus, open 2-inch piezometers may be subject to a time lag of a day or two as far as recording rapid changes in potential is concerned. This is of little consequence, however, if the piezometers are measured once a month only.

No attempt was made to install several piezometers in one hole, for the cost of drilling 12-24-inch diameter holes would have rendered the operation prohibitively expensive.

PATTERNS OF GROUNDWATER FLOW IN DISCHARGE AREAS OF INCREASING MAGNITUDE

General Statement

The sequence of the following examples reflects the theory that essentially the same groundwater phenomena occur in discharge areas whatever their size, a fact that has been referred to as "the sequence of magnitude" in a previous publication (Meyboom, 1963). The examples cited hereafter illustrate some of the principles that determine the extent of a discharge area in a typical prairie topography, consisting of rolling or hummocky country, drained by deeply incised rivers. Each of the investigated sites will be described briefly in terms of topography and geology, followed by a comprehensive description of the groundwater flow pattern. It has not been the purpose of this publication to examine the geographic origin of the water being discharged.

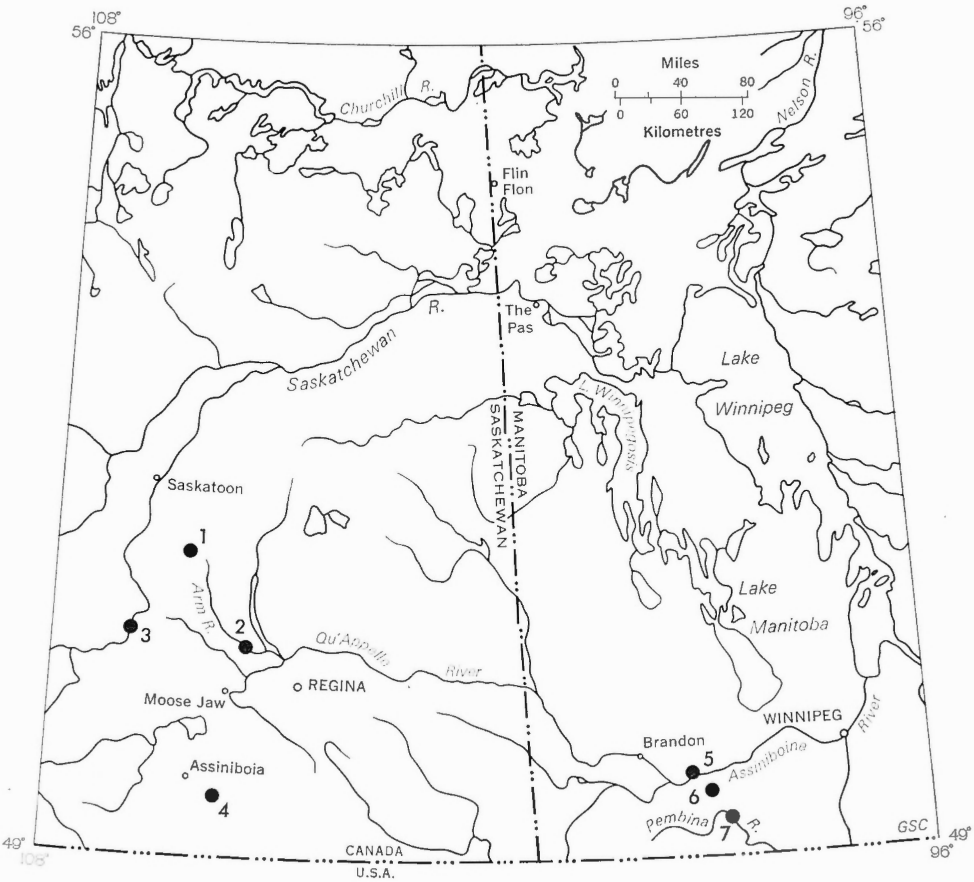
Figure 4 shows the locations of the investigated areas, each one of which is designated by a code consisting of letters and numbers. The first number and first two letters are the official drainage basin designation given by the Department of Northern Affairs and National Resources, Water Resources Branch, whereas the letters GS and the last figure refer to the number given by the Geological Survey to the piezometer cross-section.

Willow Ring in Allan Hills, Saskatchewan

Willow rings in hummocky moraine were first reported as groundwater outcrops by Meyboom (1963), who stated that "within a region of approximately 50 feet outside the willow ring, groundwater flowed towards the willows and probably upward into the depression." Study of the willow ring, which was instrumented during the summer of 1962, continued from May 1963 to September 1963, and the new results revealed a more complicated flow pattern than the original measurements suggested.

The Allan Hills are the northward continuation of the Missouri Coteau and form the water divide between the South Saskatchewan River drainage basin and the Assiniboine River drainage basin. The area is covered with till, overlying Bearpaw shales. The till is developed as hummocky moraine, which can be best described as knob-and-kettle topography.

The flow pattern in May 1963 (Table I) indicated flow away from the depression with a continuous gradient of 0.05 ft./ft. between piezometers m and c. The measure-



Piezometer locations

1. *5 JH-GS 1, willow ring in Allan Hills*
2. *5 JH-GS 2, Arm River*
3. *5 HF-GS 1, South Saskatchewan River*
4. *5 JD-GS 1, Readlyn spillway*
5. *5 MH-GS 3, Assiniboine River*
6. *5 MH-GS 2, Cypress River*
7. *5 OB-GS 2, Pembina River*

FIGURE 4. Location of piezometer installations

ments in May showed that the potential underneath the depression had risen during the spring, contrary to the heads underneath the ridge, which were even lower than during the summer of 1962. This would indicate recharge from the depression, and continuous downward flow underneath the rim. On June 25, 1963, the installation was augmented with five Olson-type piezometers i, j, k, g, and h in nests III and IV. The deep piezometer 'k' (Fig. 5) was intended to reach into the zone of regional downward flow, which was assumed to exist underneath the depression. However, the potential underneath the depression continued to increase to a depth of 50 feet, with an upward gradient of 0.07 foot and the position of the boundary of the presumed zone of downward flow remained as yet unknown.

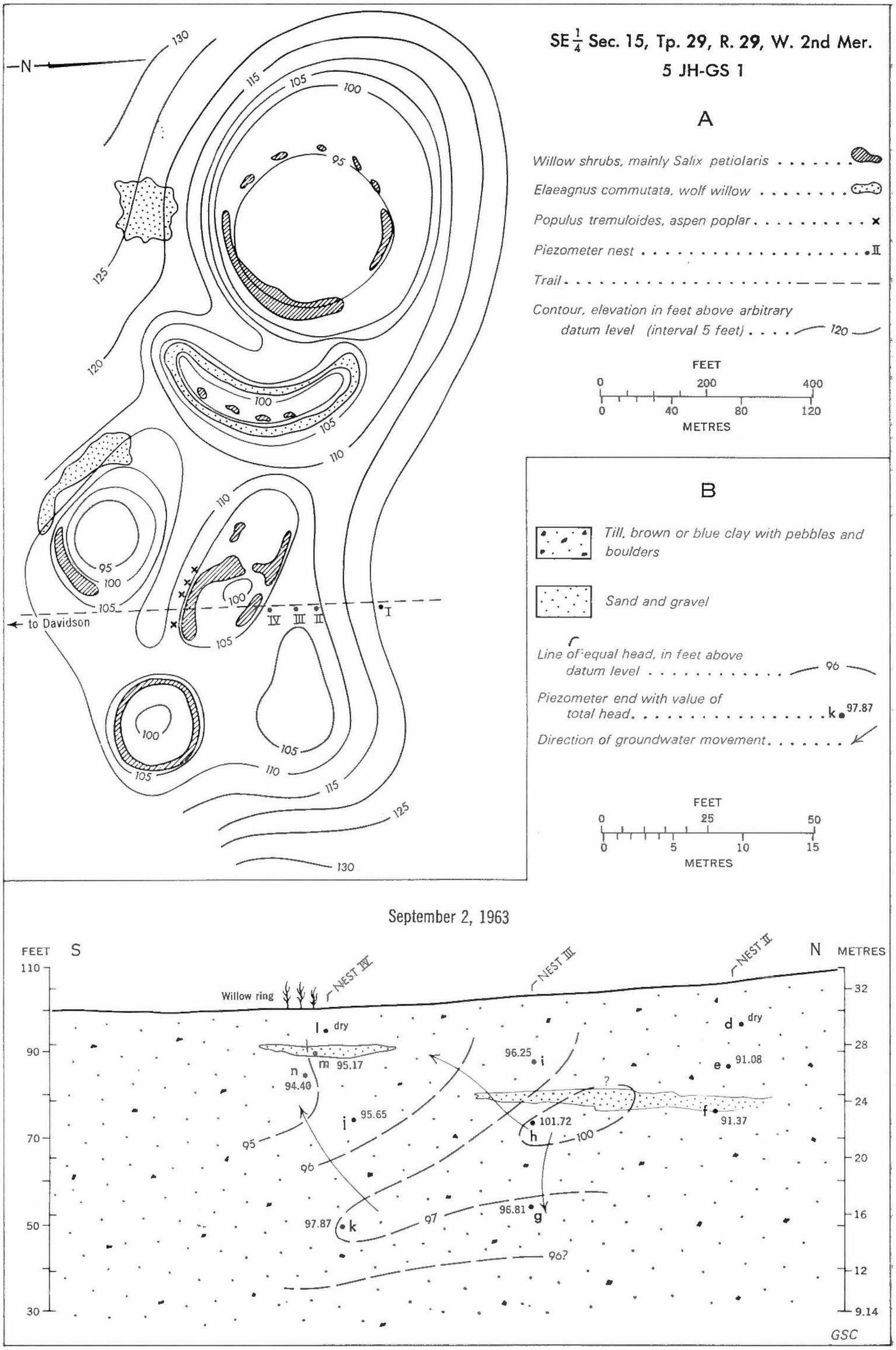


FIGURE 5. Groundwater flow near willow ring, in the Allan Hills, Saskatchewan

The new piezometers i, h, and g revealed the existence of a region of higher head north of the depression, with flow both to the north and south. The 1962 piezometers d, e, and f seemed to register head values wholly out of place in the new flow pattern (Fig. 5).[1]

Notwithstanding the more complicated picture and the few unresolved discrepancies, it may be reiterated that during the summer months groundwater flows towards the willows from a region of about 50 feet around the willow ring, and upward into the depression from a depth of at least 50 feet.

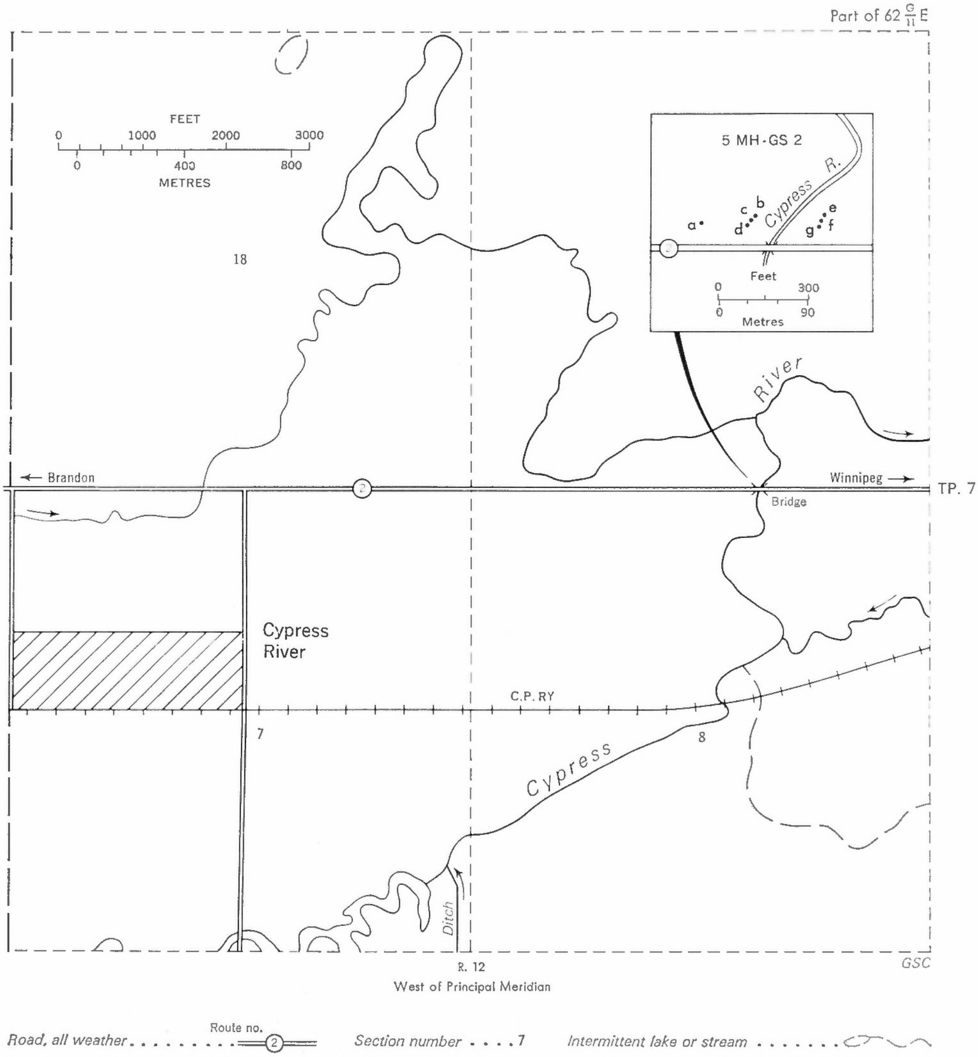


FIGURE 6. Location and arrangement of piezometers at Cypress River, Manitoba

[1]Further observations during the time this publication was in press revealed that the situation described here is not a steady-state flow pattern, but the final stage of a transient response to evapotranspiration. A complete description of the various stages of the flow pattern near the willow ring has been made the subject of a separate publication (Meyboom, 1966).

Small flow patterns like the one just described, seem to exist by the virtue of three conditions: low permeability of the flow medium, sufficient rainfall and relief to maintain a nearby water table higher than the bottom of the depression, or sufficient phreatophytic vegetation to cause a depression in the water table. Although the ultimate flow pattern in an area of hummocky moraine is shown to be very complicated owing to the irregular topography and the unhomogeneities in the flow medium, a clear distinction can be made between recharge and discharge areas. In the example described here the discharge area proper is confined to the depression, whereas upward and lateral flow is evident in a region of about 50 feet around the willow ring.

Cypress River, Manitoba

Cypress River is a small tributary to Assiniboine River. The piezometer cross section has been installed along highway No. 2 nearly a mile east of the town of Cypress River (Fig. 6). The river at this point is merely a small creek, which rises in the watershed area between Red River and Assiniboine River. The valley, which is 30 feet deep and 300 to 400 feet wide, carries a lush vegetation of trees and shrubs, the predominant species being pussy willow, dogwood, and Manitoba maple.

The piezometers were installed in March 1962, by the modified Christiansen method. Weekly measurements were taken between the time of installation and November 1, 1963 (Tables II and III).

The surficial deposits northwest of the river are a few feet of sandy lake deposits overlying Vermilion River shales. Southeast of the river the bedrock is covered with till and the eastern edge of an alluvial fan, which reaches from the Pembina Hills to the Assiniboine lowland, covering about 20 square miles. The alluvial deposits in this fan consist of poorly sorted sand, silt, and clay. The bedrock shales in this area belong to the Riding Mountain Formation (Elson, 1952).

Flow Pattern

During 1962, the flow pattern in the vicinity of Cypress River (Fig. 7) showed groundwater flow towards an effluent stream (cf. Pennink, 1905, Figs. 8 and 34). Measurements in piezometer 'a' suggested upward as well as lateral flow towards the stream. In April 1962 the flow pattern was asymmetrical with a concentration of flow lines at the east side of the river (Fig. 7). However, throughout the summer and winter of 1962 the upward flow gradient at the east bank diminished from 0.29 ft./ft. to 0 (Table III; Fig. 8). During the same period the upward gradient along the west bank rose from 0.03 ft./ft. to 0.40 ft./ft. (Table II; Fig. 8), reflecting a shift in groundwater flow concentration from the east bank to the west bank, in the course of about one year. This observation leads to further understanding of the problem of groundwater flow in river meanders.

In a recent study of groundwater flow into the Mullica River in New Jersey, Lang and Rhodehamel (1962) concluded that "the chief areas of upward movement of groundwater into the stream are the result of natural scour." If this conclusion has

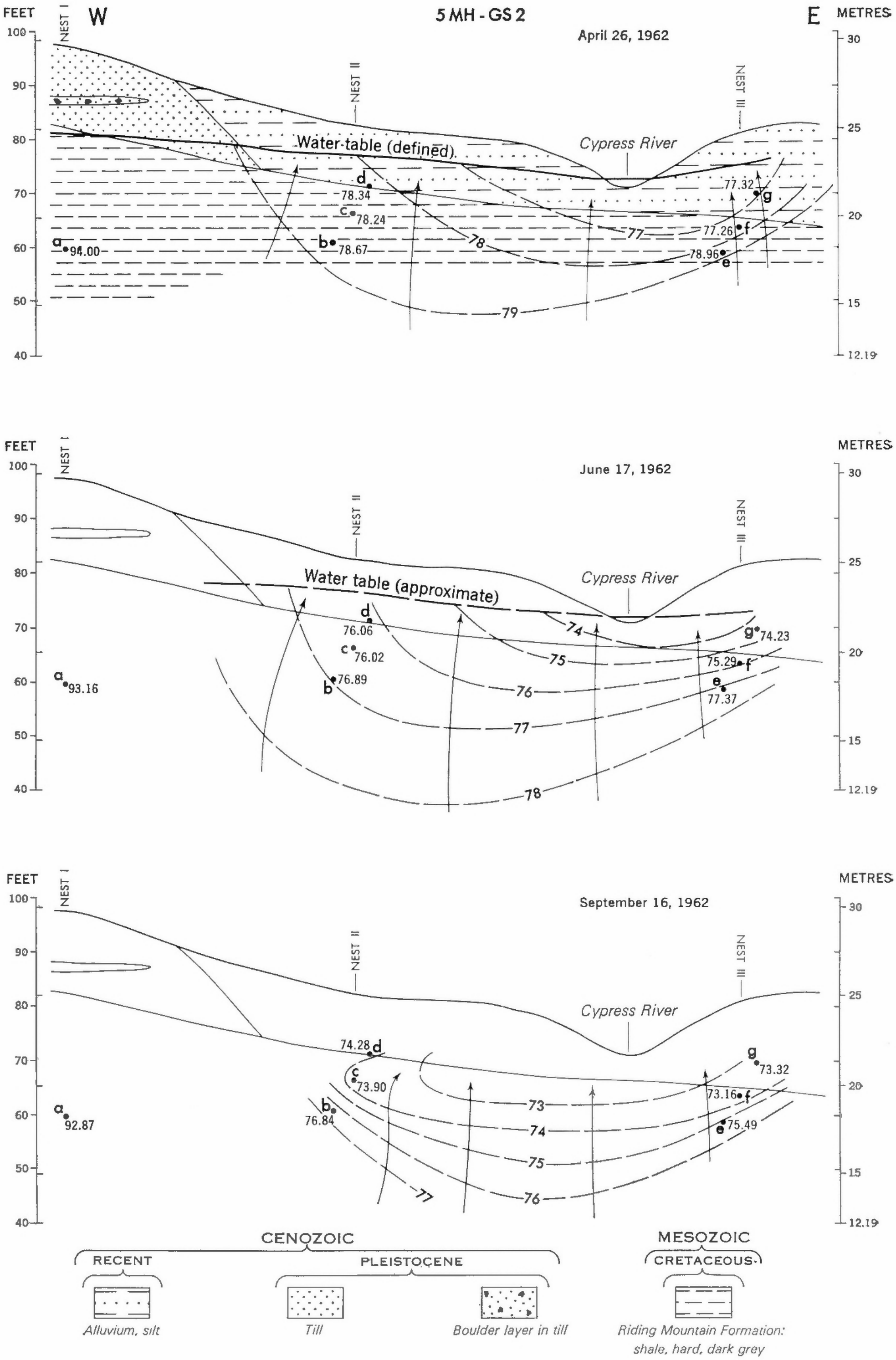
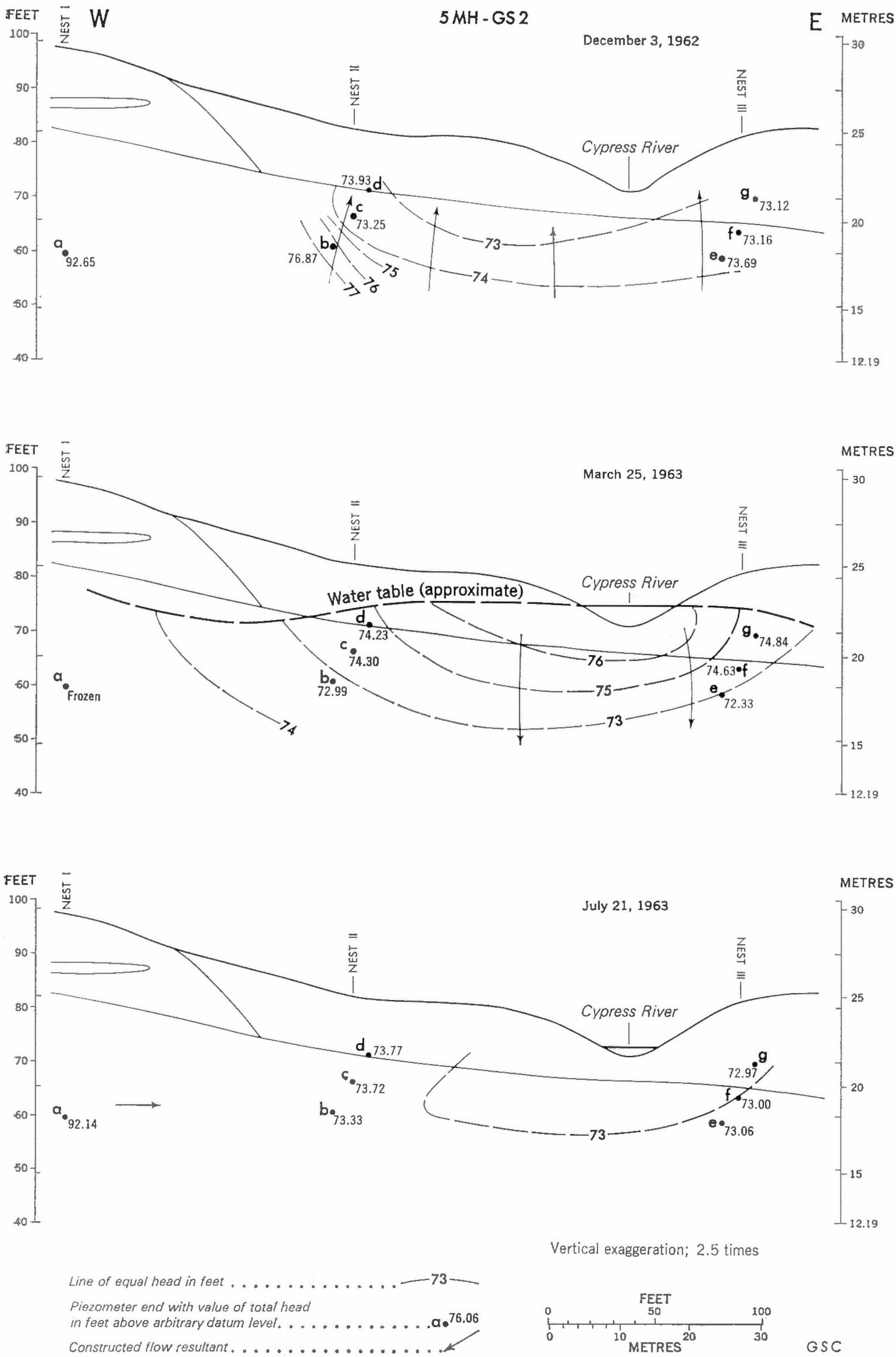


FIGURE 7. Patterns of groundwater



flow along Cypress River, Manitoba

general validity, the observed changes in groundwater flow near Cypress River would reflect minute changes in river regime. Shifting of the channel-flow and the accompanying changes in erosion and sedimentation patterns would continually alter the resistance of the river-bed to groundwater inflow, which in turn might give rise to the observed changes in flow patterns (Pl. III).

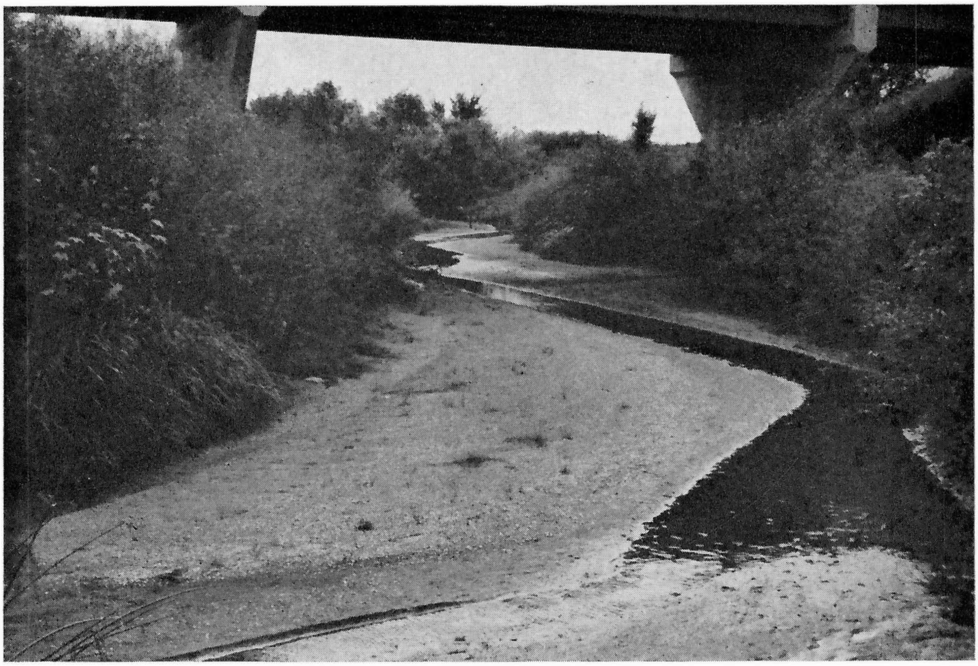


PLATE III. Shifting channel-flow in Cypress River, Manitoba.

The maximum upward gradient along the western bank of Cypress River was recorded on February 10, 1963, after which date the gradient suddenly dropped to 0.04 ft. /ft., indicating a virtual standstill in groundwater discharge. Between March 15 and 21 both gradients continued to decrease (Fig. 8), resulting in negative (downward) gradients at both sides of Cypress River. The river hydrograph for the same period (inset, Fig. 8) shows a rapid increase in discharge and it is likely that the sudden reversal of groundwater gradient was caused by the swift rise in river stage.

It is uncertain whether river water physically entered the river-bed and banks (bank storage effect) or whether the negative gradients existed only during the time that the pressure exerted by the increased load of surface water was being transferred from the groundwater to the aquifer skeleton, a condition known in soil mechanics as "excess hydrostatic pressure." In either case, groundwater flow has been temporarily downward. If it were a condition of excess hydrostatic pressure only, spring break-up would offer no mechanism for local groundwater recharge.

Appreciable negative gradients existed until the end of May 1963, six weeks after the river had resumed its low-flow level. During the summer months that followed the flow pattern was much less spectacular than the one during the previous

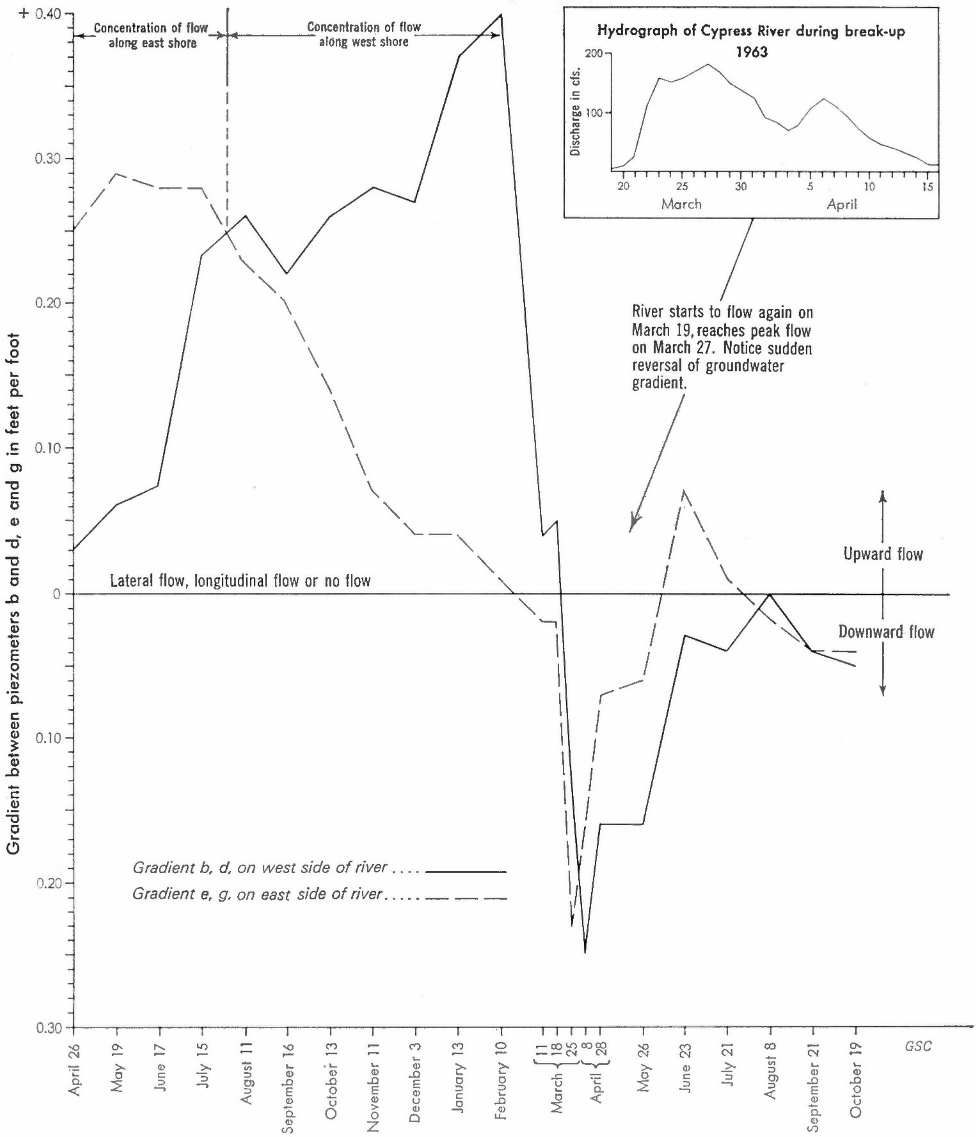


FIGURE 8. Variations in groundwater gradient along Cypress River, between April 1962 and October 1963

summer. The gradients were small, indicating little movement in the plane of the section. From this it may be concluded that during the period most groundwater movement was (longitudinal) underflow.

The most important inference from these flow patterns is the unsteady nature of the direction of groundwater flow near a small river such as Cypress River. As has been shown, the concentration of flow lines may shift from one side of the stream to the other, and strong upward flow may give way to longitudinal flow with little or no upward component.

Hydraulic Conductivity

As shown on Figure 7, in June 1962 groundwater was being discharged both underneath the stream bed and at the water table. The latter condition suggests groundwater consumption by phreatophytes, an assumption that is confirmed by the phreatophytic vegetation in the valley. From studies of phreatophytes in Saskatchewan, the senior author (Meyboom) estimates one summer's groundwater consumption (May–September) by an association of willow, dogwood, and Manitoba maple at 24 inches. Integrating this value over a strip along the river channel of 300 feet wide and a foot long the total groundwater consumption along this one-foot stretch can be calculated to be 600 cubic feet per summer, or about 5 cubic feet per day. Total base-flow discharge of Cypress River amounts to about 2 million cubic feet per day (Water Resources Branch, Department of Northern Affairs and National Resources) along 25 miles of contributing channel, or 15 cubic feet per day per foot of channel. The total daily groundwater discharge would thus amount to about 20 cubic feet per foot of valley. Assuming an average upward gradient of 0.15 ft./ft. (Tables II, III) the hydraulic conductivity of the Riding Mountain shales can be estimated at around 0.06″/hour.

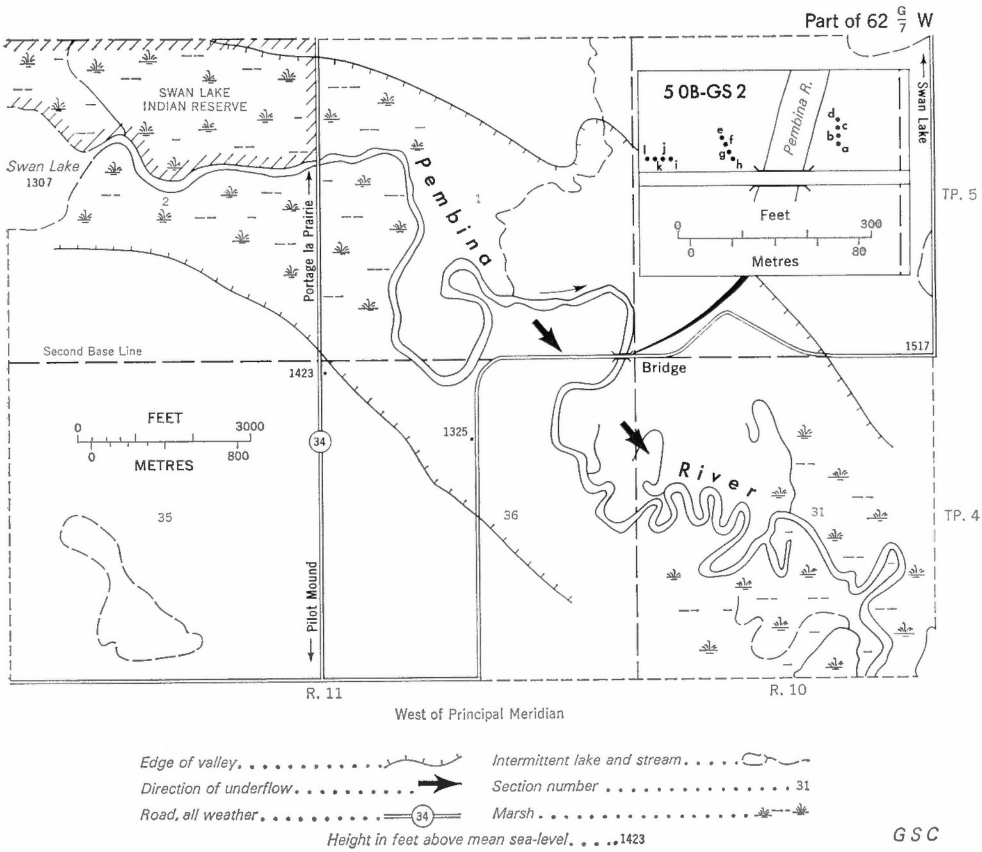


FIGURE 9. Location and arrangement of piezometers at Pembina River, Manitoba

Pembina River, Manitoba

Pembina Valley near Swan Lake is about a mile wide and 200 feet deep (Fig. 9). The piezometer section in this valley was installed in March 1962. The twelve piezometers range in depth from 15 to 66 feet, and the section covers the immediate vicinity of the river. Readings of total head have been taken weekly and selected measurements are presented in Tables IV to VI.

The sediments in the Pembina Valley consist of 300 feet of silt with shale fragments, overlying shales of the Riding Mountain or Vermilion River Formation. The soils of the flood plain are immature, but not saline. Willows and poplars line the banks of the channel, and the floor of the valley is covered with woods of Manitoba maple, elm, and oak (Pl. IV).

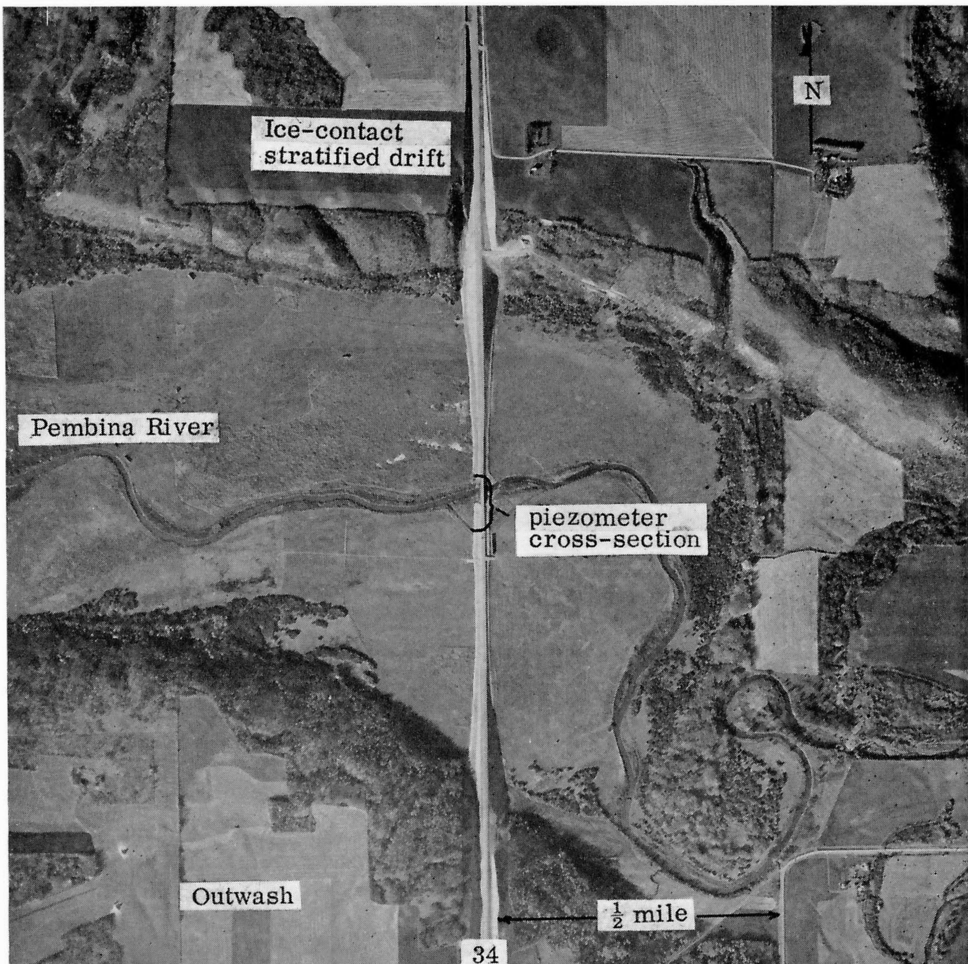


PLATE IV. Aerial view of Pembina Valley. During glaciation the deep channel of Pembina River provided an outlet for meltwater from western Canada into glacial Lake Agassiz. The floor of the valley, where not cultivated, is now covered with woods of elm, Manitoba maple, oak, birch, poplar, and willow. (RCAF A16399-157)

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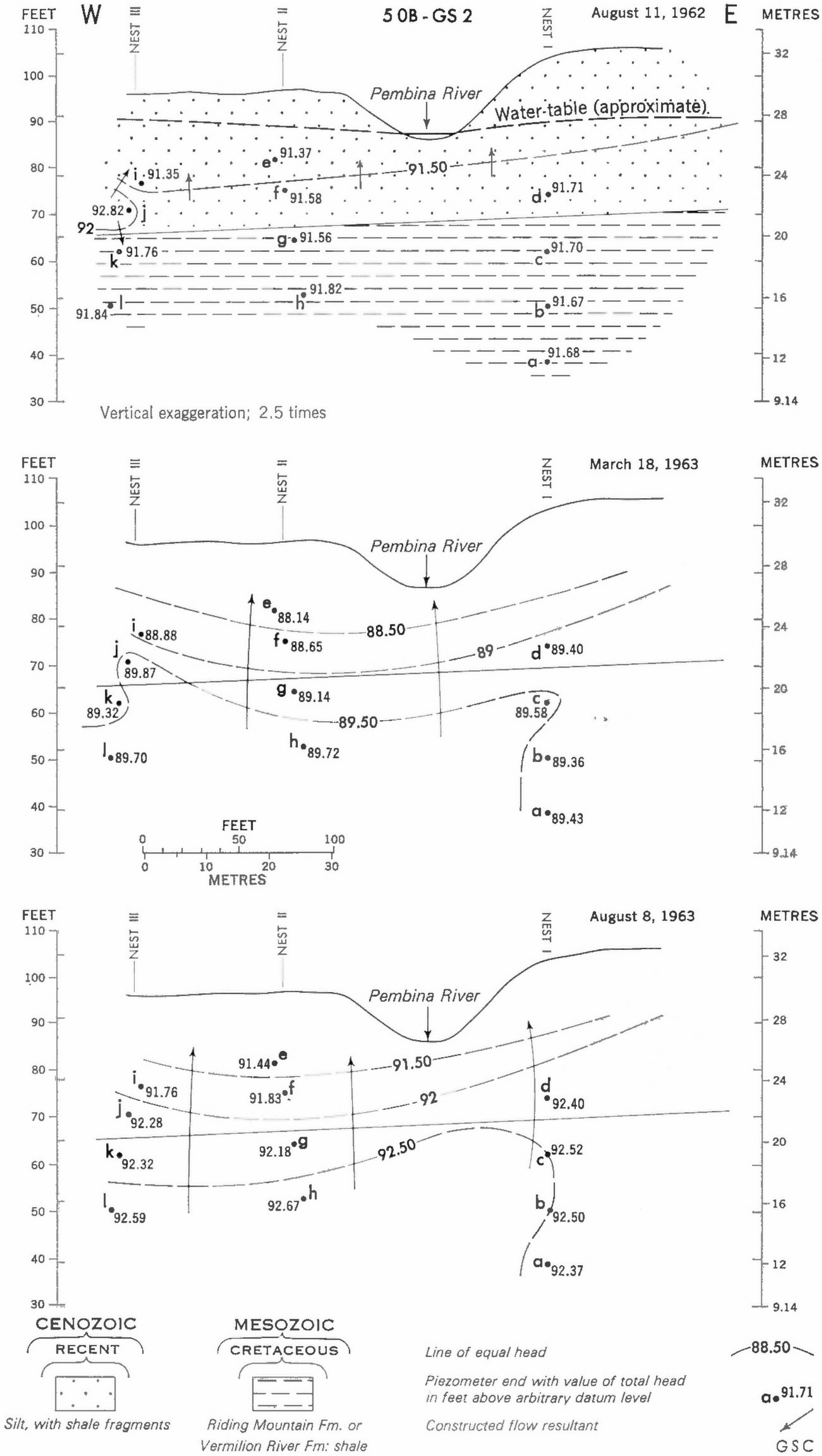

FIGURE 10. Patterns of groundwater flow near Pembina River, Manitoba

Flow Pattern

It is evident from the extremely small upward and lateral gradients within and between the various piezometer nests (Fig. 10) that the direction of groundwater movement is perpendicular to the cross-section. The situation is probably also one of underflow with a slight upward component, which was particularly noticeable during the summer of 1963. Contrary to Cypress River, these small upward gradients show no variations throughout the year. The direction of underflow is shown in plan view in Figure 9.

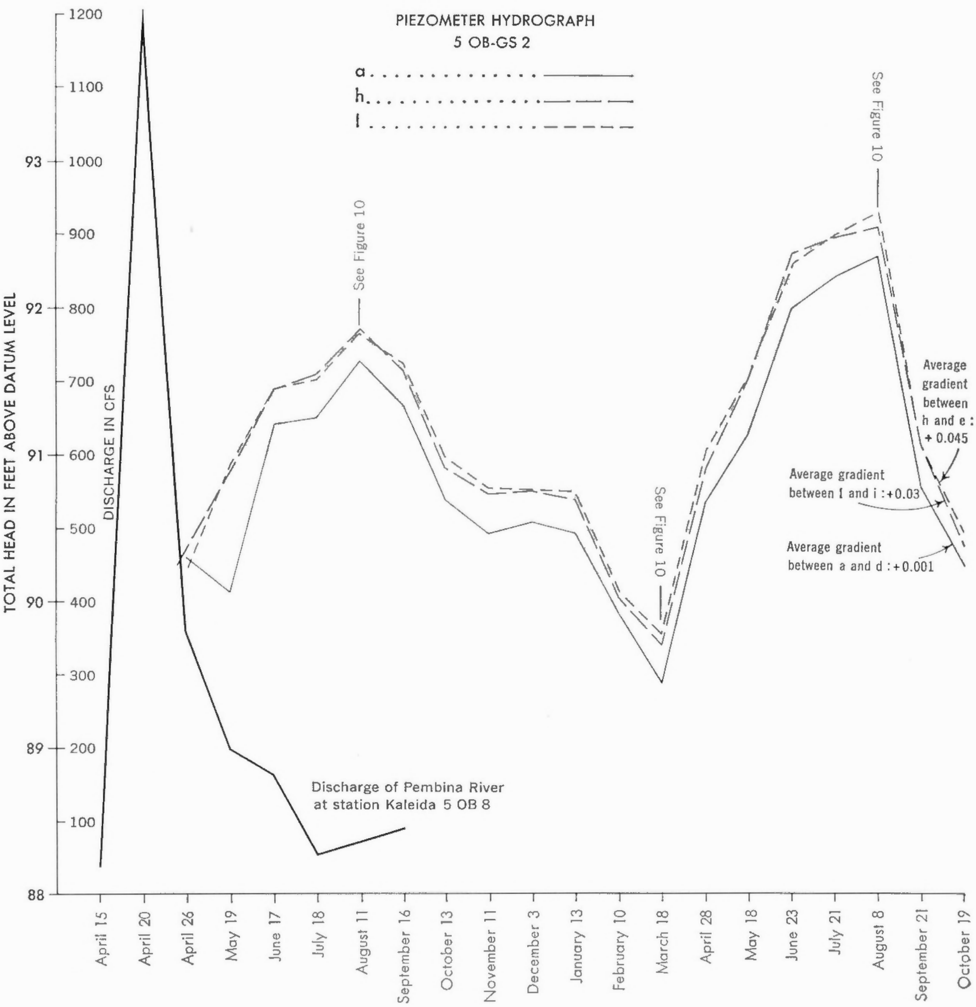

FIGURE 11. Relation between stream discharge of Pembina River and values of total head in deepest piezometer in each nest

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An irregularity in the flow pattern was noticed shortly after installation in piezometer 'j' (nest III), which indicated a zone of higher head. Movement from this area was at its peak during April 1962, but declined steadily throughout the year and eventually ceased.

A plot of the total head in the deepest piezometer of each nest (Fig. 11) shows a regular seasonal variation and an *inverse* relationship with stream discharge. Both facts are contrary to Cypress River, where seasonal variations were not the same for all piezometers and where the increased amount of surface run-off after break-up produced a sudden rise in potentials. Only piezometer 'd' (Table IV) showed a momentary rise on April 28, 1963, but the high head disappeared within a week and the flow pattern remained unchanged.

The absence of strong upward leakage underneath Pembina River is surprising. Its proximity to the Pembina Mountains—a pronounced highland, 3 miles east of the cross-section—would suggest that the Pembina River was an important discharge area. Records of a test well a few miles downstream from the present cross-section (Commonwealth Manitou No. 2, Charron, 1962) show the opposite to be true. Underneath Pembina Valley, total head decreases with increasing depth at a rate of 0.92 ft. /ft. to a depth of 912 feet. As could be expected, the log of the well shows poorly permeable Cretaceous shales, and downward flow occurs through the shales into the permeable Lower Cretaceous Swan River sandstone, which discharges in the Red River artesian area (Charron, 1961). It may thus be concluded that the drainage influence of the very deep Pembina Valley on the regional groundwater flow is seriously restricted by the adjacency of a topographically lower discharge area and by the low permeability of the Upper Cretaceous shales.

Assiniboine River, Manitoba

The wide valley of the Assiniboine River at Steel's Ferry is about 150 feet below the gentle topography of the "Upper Assiniboine Delta", most of which is occupied by sand dunes (Elson, 1952). The river valley contains an immature soil. The banks of the stream are wooded with heavy stands of Manitoba maple, willow, and elm.

Logs of the piezometers show that the valley at Steel's Ferry is underlain by 15 to 30 feet of sand and gravel (Figs. 13 and 14), which in turn is underlain by at least 25 feet of sandy clay, resting on grey shales of the Upper Cretaceous Vermilion River Formation. Similar to the cross-section at Pembina River, the piezometers at Steel's Ferry are confined to the vicinity of the river (Fig. 12).

The twenty piezometers range in depth from 22 to 55 feet. Measurements were taken once every week between April 1962 and October 1963. Selected readings of total head are set out in Tables VII to XI.

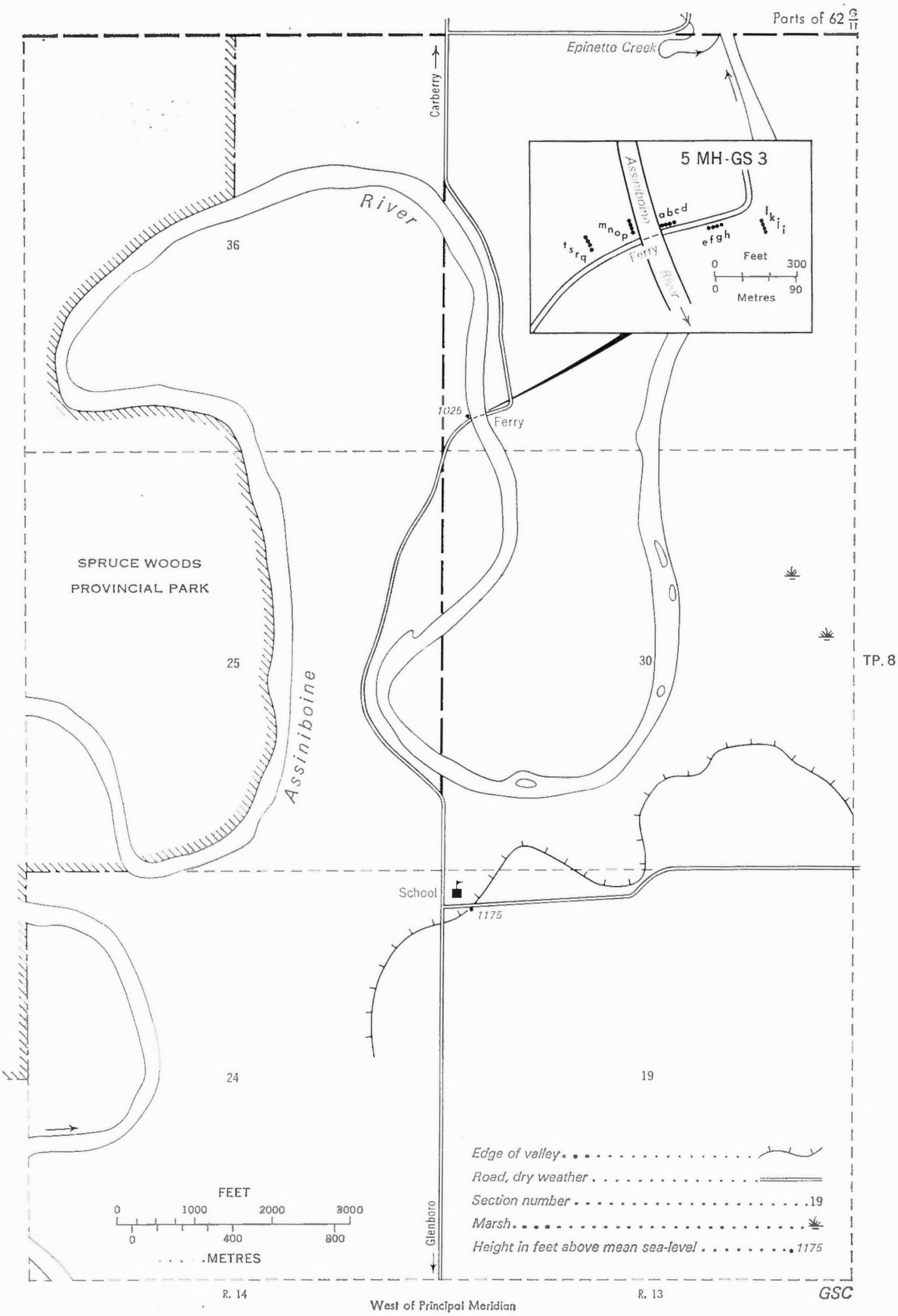

FIGURE 12. Location and arrangement of piezometers at Assiniboine River, Manitoba

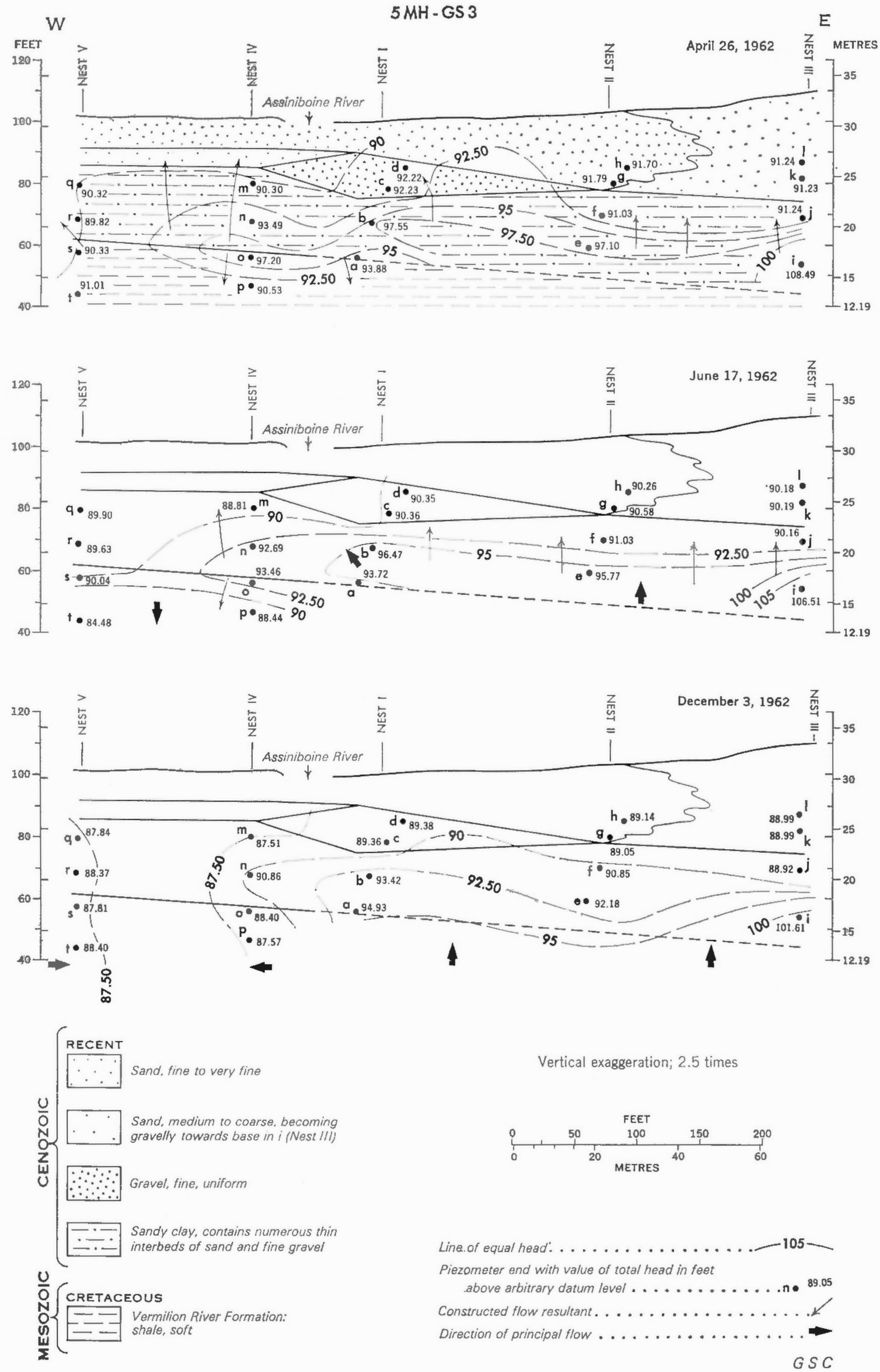

FIGURE 13. Patterns of groundwater flow near Assiniboine River, Manitoba

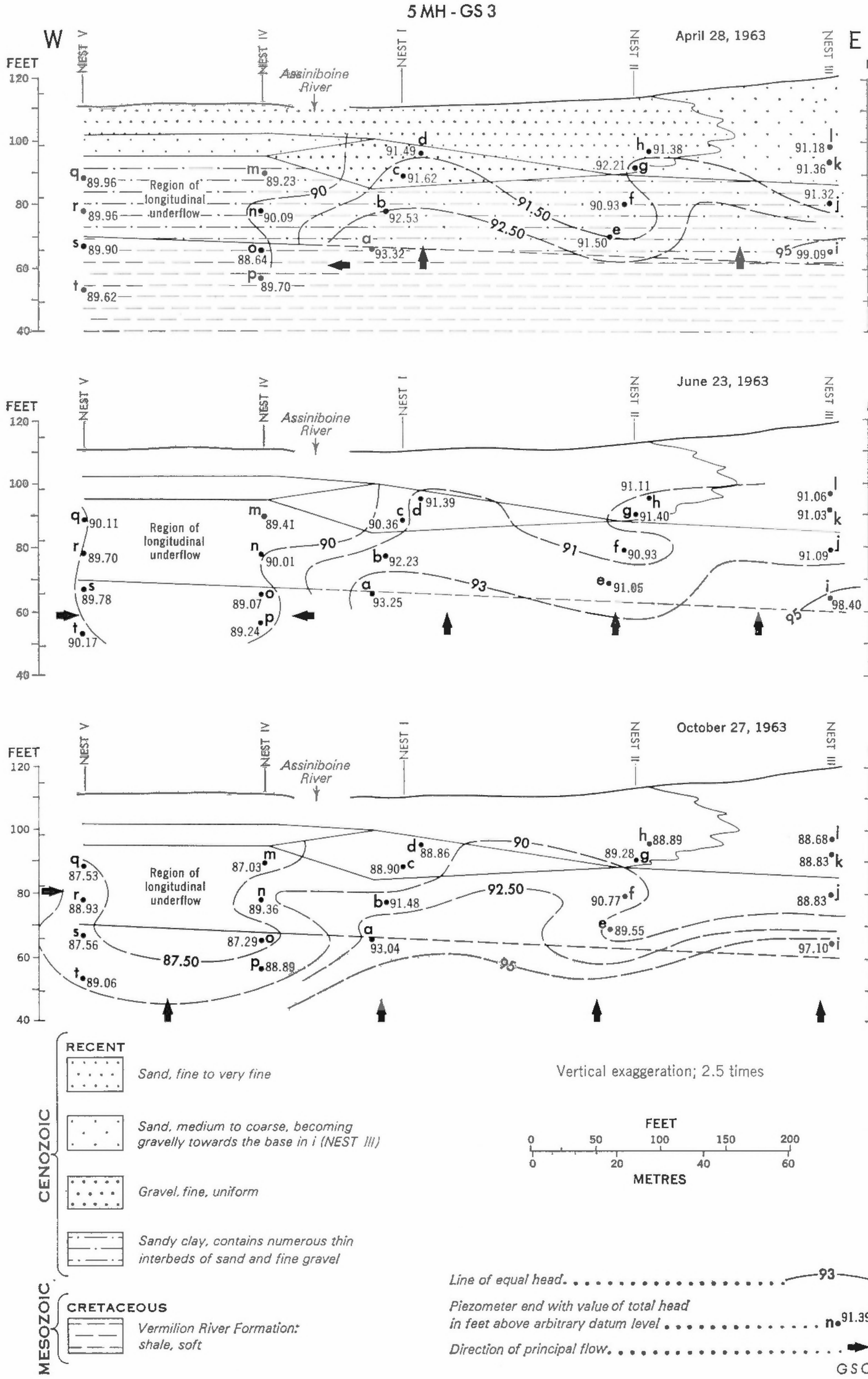

FIGURE 14. Patterns of groundwater flow near Assiniboine River, Manitoba

Flow Pattern

It is evident from Figures 13 and 14 that groundwater moves upward everywhere along the eastern bank of the river. Most of the inflow here is directed towards the water table, as can be learned from a comparison between the strong upward gradients and the negligible lateral gradients. Phreatophytes are probably the main means of discharge at the water table.

Maximum upward movement along the east bank was recorded in June 1962 (Fig. 13). After June the flow decreased gradually and reached a minimum in March 1963, but increased again after that month. The regular seasonal fluctuations in total head, without major changes in the overall flow pattern, are very similar to those reported from Pembina River.

At the west bank the situation is different. At first (Fig. 13) a "tongue" of high head extended from the eastern bank underneath the river. From this zone of high potential flow was upward, westward (*opposite* the direction of surface flow), and downward into the Vermilion River shales. By observing the position of the 92.50 line of equal head in the successive flow patterns it can be seen that this tongue gradually retreated in the course of 1962, giving way to an area of longitudinal flow (Fig. 14, April 1963). In this zone, upward flow became increasingly significant, as can be seen from the ensuing flow patterns. By October 1963 upward flow was manifest under the entire river valley. These changing flow patterns illustrate once more the unsteady character of particular details of groundwater flow towards a river.

The aforementioned tongue of higher head was probably connected with the sandhills north of the river. Hence, it may have reflected a very strong inflow from this large—and probably very effective—recharge area.

The effect of spring break-up is similar to that in the Pembina River. Gradients and values of total head reached a minimum during March 1963, and showed a gradual rise throughout the summer of 1963. The measurements of October 1963 indicate the beginning of another decline. Abrupt reversals of gradient, such as occurred near Cypress River, were not observed near Assiniboine River.

Although the piezometer cross-sections of Cypress River, Pembina River, and Assiniboine River have revealed important information as to the mode of groundwater discharge in these valleys, none of the cross-sections has disclosed the boundaries of the discharge area. Hence, it was felt that in order to determine this boundary, piezometer cross-sections should encompass much larger areas, as is illustrated in the following examples.

Glacial Spillway Near Readlyn, Saskatchewan

The piezometers near Readlyn are installed across a prominent valley in the east half of section 30, township 7, range 27, west of the 2nd meridian (Fig. 15). The flat valley floor is about three quarters of a mile wide, and lies approximately 150 feet below the surrounding hummocky moraine. The valley may have originated as a spillway along the margin of a glacier, although the geology of the area suggests

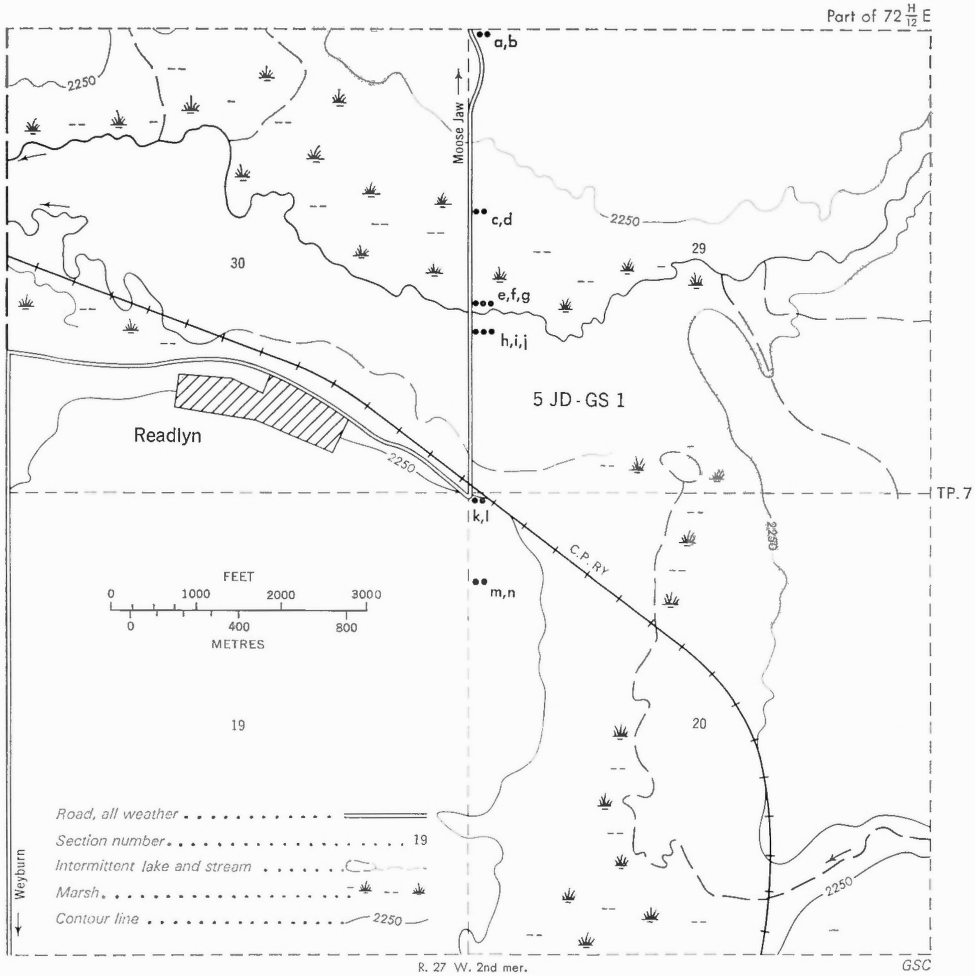

FIGURE 15. Location and arrangement of piezometers in glacial spillway near Readlyn, Saskatchewan

that it already existed before the ice advanced. Its present sinuous course leads from Old Wives Lake across the United States border into the Missouri River drainage system.

At present the valley is occupied at irregular intervals by saline lakes, fed by small intermittent creeks, which flow from either side along the valley. The piezometer cross-section is located close to the 'divide' between two such lakes. The valley bottom is swampy in the spring; it dries out through the summer, leaving a heavy salt encrustation.

The piezometers were installed according to the Freeze method, during the 1962 field season in order to test the hypothesis of upward-leaking groundwater as a cause of the saline environment in the valley. Measurements of total head were taken once every month and selected readings are presented in Table XII.

Flow Pattern

Figure 16 indicates the presence of three vertical flow zones. Groundwater flow is downward south and north of the channel and upward underneath it. Measured from the bottom of the valley, the boundary between the successive zones lies approximately one fifth up the valley wall. The flanks of the valley slope at 0.05 ft. /ft. as compared to a regional topographic slope of 0.014 ft. /ft.

The upward gradient underneath the Readlyn spillway is of the order of 0.07 ft. /ft., with slight differences between summer and winter values. South of the valley the downward gradient is of the order of 0.40 ft. /ft., and the gradient north of the valley is estimated at 0.50 ft. /ft.

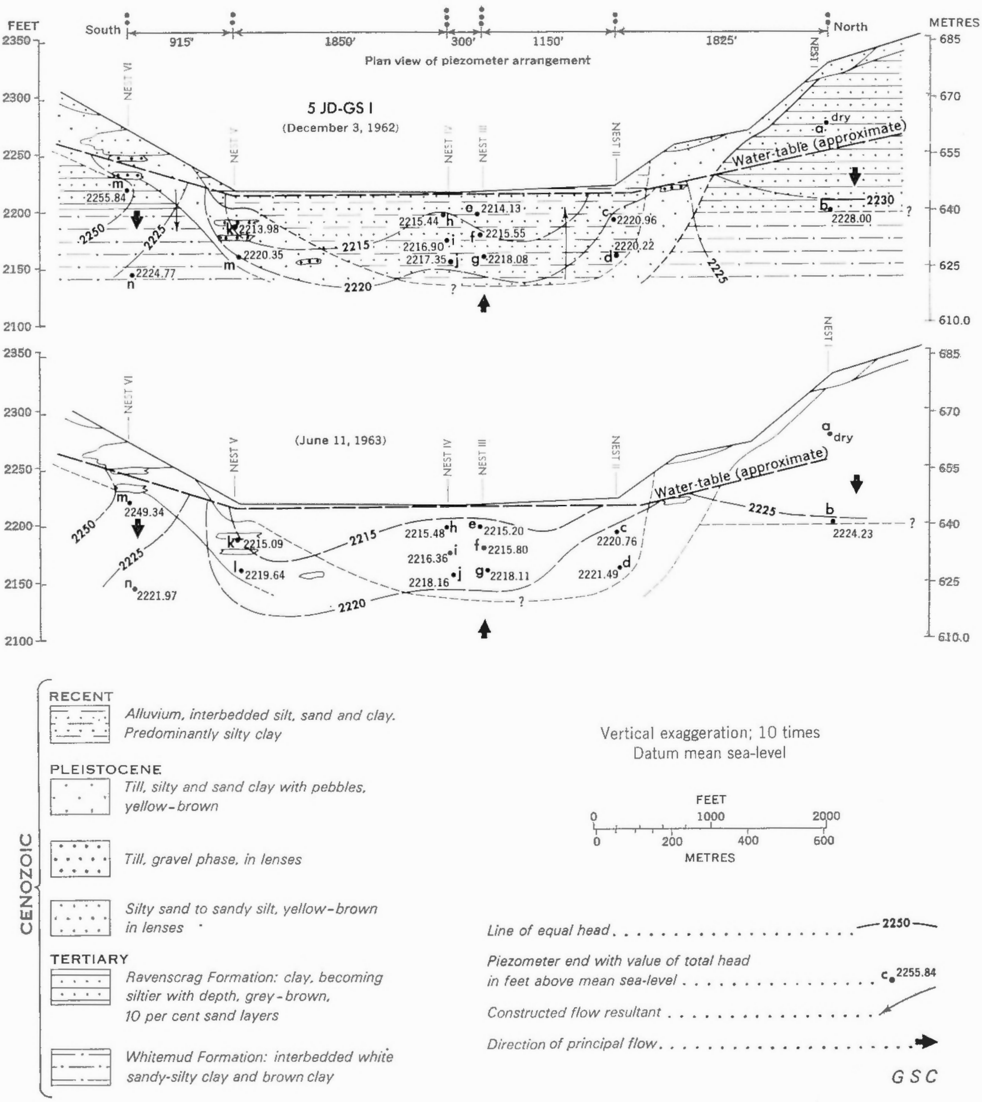

FIGURE 16. Patterns of groundwater flow near Readlyn, Saskatchewan

The amount of groundwater that is being discharged in the valley is governed by the permeability of the valley fill, by the cross-sectional area of flow, and by the gradient. Similarly, the amount of downward flow in the adjacent moraines is related to the permeability, area of flow and gradient. Depending on three different premises, the following inferences may be drawn from the fact that the upward and downward gradients are in the proportion of 1:6.

(a) Assuming that the groundwater discharge in the valley is replenished by nearby recharge and assuming also that the hydraulic conductivity of the combined till-bedrock section does not differ significantly from the permeability of the argillaceous valley sediments, it can be concluded that the cross-sectional area through which recharge flow occurs must be approximately one sixth of the surface of the valley. In other words, recharge is obtained from a 270-foot-wide zone at either side of the spillway, if the permeability is uniform throughout the recharge and discharge zones.

(b) If recharge is derived from two zones along the valley, each one having a width equal to one half the width of the valley, the conclusion must be drawn that the permeability of the valley sediments is six times that of the till-bedrock sequence.

(c) Assuming that the cross-sectional area as well as the permeability are the same throughout the flow pattern, it follows that the amount of groundwater that is being discharged in the plane of cross-section is only one sixth of the amount of groundwater that enters the flow system in that plane. The remainder is being discharged according to a longitudinal component of flow.

Despite the fact that the drainage influence of the spillway may vary from 270 to about 1,600 feet at either side of the channel, the phenomenon is local. The cut-off line between the local flow system underneath the spillway and continuing downward flow may be less than 200 feet below the bottom of the channel. Because of the decreased density of downward flow lines below the alleged cut-off line, groundwater will be virtually stagnant there.

As the rate of groundwater movement diminishes towards the centre of the valley, the degree of mineralization will increase. The most saline water will be discharged near the centre line of the channel, and evaporation of such water, once it reaches the surface, will certainly give rise to the observed salt crusts.

Arm River, Saskatchewan

North of Bethune, Arm River occupies a wide and deep valley that penetrates below the drift-bedrock contact. The valley soil is extremely saline, as can be seen from the numerous large sulphate encrustations and the salt-loving vegetation.

The purpose of the piezometer cross-section at this location was twofold: first, to investigate the presumed existence of a regional northeastward flow in the middle Beechy aquifer (Meyboom, 1963) and the effect of the Arm River on this regional flow; and second, to determine the direction of groundwater movement in another saline valley.

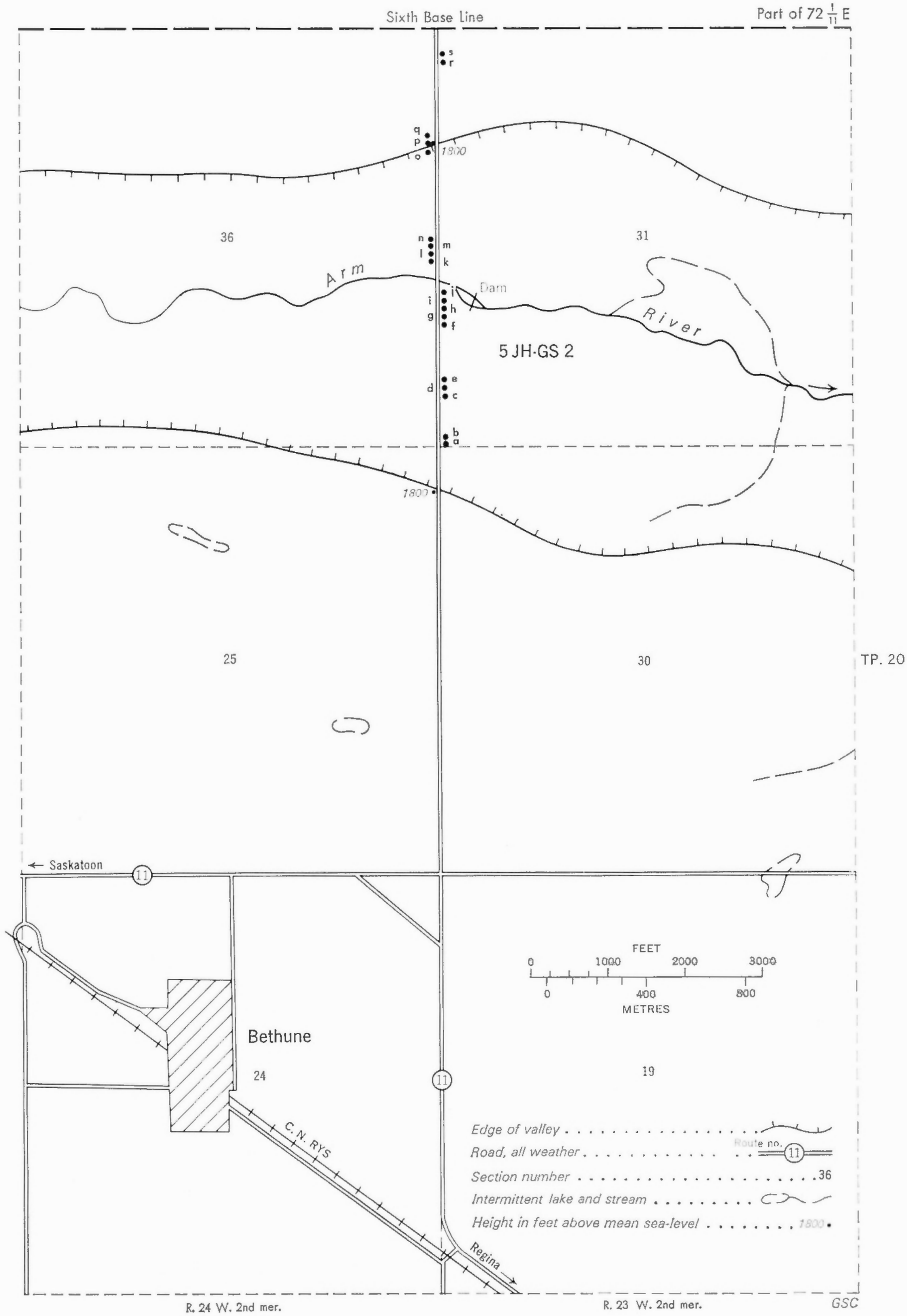

FIGURE 17. Location and arrangement of piezometers in Arm River valley near Bethune, Saskatchewan

An initial series of seventeen piezometers was installed at the Bethune site (Fig. 17) in June 1963, using the Olson method. In May 1964 the third nest was augmented with two deep piezometers fitted with a well-point and a metal petal basket. Selected measurements of total head during the summers of 1963 and 1964 are given in Table XIII.

All that is left of the glacial drift at many places along Arm River is a thin lag deposit of eroded till, consisting of sand and gravel (Christiansen, 1961). Fifteen to twenty feet of these deposits covers the south bank of Arm River (Pl. V), where the till overlies 10 feet of fairly well sorted sand (Fig. 18). Sand and gravel deposits are also present in the river channel itself. Most of the remainder of the section consists of poorly permeable till and Bearpaw shale. It was extremely difficult to determine

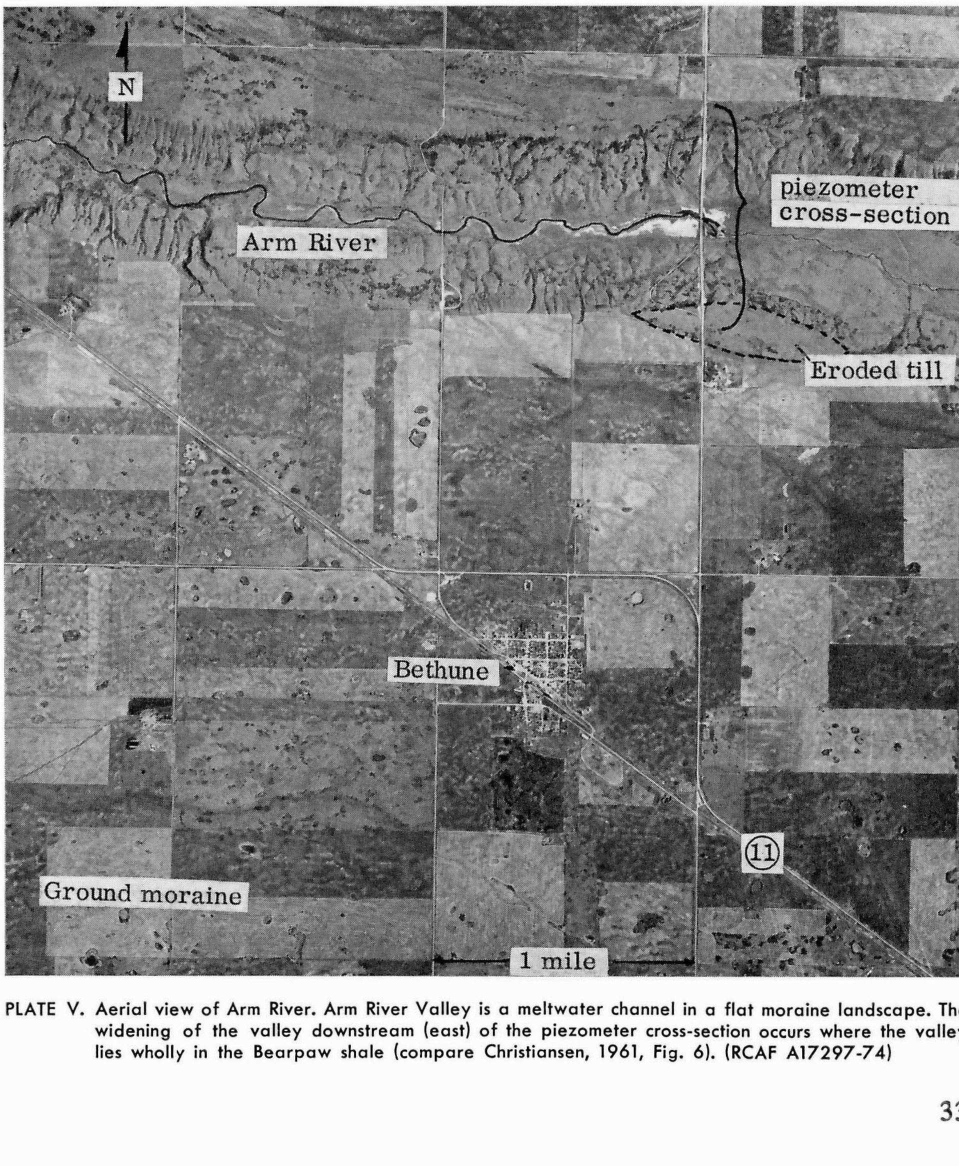

PLATE V. Aerial view of Arm River. Arm River Valley is a meltwater channel in a flat moraine landscape. The widening of the valley downstream (east) of the piezometer cross-section occurs where the valley lies wholly in the Bearpaw shale (compare Christiansen, 1961, Fig. 6). (RCAF A17297-74) from drilling samples the exact boundary between the unoxidized ("blue") till and the Bearpaw shale in piezometers a, c, r, and s. For the purpose of the piezometer cross-section, "Blue clay" as mentioned in the drillers' logs has been classed as part of the shale in all locations where the stratigraphic boundary was uncertain.

The stratigraphic equivalent of the middle Beechy sandstone (*see* Riverhurst section) was penetrated while drilling for piezometers f and g. At Bethune the middle unit of the Beechy Member ranges from a very silty shale to fine sand, with a total thickness of 50 feet. Piezometer 'h' was set 20 feet below the top of the middle unit of the Beechy Member. It flowed 2 gpm salty[1] water and a pressure recovery test indicated a hydraulic conductivity of about 2 inches per hour. Above the "middle Beechy sandstone" is hard grey shale, whereas below the sandy part of the Beechy Member the shale is somewhat silty. The deep piezometers f and g were both set in the grey silty shale of the lower unit of the Beechy Member.

Flow Pattern

The flow pattern illustrated in Figure 18 shows downward flow at either side of the river, lateral flow in the Beechy sandstone towards the main discharge zone, and upward movement underneath Arm River from a depth of 235 feet. The boundary between the zone of downward flow adjacent to the river and the zone of upward movement (measured from the valley bottom) lies about one fifth of the way up the flanks of the valley. The slope of the valley walls is 0.067 as compared to the regional topographic slope of 0.0049 ft./ft. between the watershed and Arm River.

The boundary between two flow systems lies at a depth of 235 feet below Arm River, as is indicated by the lower potentials below the cut-off line. It cannot be determined from the available information whether the flow beneath the cut-off line corresponds with a regional northeastern flow from the Missouri Coteau to Last Mountain Lake as was postulated by Meyboom (1963), or whether the flow is perpendicular to the plane of the cross-section. Chemically, the water in the deeper flow system differs distinctly from that in the superficial one in that it has a conductance of more than 10,000 micromhos per cm.

The Arm River flow pattern differs from that of Readlyn spillway in that the permeable part of the Beechy Member widens the drainage influence of the stream, although leakage from the Beechy sandstone into the deeper flow system prevents the sandstone from becoming a perfect drain. Between June 21, 1963 and June 12 1964 the average downward gradient was more than twice the average upward gradient underneath the river, suggesting either a large longitudinal flow component perpendicular to the cross-section or a difference in hydraulic conductivity between the shales in the river valley and those underneath the adjacent highlands.

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[1]Analysis: 3,297 ppm total dissolved solids, 1,240 ppm sodium, 1,757 ppm chloride, 25 ppm sulphate, 440 ppm bicarbonate.

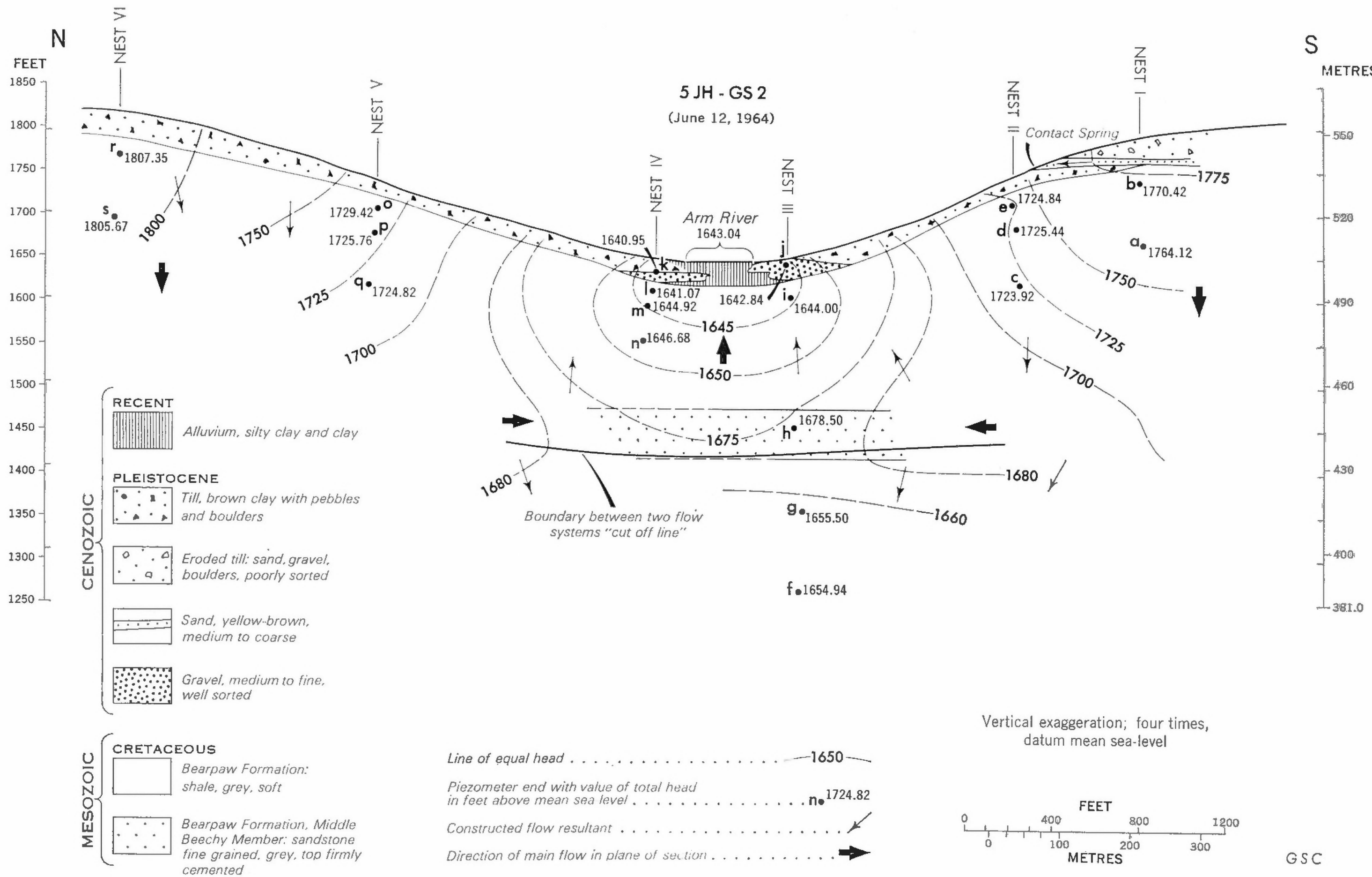

FIGURE 18. Pattern of groundwater flow in Arm River valley, Saskatchewan

South Saskatchewan River, Saskatchewan

Location and Geology

The piezometer cross-section on South Saskatchewan River is located west of Riverhurst along highway No. 42 (Fig. 19). The cross-section is nearly 3 miles long and contains much of the Upper Cretaceous strata in the area. The purpose of this installation is to study the influence of the future South Saskatchewan reservoir on the adjacent Cretaceous aquifers.

In the Riverhurst area flat-lying Upper Cretaceous strata are overlain by unoxidized ("blue") till (Fig. 20), the upper part of which is commonly oxidized to a brown colour. On the east side of the valley some extensive beds or lenses of coarse sand and gravel were encountered in the till. The thickest gravel bed is just over 70 feet (nest IV, Fig. 20). On the west side only a few feet of surface sand and fine gravel is present.

The central part of the valley is largely filled with till, containing some gravel lenses; in the upper part the fill consists of recent alluvial sand and some gravel. Depth to the bedrock surface is up to 150 feet. A low in the bedrock surface under the eastern slope of the present valley may be interpreted as an older drainage channel.

The Upper Cretaceous strata in the Riverhurst area consists of alternating beds of blue-grey shale, sandy shale, and fine-grained, greenish sandstone (cf. Evans, 1961). In descending order the following Upper Cretaceous beds were encountered in the drill holes:

1. *Bearpaw Formation*

   (a) Snakebite Member: grey shale, soft, and bentonitic. Maximum thickness encountered, nearly 190 feet.

   (b) Ardkenneth Member: greenish sandstone, fine-grained, only partly indurated. Member contains two distinct more shaly zones. Downward it grades into sandy shale. Thickness in the section ranges from 99 to 109 feet.

   (c) Beechy Member (consisting of three units):

      1. Upper shale unit: dark grey shale, partly silty, thickness between 62 and 67 feet;
      2. Middle sandstone unit: greenish, fine-grained, well-indurated sandstone. Unit contains two silty or shaly zones, and ranges in thickness from 26 to 35 feet;
      3. Lower shale unit: dark grey, very dense shale. A bed of shaly sandstone, 15 to 18 feet thick, occurs about 80 feet below the top of the unit. Thickness of the unit as a whole ranges from 200 to 220 feet.

2. *Belly River Formation*

   Sandstone, dark, non-marine, well-indurated, containing some silty or shaly zones. The formation was penetrated to a depth of 77 feet in nest V.

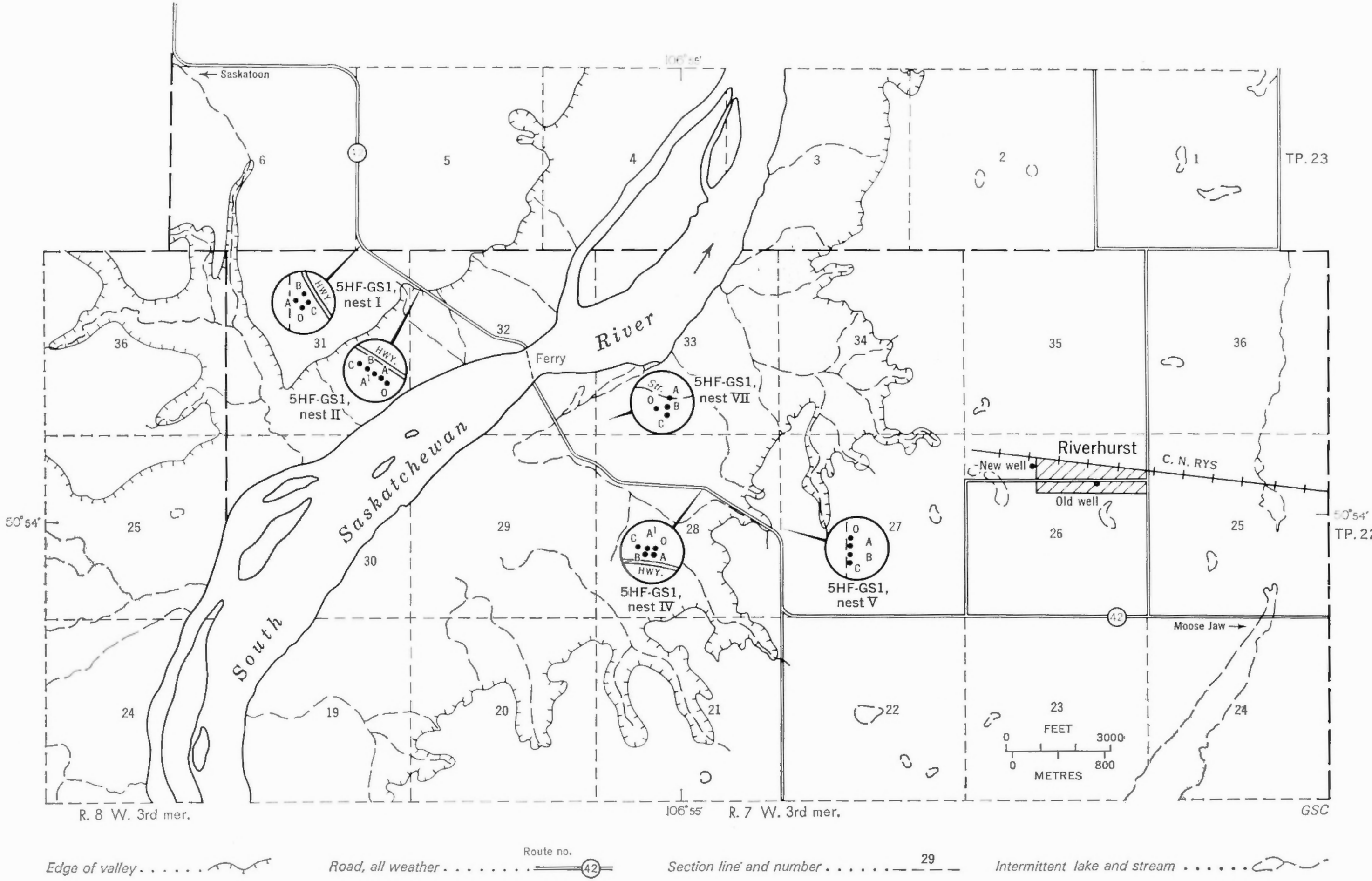

FIGURE 19. Location and arrangement of piezometers along South Saskatchewan River near Riverhurst, Saskatchewan

Piezometers

In the section described here *two* nests (I and II), of four and five piezometers respectively, lie on the west side of the valley. *One* nest of four piezometers (VII) lies in the valley bottom; and *two* nests (IV and V) of five and four piezometers, respectively, are located on the east side of the river (Figs. 19 and 20). In all nests piezometers were placed in the drift, in the Ardkenneth Member, in the middle sandstone unit of the Beechy Member, and in the Belly River sandstone. Nest III has piezometers in the Ardkenneth Member and Belly River Formation only. In nests I, II, and VII the drift piezometers are installed in till, in nests IV and V in gravel. Both nests II and IV have two piezometers in the Ardkenneth Member in order to measure vertical gradients in this member.

Nests I and II were established in November 1962, nests IV and V in June–July of 1963, nest VII as well as additional piezometers in nests I, II and IV in June–July 1964.

The piezometers were constructed according to the Hall method as illustrated in Figure 3, except that those installed in 1964 were not swabbed and filled with water, but rather developed with compressed air and then left to recover.

Distances between adjacent piezometers in one nest are between 15 and 25 feet, sufficient to avoid interference during drilling. Details regarding elevations and measurements of total head are given in Table XIV. Weekly readings with an electric tape (or pressure gauge in case of flowing wells) have been taken on all piezometers since their completion.

Flow Pattern

The lines of equal head shown in Figure 20 are based on readings taken during August and September 1964. At present no appreciable seasonal changes in head have been recorded in any of the piezometers in this section. Apparently the groundwater regime in the Upper Cretaceous aquifers and in the lower parts of the drift is not affected to any significant extent by seasonal changes in precipitation and evapotranspiration.

The head distribution in Figure 20 indicates that water is moving from both sides along appreciable lateral flow components into the immediate vicinity of South Saskatchewan River. Most of the groundwater movement in the three sandstone members and in the gravel lenses is horizontal, whereas movement through the till[1] and the shales is predominantly vertical. In Figure 20 the flow resultant in the till and in the Bearpaw shales is indicated at a few places, after correction for the exaggeration of the vertical scale (van Everdingen, 1963).

Downward movement in the till prevails all the way down the flanks of the valley. Thus the actual discharge area is restricted to the valley bottom between the elevations 1,710 on the west side and 1,775 on the east side.

[1]The fact that movement of water through glacial till is possible was demonstrated during drilling in locations IV and V. In location IV circulation was lost at 55 feet depth, just above the gravel; in location V at a depth of 44 feet. In both locations circulation fluid (a mixture of water, aquagel, and wheatbran) started issuing from parallel "cracks" in the ground, up to 20 feet away from the drill-holes shortly after the beginning of the losses.

On the west side of the valley the Ardkenneth Member derives water from both the Belly River and Beechy sandstones, by upward movement, and from the glacial till by downward movement. On the east side of the valley the Beechy sandstone derives water from the underlying Belly River sandstone and the overlying Ardkenneth sandstone; the large gravel bed receives water from overlying till and the underlying Ardkenneth sandstone. Under the central part of the valley upward movement of water persists from the Belly River Formation into the till and gravel fill. An appreciable longitudinal component of flow has been determined for the Beechy and Belly River sandstones in the central part of the valley.

The groundwater divide to the east of South Saskatchewan River lies about 12 miles from the river and coincides closely with the surface divide (Meyboom, 1963). If the gravel bed that catches most of the water infiltrating through the till extends too far east, the recharge to the underlying Cretaceous beds is severely restricted.

The average topographic gradient between the surface divide and the edge of South Saskatchewan valley is 0.0053 ft./ft., which is low, compared to the slope of the valley flanks of 0.05 ft./ft.

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CONCLUSIONS

It is apparent that groundwater discharge is a striking phenomenon in the seven sections that have been described. The following conclusions may be drawn from a comparison of the flow patterns:

1. Groundwater discharge is limited to the valley bottoms in areas of poorly permeable materials that are drained by deeply incised rivers or valleys, the flanks of which are five to fifteen times steeper than the regional slope between the water divide and the edge of the valley. The boundary between downward flow and lateral or upward flow may lie anywhere between the toe of the valley wall and one third of the way up the valley flank.

2. Steep downward gradients in extensive groundwater recharge areas and gentle upward gradients in the limited discharge areas indicate:

   (a) much higher permeability in the discharge area than in the area of downward flow (recharge area) or:

   (b) the movement of water along a longitudinal flow component, which is normal to the piezometer cross-section.

3. It is impossible to describe all discharge phenomena in one vertical cross-section; for, although the flow resultant in a vertical cross-section through an area of predominantly downward flow may be a good approximation of the total flow vector, it follows from conclusion 2(b) above that the discrepancy between flow resultant and total-flow vector increases towards the centre of the discharge area, owing to the increasing magnitude of the longitudinal component of flow.

Therefore, piezometer nests should be arranged in a triangular pattern in order to measure all components of flow in a discharge area.

4. Groundwater discharge in a river valley with homogeneous and uniform geology is the sum of evapotranspiration, base-flow in the river, and underflow. In a stratified flow medium with a permeable layer at some depth below the river, an important longitudinal component of flow may exist in the permeable layer. Groundwater will then leave the basin through a narrow strip in the aquifer underneath the surface stream and in the same direction as the surface run-off. Under certain conditions this type of discharge may act as a subdrain in a river valley, thus preventing salinization of the valley soils.

5. The depth of the cut-off line in Bethune suggests that the drainage influence of a valley such as the Arm River is not extremely deep.

With regard to the lateral extent of the flow systems, it can be said that the drainage influence of a valley in uniform poorly permeable material is of the same magnitude as the width of the valley. The presence of a permeable layer in the geological section below the river increases the drainage influence of the stream. However, the extent of this increase depends on the amount of leakage from that layer into a deeper flow system.

6. Movement of groundwater in sandstones and gravel beds away from the discharge area is mainly horizontal; in till and shale it is mainly vertical. Groundwater movement at shallow depths in till may be essentially restricted to cracks and fractures.

7. The most striking difference between patterns of groundwater flow in small discharge areas as compared to those in large discharge areas is the instability of the flow patterns in the small ones. Thus, the regimen of the Upper Cretaceous aquifers is not affected to any appreciable extent by seasonal changes in precipitation or evapotranspiration, whereas groundwater flow in the shallow Pleistocene deposits near a small river may virtually come to a standstill in early spring, or may be subjected to a reversal in flow during spring break-up.

Upward flow from the Cretaceous aquifers follows well-established and stable patterns, whereas areas of concentrated upward movement through the valley fill may shift according to changes in the river regimen.

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APPENDIX

Table I

Piezometers in Willow Ring, 5 JH-GS 1

Selected readings between July 1962 and September 1963

Piezometer No.	Depth (feet)	Elevation of top, in feet above datum level	Value of total head, in feet above arbitrary datum level						
			July 7, 1962[2]	July 15, 1962	May 25, 1963	June 9, 1963	June 28, 1963[3]	July 11, 1963	Sept. 2, 1963[4]
a	10	121.45	dry	dry	dry	dry	dry	dry	dry
b	30	121.84	98.04	97.96	dry	dry	dry	dry	dry
c	50	121.90	100.52	87.96	85.08	85.22	85.00	85.09	84.95
d	10	109.05	99.79	dry	dry	dry	dry	dry	dry
e	20	108.89	92.50	92.45	91.90	90.99	90.82	90.93	91.08
f	30	109.90	92.49	92.98	91.17	90.81	90.77	91.01	91.37
g[1]	50	109.16					99.51	98.10	96.87
h[1]	30	108.55					104.25	103.55	101.72
i[1]	15	107.89					100.95	99.36	96.25
j[1]	25	103.18					98.62	98.21	95.65
k[1]	50	102.77					101.15	99.99	97.87
l	5	100.43	96.24	97.05	97.44	98.75	97.08	98.38	dry
m	10	100.39	96.27	96.91	98.48	98.79	97.00	98.39	95.17
n	15	101.30	95.57	97.42	97.39	98.54	97.09	98.36	94.40

[1]1963 installation
[2]24 hours after completion
[3]3 days after completion of 1963 piezometers
[4]Complete flow pattern shown in Figure 5B

Table II

Piezometer Cross-section 5 MH-GS 2, Cypress River

Selected readings between April 1962 and October 1963

Piezometer No.	Nest I	Nest II			
	a	b	c	d	gradient b-d ft./ft.
Depth (feet)	37	22	16	11	
Elevation of top, in feet above datum level	97.72	83.44	82.77	82.75	
Date	Value of total head, in feet above arbitrary datum level				
1962:					
April 26[1]	94.00	75.08	75.60	75.61	+0.03
May 19	93.31	76.90	76.01	76.09	+0.06
June 17[1]	93.16	76.89	76.02	76.06	+0.075
July 15	93.07	76.89	74.35	74.39	+0.23
Aug. 11	92.96	76.85	73.85	73.87	+0.26
Sept. 16[1]	92.87	76.84	73.90	74.28	+0.22
Oct. 13	92.72	76.84	73.77	73.85	+0.26
Nov. 11	92.72	76.87	73.77	73.83	+0.28
Dec. 3[1]	92.65	76.87	73.95	73.93	+0.27
1963:					
Jan. 13	92.47	77.02	72.97	73.00	+0.37
Feb. 10	frozen	77.11	72.60	72.58	+0.40
March 11	frozen	72.99	72.52	72.56	+0.04
March 25[1]	frozen	72.99	74.30	74.23	−0.10
April 8	frozen	72.99	75.62	75.70	−0.25
April 28	92.24	73.12	74.95	75.03	−0.16
May 26	92.24	73.08	74.76	74.83	−0.16
June 23	92.15	73.99	74.35	74.47	−0.03
July 21[1]	92.14	73.33	73.72	73.77	−0.04
Aug. 8	92.68	73.99	73.66	73.99	0
Sept. 21	91.83	74.62	75.01	75.03	−0.04
Oct. 19	91.81	72.89	73.33	73.39	−0.04

[1]Complete flow pattern shown in Figure 7

Table III

Piezometer Cross-section 5 MH-GS 2, Cypress River

Selected readings between April 1962 and October 1963

Piezometer No.	Nest III			
	e	f	g	gradient e-g ft/ft
Depth (feet)	22	16	11	
Elevation of top, in feet above datum level	82.28	81.58	81.44	
Date	Value of total head, feet above arbitrary datum level			
1962:				
April 26[1]	78.96	77.26	77.32	+0.25
May 19	78.17	74.86	74.84	+0.29
June 17[1]	77.37	75.29	74.23	+0.28
July 15	76.76	73.78	73.76	+0.28
Aug. 11	76.05	73.40	73.56	+0.23
Sept. 16[1]	75.49	73.16	73.32	+0.20
Oct. 13	74.60	73.11	73.06	+0.14
Nov. 11	74.03	73.08	73.12	+0.07
Dec. 3[1]	73.69	73.16	73.12	+0.04
1963:				
Jan. 13	73.03	72.33	72.44	+0.04
Feb. 10	72.71	72.58	72.62	+0.01
March 11	72.36	72.57	72.57	−0.02
March 25[1]	72.33	74.63	74.84	−0.23
April 8	73.38	75.12	75.14	−0.16
April 28	73.40	74.17	74.15	−0.07
May 26	73.03	73.62	73.69	−0.06
June 23	73.24	73.51	72.48	+0.07
July 21[1]	73.06	73.00	72.97	+0.01
Aug. 8	72.85	73.06	73.04	−0.02
Sept. 21	72.44	72.91	72.87	−0.04
Oct. 19	72.34	72.90	72.90	−0.05

[1]Complete flow pattern shown in Figure 7

Table IV

Piezometer Cross-section 5 OB-GS 2, Pembina River

Selected readings between April 1962 and October 1963

Piezometer No.	Nest I			
	a	b	c	d
Depth (feet)	66	54	42	30
Elevation of top, in feet above datum level	103.73	103.61	103.56	103.40
Date	Value of total head, in feet above arbitrary datum level			
1962:				
April 26	90.31	90.15	90.15	90.04
May 19	90.70	90.86	90.85	90.70
June 17	91.24	91.37	91.40	91.20
July 15	91.28	91.49	91.42	91.23
Aug. 11[1]	91.68	91.67	91.70	91.71
Sept. 16	91.38	91.51	91.52	91.33
Oct. 13	90.69	90.86	90.89	90.60
Nov. 11	90.48	90.61	90.64	90.40
Dec. 3	13.17	90.69	90.74	90.40
1963:				
Jan. 13	90.48	90.54	90.64	90.48
Feb. 10	89.91	90.04	89.81	89.73
Mar. 11	89.47	89.61	89.62	89.50
Mar. 18[1]	89.43	89.56	89.58	89.40
April 28	90.71	90.80	90.91	96.38
May 18	91.18	91.32	91.24	91.12
June 23	92.01	92.14	92.16	91.96
July 21	92.23	92.36	92.38	92.25
Aug. 8[1]	92.37	92.50	92.52	92.40
Sept. 21	90.79	90.92	90.91	90.70
Oct. 19	90.25	90.30	90.32	90.11

[1]Complete flow pattern shown in Figure 10

Table V

Piezometer Cross-section 5 OB-GS 2, Pembina River

Selected readings between April 1962 and October 1963

Piezometer No.	Nest II			
	e	f	g	h
Depth (feet)	15	22	33	44
Elevation of top, in feet above datum level	96.86	96.90	97.36	96.83
Date	Value of total head, feet above arbitrary datum level			
1962:				
April 26	90.09	90.12	90.24	90.26
May 19	90.06	90.32	90.50	90.96
June 17	89.96	90.52	90.89	91.49
July 15	90.05	90.57	91.03	91.52
Aug. 11[1]	91.37	91.58	91.56	91.82
Sept. 16	90.11	90.63	91.14	91.63
Oct. 13	88.70	89.50	90.31	90.98
Nov. 11	88.34	89.23	90.04	90.76
Dec. 3	89.04	89.58	90.19	90.76
1963:				
Jan. 13	89.29	89.83	90.29	90.76
Feb. 10	88.29	88.83	89.44	90.08
March 11	88.14	88.66	89.21	89.76
March 18[1]	88.14	88.65	89.14	89.72
April 28	90.20	90.42	90.54	91.04
May 18	90.11	90.60	91.04	91.56
June 23	90.50	89.13	91.74	92.32
July 21	91.82	91.80	92.17	92.54
Aug. 8[1]	91.44	91.83	92.18	92.67
Sept. 21	88.92	89.74	90.48	91.09
Oct. 19	88.20	89.15	89.94	90.47

[1]Complete flow pattern shown in Figure 10

Table VI

Piezometer Cross-section 5 OB-GS 2, Pembina River

Selected readings between April 1962 and October 1963

Piezometer No.	Nest III			
	i	j	k	l
Depth (feet)	18	24	33	44
Elevation of top, in feet above datum level	95.33	95.87	96.22	96.57
Date	Value of total head, in feet above arbitrary datum level			
1962:				
April 26	90.89	94.39	90.15	90.25
May 19	90.19	93.88	90.72	90.97
June 17	90.58	93.41	91.15	91.47
July 15	90.60	93.10	91.18	91.50
Aug. 11[1]	91.35	92.82	91.76	91.84
Sept. 16	90.77	92.54	91.27	91.62
Oct. 13	89.73	92.32	90.42	90.91
Nov. 11	89.51	91.87	90.30	90.75
Dec. 3	89.41	91.62	90.30	90.75
1963:				
Jan. 13	89.83	91.45	90.47	90.75
Feb. 10	89.33	90.70	89.53	90.00
March 11	88.93	89.94	89.35	89.70
March 18	88.88	89.87	89.32	89.70
April 28	90.03	90.23	90.66	91.00
May 18	90.51	90.82	91.15	91.52
June 23	90.82	91.47	91.84	92.38
July 21	91.39	92.04	92.22	92.48
Aug. 8[1]	91.76	92.28	92.32	92.59
Sept. 21	90.53	90.69	90.59	91.05
Oct. 19	89.61	89.94	89.93	90.38

[1]Complete flow pattern shown in Figure 10

Table VII

Piezometer Cross-section 5 MH-GS 3, Assiniboine River

Selected readings between April 1962 and October 1963

Piezometer No.	Nest I			
	a	b	c	d
Depth (feet)	44	33	22	15
Elevation of top, in feet above datum level	100.00	100.49	100.61	100.63
Date	Value of total head, in feet above arbitrary datum level			
1962:				
April 26[1]	93.88	97.55	92.23	92.22
May 26	93.84	96.95	90.45	90.43
June 17[1]	93.72	96.47	90.36	90.35
July 21	93.72	95.71	89.10	88.98
Aug. 18	93.66	95.15	89.23	89.25
Sept. 16	93.64	94.59	88.80	88.75
Oct. 13	93.62	94.09	88.73	88.68
Nov. 11	93.50	93.67	88.94	88.88
Dec. 3[1]	94.93	93.42	89.36	89.38
1963:				
Jan. 13	93.43	92.92	89.79	89.71
Feb. 17	frozen	92.67	90.36	90.56
March 11	frozen	92.48	91.11	90.87
April 28[1]	93.32	92.53	91.62	91.49
May 18	93.40	92.38	90.63	90.63
June 23[1]	93.25	92.23	90.36	91.39
July 21	93.90	92.18	90.33	90.58
Aug. 25	93.15	91.83	89.19	90.23
Sept. 21	94.24	90.01[2]	91.16	91.25
Oct. 27[1]	93.04	91.48	88.90	88.86

[1]Complete flow patterns shown in Figures 13 and 14

[2]May be erroneous measurement, 91.61′ in the previous week and 91.62′ in the week afterwards

Table VIII

Piezometer Cross-section 5 MH-GS 3, Assiniboine River

Selected readings between April 1962 and October 1963

Piezometer No.	Nest II			
	e	f	g	h
Depth (feet)	44	33	22	17
Elevation of top, in feet above datum level	103.50	103.17	103.55	103.06
Date	Value of total head, in feet above arbitrary datum level			
1962:				
April 26[1]	97.10	91.03	91.79	91.70
May 26	96.54	91.06	91.20	90.60
June 17[1]	95.77	91.03	90.58	90.26
July 21	94.82	90.99	90.01	89.26
Aug. 18	94.08	91.00	89.53	89.11
Sept. 16	93.45	89.91	89.34	88.87
Oct. 13	92.92	90.92	89.06	88.70
Nov. 11	92.58	90.85	88.98	88.81
Dec. 3[1]	92.18	90.85	89.05	89.14
1963:				
Jan. 13	91.83	90.75	89.30	89.49
Feb. 17	91.43	90.75	90.05	90.24
Mar. 11	91.31	90.77	90.39	90.55
April 28[1]	91.50	90.93	92.21	91.38
May 18	91.32	90.92	91.45	90.68
June 23[1]	91.05	90.93	91.40	91.11
July 21	90.94	91.12	91.18	90.18
Aug. 25	90.65	90.89	90.20	89.66
Sept. 21	89.99	90.21	89.72	89.06
Oct. 27[1]	89.55	90.77	89.28	88.89

[1]Complete flow patterns shown in Figures 13 and 14

Table IX

Piezometer Cross-section 5 MH-GS 3, Assiniboine River

Selected readings between April 1962 and October 1963

Piezometer No.	Nest III			
	i	j	k	l
Depth (feet)	55	40	27	22
Elevation of top, in feet above datum level	110.18	110.42	110.41	110.06
Date	Value of total head, in feet above arbitrary datum level			
1962:				
April 26[1]	108.49	91.24	91.23	91.24
May 26	107.30	90.67	90.66	90.68
June 17[1]	106.51	90.16	90.19	90.18
July 21	105.42	89.56	89.57	89.46
Aug. 18	104.59	89.06	89.04	88.90
Sept. 16	103.67	88.94	88.97	88.90
Oct. 13	102.91	88.66	88.64	88.70
Nov. 11	102.26	88.67	88.66	88.74
Dec. 3[1]	101.61	88.92	88.99	88.89
1963:				
Jan. 13	100.68	89.25	89.24	89.31
Feb. 17	100.01	89.85	89.91	89.89
Mar. 11	99.67	90.22	90.20	90.12
April 28[1]	99.09	91.32	91.36	91.18
May 18	98.96	90.67	90.67	90.66
June 23[1]	98.40	91.09	91.03	91.06
July 21	98.24	90.63	90.74	90.91
Aug. 25	97.66	89.52	89.46	89.51
Sept. 21	97.35	89.10	89.10	89.91
Oct. 27[1]	97.10	88.83	88.83	88.68

[1]Complete flow pattern shown in Figures 13 and 14

Table X

Piezometer Cross-section 5 MH-GS 3, Assiniboine River

Selected readings between April 1962 and October 1963

Piezometer No.	Nest IV			
	m	n	o	p
Depth (feet)	22	33	44	55
Elevation of top, in feet above datum level	101.58	101.11	99.72	101.49
Date	Value of total head, in feet above arbitrary datum level			
1962:				
April 26[1]	90.30	93.49	97.20	90.53
May 26	88.46	92.95	94.86	88.99
June 17[1]	88.81	92.69	93.46	88.44
July 21	87.42	92.23	91.74	87.94
Aug. 18	87.42	91.80	90.58	87.32
Sept. 16	86.97	91.55	88.78	87.44
Oct. 13	86.83	91.20	89.18	87.29
Nov. 11	87.08	91.04	88.65	87.32
Dec. 3[1]	87.51	90.86	88.40	87.57
1963:				
Jan. 13	88.01	90.44	88.22	87.82
Feb. 17	89.01	90.29	89.40	88.24
Mar. 11	89.38	90.11	88.72	88.54
April 28[1]	89.23	90.09	88.64	89.70
May 18	88.58	90.16	88.77	93.64
June 23[1]	89.41	90.01	89.07	89.24
July 21	88.08	89.98	88.74	89.09
Aug. 25	87.28	89.69	87.74	88.54
Sept. 21	87.04	89.58	86.33	89.39
Oct. 27[1]	87.03	89.36	87.29	88.89

[1]Complete flow pattern shown in Figures 13 and 14

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Table XI

Piezometer Cross-section 5 MH-GS 3, Assiniboine River

Selected readings between April 1962 and October 1963

Piezometer No.	Nest V			
	q	r	s	t
Depth (feet)	22	33	44	55
Elevation of top, in feet above datum level	100.76	101.19	101.31	99.72
Date	Value of total head, in feet above arbitrary datum level			
1962:				
April 26[1]	90.32	89.82	90.33	91.01
May 26	89.07	89.83	89.15	89.83
June 17[1]	89.90	89.63	90.04	89.48
July 21	88.13	89.49	88.18	89.16
Aug. 18	87.98	89.11	87.98	88.87
Sept. 16	87.65	88.87	87.73	88.65
Oct. 13	87.45	88.64	87.50	88.39
Nov. 11	87.51	88.52	87.56	88.40
Dec. 3[1]	87.84	88.37	87.81	88.40
1963:				
Jan. 13	88.19	88.27	88.24	88.30
Feb. 17	89.01	88.37	88.99	88.40
Mar. 11	89.22	88.42	89.26	88.48
April 28[1]	89.96	89.86	89.90	89.62
May 18	89.14	89.79	89.16	88.87
June 23[1]	90.11	89.70	89.78	90.17
July 21	88.67	89.68	89.20	90.20
Aug. 25	87.96	89.34	87.98	90.41
Sept. 21	87.66	89.17	87.73	89.49
Oct. 27[1]	87.53	88.93	87.56	89.06

[1]Complete flow pattern in Figures 13 and 14

Table XII

Piezometer Cross-section 5 JD-GS 1, Readlyn, Sask.

Selected readings between September 1962 and June 1963

Nest No.	Piezometer No.	Depth (feet)	Total head, in feet above sea level			
			Sept. 1, 1962	Dec. 3, 1962[1]	Feb. 28, 1963	June 11, 1963[1]
I	a	50	Dry	Dry	Dry	Dry
	b	125	2220.53	2228.23	2224.02	2224.23
II	c	30	2220.07	2220.26	Frozen	2220.76
	d	60	2220.11	2220.22	Frozen	2221.49
III	e	20	2215.09	2214.33	2213.85	2215.20
	f	40	2214.95	2215.55	Frozen	2215.80
	g	60	2217.92	2218.08	Frozen	2218.11
IV	h	20	2214.62	2215.44	Frozen	2215.48
	i	40	2215.71	2216.90	Frozen	2216.36
	j	60	2217.10	2217.35	Frozen	2218.16
V	k	30	2214.30	2213.98	2213.22	2215.09
	l	60	2221.03	2220.35	Frozen	2219.64
VI	m	50	2259.44	2255.84	2251.02	2249.34
	n	125	2222.77	2224.77	2222.14	2221.97
	gradients					
	j-h		0.062	0.048	—	0.067
	g-e		0.071	0.094	—	0.073
	m-n		−0.49	−0.40	−0.38	−0.35

[1]Complete flow pattern shown in Figure 16

Table XIII

Piezometer Cross-section 5 JH-GS 2, Arm River

Selected readings between June 21, 1963 and August 15, 1964

Nest No.	Piezometer No.	Elevation	Total head, in feet above mean sea-level					
			June 21 1963	July 8 1963	August 30 1963	June 12[2] 1964	July 15 1964	August 15 1964
I	a	1789.46	1763.91	1762.72	1762.66	1764.12	—	—
	b	1789.94	1778.87	1776.66	1775.50	1770.42	1770.09	1769.98
II	c	1743.58	1742.10	1725.28	1724.78	1723.92	1722.77	1722.90
	d	1742.09	1725.44	1726.77	1726.46	1725.47	1724.26	1723.51
	e	1742.44	1726.19	1725.54	1723.92	1724.84	1722.09	1722.54
III	f[1]	1655.23	—	—	—	1655.50	1655.23	1655.23
	g[1]	1655.52	—	—	—	1654.94	1655.32	1655.52
	h	1654.50	shut-in	1677.60	1675.51	1678.50	shut-in	shut-in
	i	1651.74	1644.18	1644.28	1643.89	1644.00	1642.94	1642.40
	j	1651.38	1643.88	1643.29	1643.27	1642.84	1641.55	1641.00
IV	k	1647.62	1641.16	1641.20	1641.27	1640.95	1639.32	1640.23
	l	1648.27	1642.62	1641.74	1641.47	1641.07	1640.49	1639.46
	m	1648.73	1644.83	1646.09	1646.48	1644.92	1645.23	1645.43
	n	1650.75	1644.75	1644.70	1645.72	1646.68	1646.57	1646.64
V	o	1743.75	1736.90	1735.58	1733.56	1729.42	1724.50	1726.15
	p	1743.79	1731.52	1729.98	1728.04	1725.76	1723.32	1725.23
	q	1743.93	1733.93	1728.64	1725.13	1724.82	1722.58	1724.66
VI	r	1817.29	1813.19	1812.29	1810.59	1807.35	1801.52	1801.30
	s	1818.38	1810.38	1811.12	1810.86	1805.67	1799.43	1799.80
	river level		—	1643.38	—	1643.04	—	—
	gradients							
	a-b		−0.20	−0.19	−0.18	−0.08	—	—
	k-n		0.043	0.044	0.056	0.07	0.09	0.08
	o-q		−0.033	−0.076	−0.094	−0.05	−0.02	−0.02

[1]Installed May 1964
[2]Complete flow pattern shown in Figure 18

Table XIV

Piezometer Cross-section 5 HF-GS 1

Average readings of total head during summer of 1964

Piezometer No.	Elevation of collar (feet)	Elevation of screen (feet)	Total head, feet a.s.l.[1]
I	1931.6	1860.1	1906.3
IA	1933.4	1585.1	1698.1
IB	1931.9	1403.1	1746.4
IC	1931.0	1150.5	1866.1
II	1869.9	1785.5	1850.9
IIA	1870.4	1571.6	1697.0
IIA′	1870.2	1485.7	1705.6
IIB	1870.3	1407.7	1744.6
IIC	1871.4	1167.9	1841.8
VII	1705.7	1609.3	1689.0
VIIA	1706.0	1529.0	1723.1
VIIB	1706.0	1437.8	1729.6
VIIC	1706.2	1211.0	1779.4
IV	1860.7	1794.4	dry
IVA	1861.0	1577.0	1835.1
IVA′	1860.1	1503.6	1834.0
IVB	1860.4	1425.9	1746.5
IVC	1859.7	1172.7	1823.7
V	1968.8	1751.6	1791.6
VA	1969.0	1577.0	1915.4
VB	1968.7	1414.2	1761.8
VC	1968.5	1177.0	1835.5

[1]Complete flow pattern shown in Figure 20

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