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Geohydrology of the metropolitan Winnipeg area as related to groundwater supply and construction

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An extensive confined aquifer, currently pumped at the rate of 3 billion gallons (13.6 billion l) per year, occurs in the fractured and jointed upper 50 ft (15 m) of the thick Paleozoic carbonate rock sequence underlying metropolitan Winnipeg. The karstic bedrock surface is mantled by 30 (9 m) to 200 ft (60 m) of glacial drift. The drift is composed of 20 ft (6 m) of till overlain by lacustrine sediments, mainly clays, that average 40 ft (12 m) in thickness. Two minor water-bearing zones occur in the drift, one in the silt deposits in the upper 5 to 15 ft (1.5 to 4.5 m) of the lacustrine unit and the other in the top few feet of the till. Moderately permeable sandstones interbedded with shales underlie the carbonate rock at depths between 250 and 800 ft (75 and 240 m). The sandstones are aquifers that contain saline water. A partially confined glaciofluvial aquifer covering 60 square miles (155 square km) occurs to the northeast of the city. The karstic bedrock surface, a controlling parameter of the groundwater flow systems, slopes towards the Red River Valley from recharge areas located in uplands along the borders of the Red River Basin.

Groundwater has been a source of water supply in the Winnipeg area since the early 1800's. The Upper Carbonate aquifer, which during the first two decades of the twentieth century supplied all of the city's water requirements, has a transmissibility ranging between 2000 and 200 000 gallons (24.8 and 2480 m^3/m/day)/ft/day. Total groundwater pumpage was 10^7 gallons (4.5×10^7 l)/day at the time groundwater usage was curtailed in 1919 following the completion of an aqueduct from the Lake of the Woods. The water in the aquifer is generally fresh to brackish; however, south of the Assiniboine River the water is brackish to saline and is not potable. The groundwater which in most places has a temperature of 39° to 43° F (3.9 to 6.1° C) is used mainly for commercial cooling purposes. Pumpage varies from 5×10^6 gallons (22.7×10^6 l)/day in the winter months to 10^7 gallons (4.5×10^7 l)/day during the summer air-conditioning period.

Groundwater withdrawals have created a major drawdown cone in the central industrial area of metropolitan Winnipeg. Elevations of the piezometric surface range between 800 and 1500 ft (240 and 450 m) in the recharge areas and are below 700 ft (210 m) in the drawdown cone. The Winnipeg drawdown cone is at the centre of a lateral radial flow system. The aquifer also loses water by natural discharge into the Assiniboine and Red Rivers and into the Red River Floodway.

Under natural conditions the saline water-bearing Upper Sandstone aquifer is isolated hydraulically from the Lower Carbonate aquifer by the 10 to 20 ft (3 to 6 m) thick upper shale unit of the Winnipeg formation. However where open well bores penetrate the sandstone aquifers, higher hydraulic heads force saline water up into the carbonate aquifers.

Hydrostatic pressure in the Upper Carbonate aquifer affects construction works that intercept the aquifer or initiate hydraulic fracturing by unloading the confining layers. Groundwater discharge from this aquifer has affected a number of excavation projects. The largest construction groundwater difficulties encountered in the metropolitan Winnipeg area occurred during the construction of the Red River Floodway. Groundwater flows from the aquifer interfered with the excavation of the lower sections of the channel and a number of structures. Groundwater seepage was first encountered on this project when artesian water discharged into a test pit that had been excavated to a depth of 20 ft (6 m) below the piezometric surface of the aquifer. Inflows commonly exceeded several hundred gallons/min. Groundwater control during construction of the floodway inlet control structure required a grout curtain 4000 ft (1220 m) long in the Upper Carbonate aquifer and the drift, and an extensive dewatering system. Knowledge of the groundwater regime prior to construction facilitated excavation and construction, and eliminated claims for unforeseen conditions.

Une nappe captive importante, pompée actuellement au rythme de 3 milliards de gallons (13.6 milliards l) par an, est située dans la zone fracturée et jointée constituant les 50 pieds

[1]Presented at the 22nd Canadian Soil Mechanics Conference, Queen's University, Kingston, Ontario, December 8–9, 1969.

(15 m) supérieurs d'une épaisse séquence de roches carbonatées du paléozoique sous la région métropolitaine de Winnipeg. La surface karstique du socle rocheux est recouverte de 30 à 200 pieds (9 à 60 m) de dépôts glaciaires composés de 20 pieds (6 m) de moraine sous jascent à des dépôts lacustres essentiellement argileux de 40 pieds (12 m) d'épaisseur moyenne. Deux zones aquifères mineures sont situées dans ces dépôts, l'une dans les silts constituant les 5 à 15 pieds (1.5 à 4.5 m) supérieurs de la couche lacustre, l'autre dans les premiers pieds de la moraine. Des grés peu perméables interlités de schistes sont situés sous les roches carbonatées à des profondeurs variant entre 250 et 800 pieds (7.5 et 240 m). Les grés sont aquifères et renferment des eaux salines. Au nord est de la ville on rencontre une couche aquifère partiellement confinée, d'origine fluvio glaciaire, d'une surface de 60 milles (96 km) carrés. La surface du soche rocheux karstique, un paramètre déterminant du réseau d'écoulement de la nappe, présente une pente des zones de recharge situées aux limites du bassin de la Rivière Rouge vers la vallée de cette rivière.

La nappe phréatique a constitué la source d'approvisionnement en eau de la région de Winnipeg depuis le début des années 1800. La nappe située dans la partie supérieure des carbonates, qui a fourni toute la demande en eau de la ville entre 1900 et 1920, a une transmissibilité comprise entre 2000 et 200 000 gallons (9000 et 900 000 l) par pied et par jour. Le débit pompé était de 10 millions de gallons (4.5×10^7 l) par jour lorsque l'usage de la nappe a été réduit en 1919 après la mise en service d'un aqueduc venant du Lac des Bois. L'eau de la nappe est généralement douce à saumâtre, bien qu'elle soit saumâtre à saline et non potable au sud de la rivière Assiniboine. Cette eau qui est généralement à une température de 39° à 43° Fahrenheit (3.9 à 6.1 °C) est utilisée essentiellement comme agent de refroidissement industriel. Le débit pompé varie de 5 millions de gallons par jour en hiver à 10 millions de gallons (22.7×10^6 l) par jour pendant la période d'été.

Ces pompages ont amené la formation d'un important cône de drainage dans la zone du centre industriel de la région métrolopitaine de Winnipeg. Les élévations de la surface piézométriques sont comprises entre 800 et 1500 pieds (240 et 450 m) dans les zones de recharges, et sont inférieures à 700 pieds (210 m) dans le cône de drainage. Ce cône est situé au centre d'un système d'écoulement latéral, radial. La nappe perd également de l'eau par décharge naturelle dans les rivières Assiniboine et Rouge et dans le chenal de déviation de cuve de la rivière Rouge.

Dans les conditions naturelles, la nappe saline située dans le grès supérieur est isolée hydrauliquement de la zone inférieure des carbonates aquifères par les 10 ou 20 pieds (3 à 6 m) de schistes de la formation Winnipeg. Cependant, si on ouvre des puits forés jusque dans les grès, des charges hydrauliques plus fortes entrainent la pénétration d'eau salée dans la nappe située dans les carbonates.

Les pressions hydrostatiques dans la partie supérieure de la nappe située dans les carbonates affectent les travaux de construction qui intercepte cette nappe ou provoquent des ruptures hydraustitiques par déchargement des couches confinantes. L'écoulement d'eau de cette nappe a affecté de nombreux chantiers. Les plus gros problèmes ont été rencontrés lors de la construction du chenal de dérivation de cuves de la rivière Rouge. Des écoulements en provenance de la nappe ont affecté les excavations des sections inférieures du chenal et un nombre important de structures. De tels écoulements ont été observés pour la première fois sur ce site lorsque de l'eau artésiene apparue dans un puit d'observation excavé à une profondeur de 20 pieds (6 m) sous la surface piézométrique de la nappe. Les débits excédaient couramment plusieurs centaines de gallons à la minute. Le contrôle de la nappe pendant la construction de la structure de controle en tête de chenal a nécessité la mise en place d'un rideau d'injection de 4000 pieds (1220 m) de long à travers les dépôts de surface et le carbonate supérieur, et d'un important système de drainage. La connaissance des propriétés de la nappe avant le début des travaux a facilité les excavations et la construction et a éliminé les réclamations dues à des conditions imprévues.

Introduction

The Winnipeg area (Figs. 1 and 2) is underlain by an extensive carbonate rock aquifer which currently yields approximately 3 billion gallons (13.6 billion l) of water/year. Groundwater from this confined aquifer has been extracted for at least 130 y. During this interval over 200 commercial and industrial wells and thousands of domestic wells have been installed. Total pumpage has varied from less than 10^6 to 10^7 gallons/day (4.54×10^6 to 4.54×10^7 l/day). Construction excavations in the glacial drift that confines the aquifer, or which are directly involved with the rock have encountered excessive groundwater inflow. Prior to the start of construction of the Red River Floodway, an extensive hydrogeological investigation was undertaken. The data obtained were used

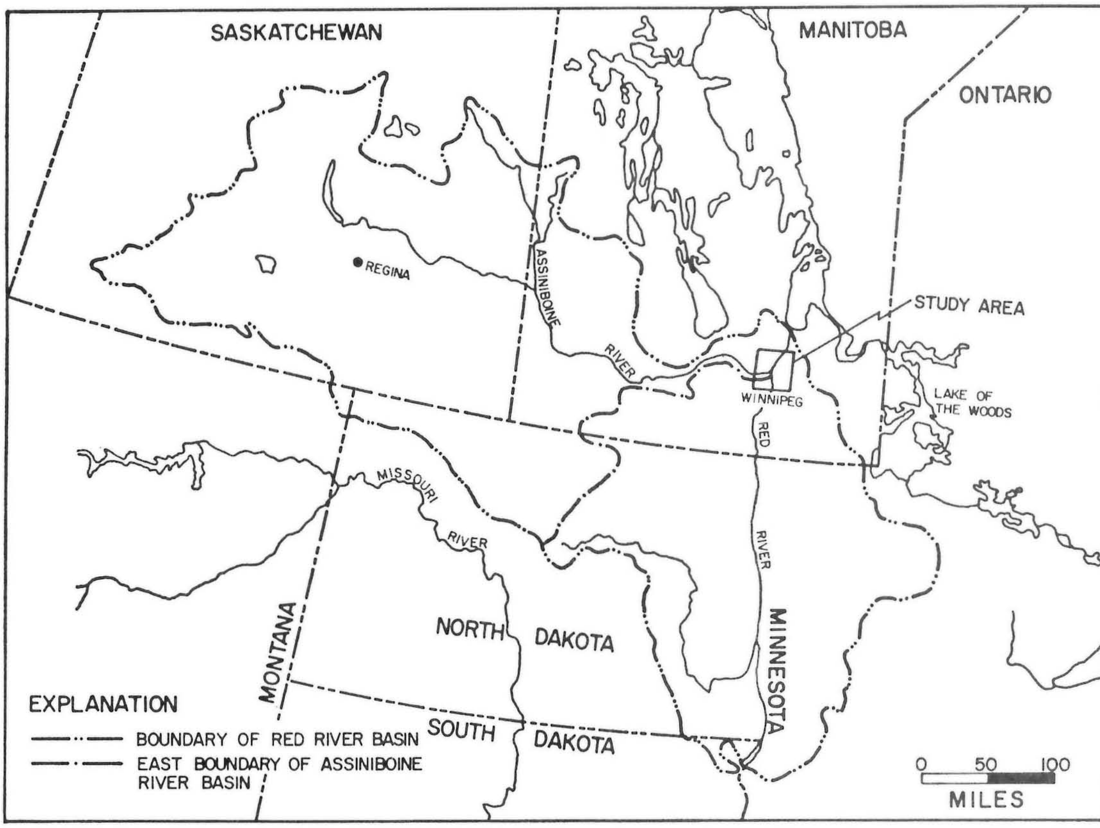

FIG. 1. Location of the study area.

to predict the interrelationships of groundwater and construction, thus preventing unanticipated construction problems.

The industrial and commercial development of the metropolitan area has, to a large extent, been influenced by the excellent surface water supply that is brought in by the 85 $\times$ 10^6 gallons/day (386 $\times$ 10^6 l/day) capacity aqueduct from the Lake of the Woods 90 miles (145 km) east of Winnipeg. Carbonate aquifer wells provide approximately 17% of the water supply used in the area. Pumpage from this aquifer reached a maximum of 3.6 billion gallons (16.3 $\times$ 10^6 l)/year in 1918 (Fig. 3). Following the completion of the aqueduct in 1919, pumpage abruptly declined but has since gradually increased due to groundwater development for industrial and air conditioning purposes.

The Red River Valley is located along the mid-continent topographic low. Consequently surface and groundwater systems flow toward it both from the east and the west.

Although natural drainage of the urban area consists of the two main rivers and several small streams, the extreme flatness of the prairie surface has required the construction of an extensive network of agriculture and flood protection drains. The largest of these is the recently completed Red River Floodway. In the metropolitan area the sewer systems remove most of the average annual 19 in. (48 cm) of precipitation before it percolates down to the water table.

Geologic Environment

The stratigraphy of the Red River Basin is a controlling parameter of the groundwater system. The Winnipeg area is located stratigraphically on the northeast fringe of a sequence of gently dipping sedimentary rock units (Fig. 4). The bedrock surface is characterized by Paleozoic carbonate formations (Fig. 5) which under Winnipeg range in thickness from

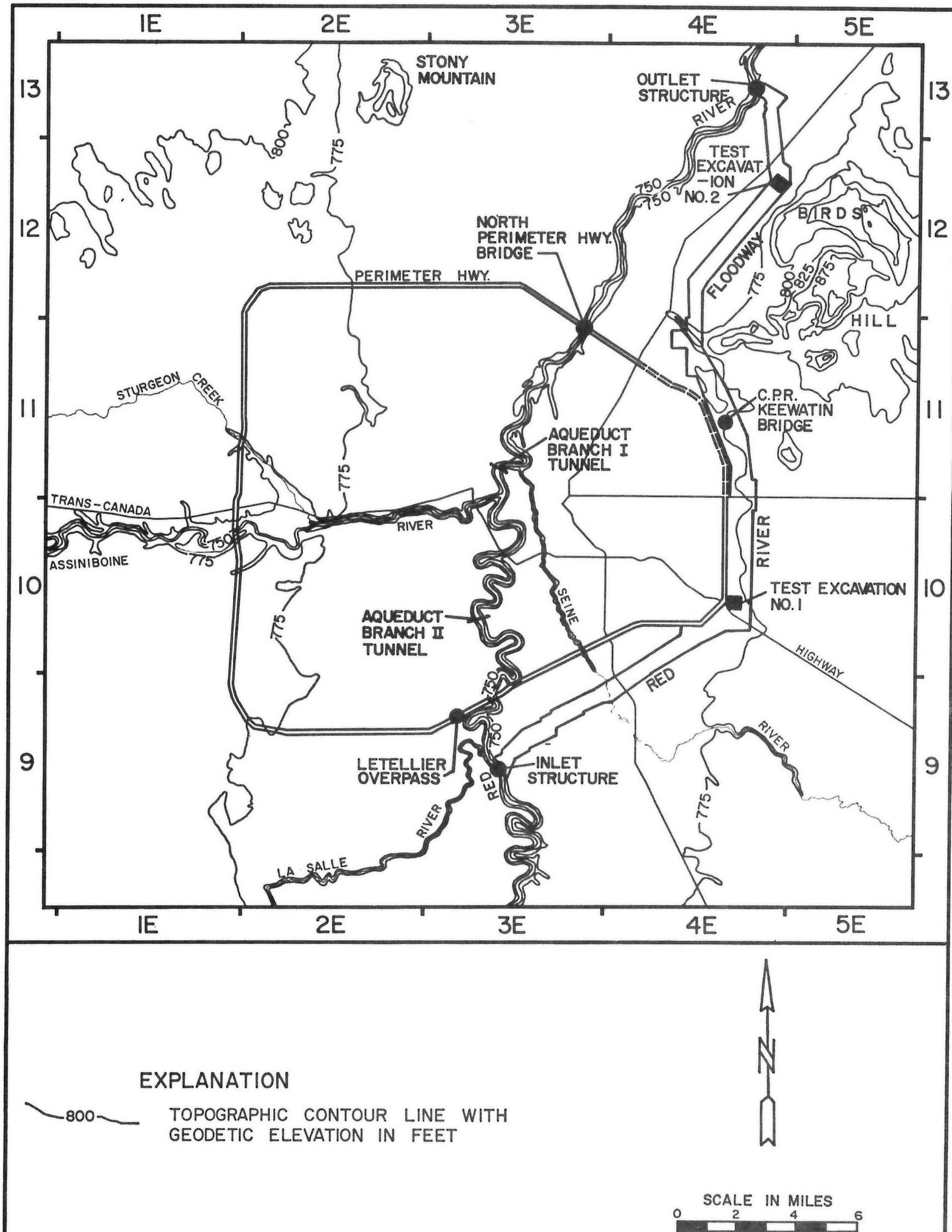

FIG. 2. Topography of the Winnipeg area.

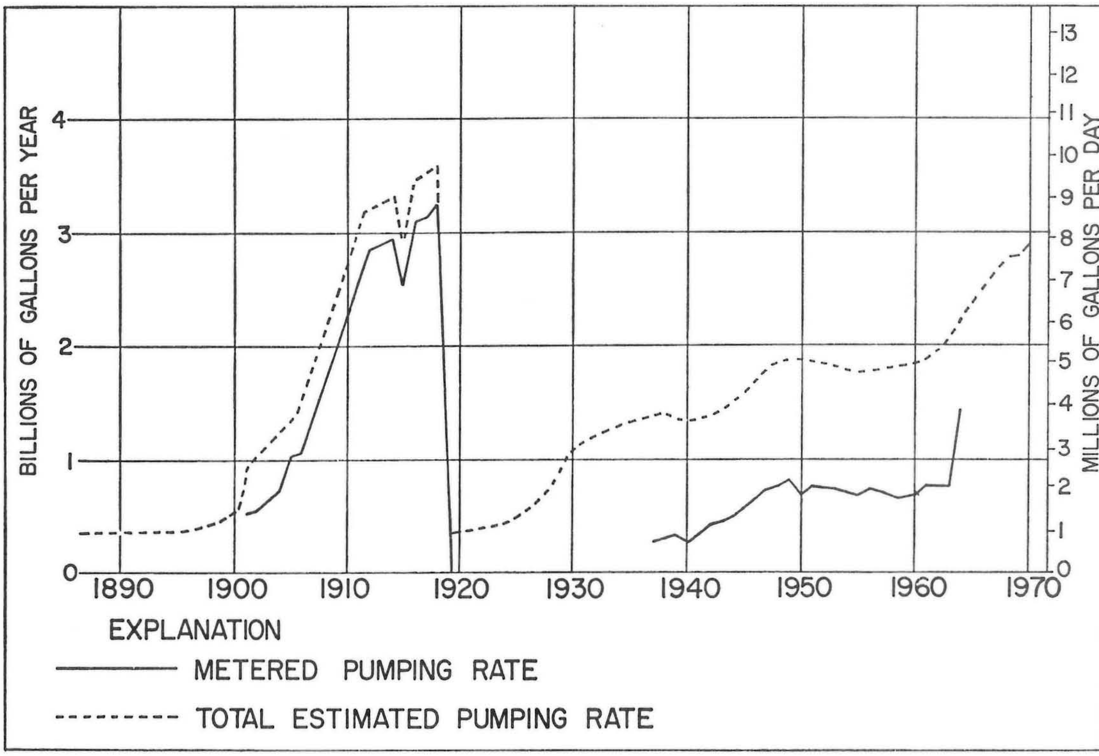

FIG. 3. Groundwater pumping rates.

250 to 750 ft (76 to 230 m). The bedrock surface (Fig. 6) has a number of closed depressions which suggest a karst topography similar to that observed in rock exposures between Lakes Winnipeg and Manitoba. A mantle of Pleistocene drift overlies the bedrock (Fig. 4). The drift has a maximum thickness over 400 ft (120 m), and is generally thicker immediately east of the Pembina Escarpment and in the Sandilands Forest Reserve area (Davies *et al.* 1962). In the central Red River Basin, the drift comprises Glacial Lake Agassiz clay and recent fluvial deposits overlying till (Fig. 7). Under the metropolitan Winnipeg area the surficial deposits have a maximum thickness of approximately 200 ft (60 m). The average thickness is 60 ft (18 m) (Fig. 8).

Hydrogeology

Introduction

The major aquifer underlying the Winnipeg area, referred to as the Upper Carbonate aquifer, occurs in the top 50 to 100 ft (15 to 30 m) of the Paleozoic limestones and dolomites (Fig. 9). The aquifer is partially confined above by the glacial drift and below by the slightly pervious underlying carbonate rock. A relatively minor aquifer, called the Lower Carbonate aquifer, occurs in the bottom 25 to 50 ft (7.5 to 15 m) of the Red River formation, along the contact with the upper shale unit of the Winnipeg formation. The Winnipeg formation contains an Upper Sandstone aquifer, 20 to 40 ft (6 to 12 m) thick and a Lower Sandstone aquifer 10 ft (3 m) thick. Both of these aquifers contain saline water. Recharge occurs through the glacial till and glaciofluvial deposits located in the uplands along the borders of the Red River Basin and in the Birds Hill. In a few places, large diameter dug wells have been installed to provide domestic water supplies from silt and very fine sand in the upper 15 ft (4.5 m) of the glacial lake clay, or from an uncemented zone in the top of the till.

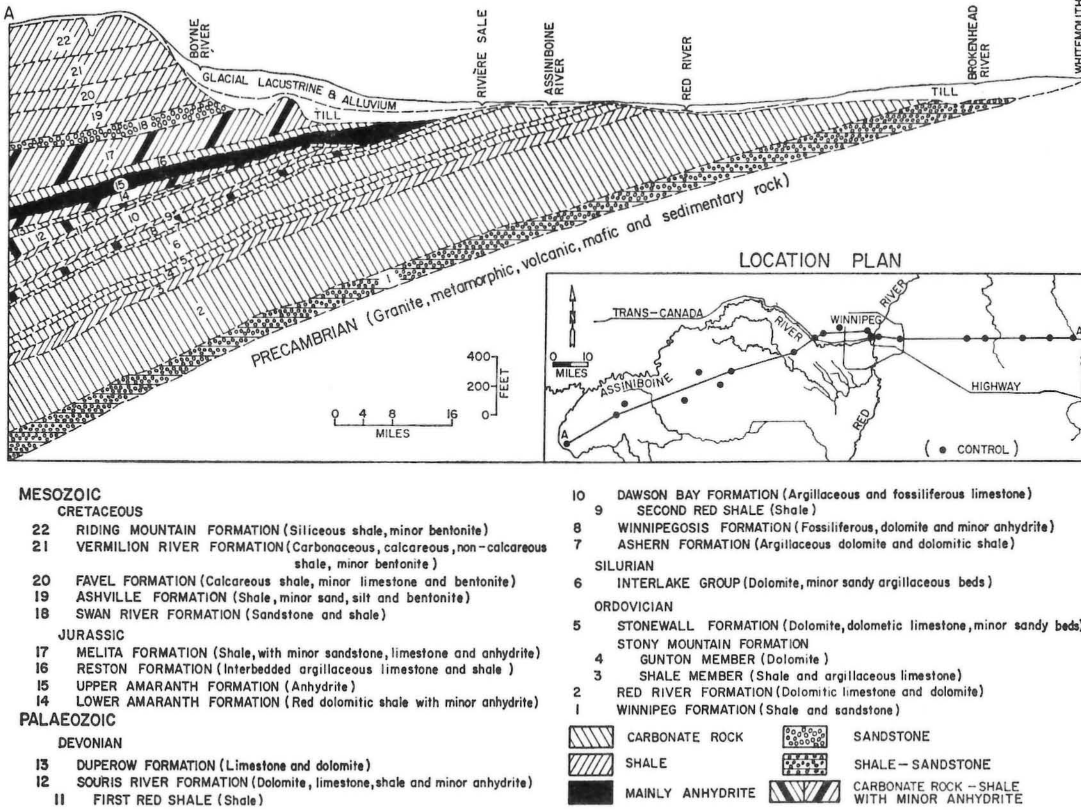

FIG. 4. Geologic cross section of the Red River Basin through Winnipeg.

Carbonate Aquifers

The Upper Carbonate aquifer is characterized by a network of fractures, joints, and bedding planes which provide aquifer permeability. Geochemical solution processes acting for at least the past several thousand years have enlarged the pore spaces and modified the network. Fracture openings generally have maximum widths at the bedrock surface and decrease in size with depth. The upper 25 ft (7.5 m) of the carbonate rock is the major zone of permeability in the aquifer, and is thus the section of most active flow. The character of the fracture permeability in the upper part of the bedrock at the Inlet Structure of the Red River Floodway is shown in Fig. 10. While the entire thickness of the carbonate rock is saturated, bore-hole pressure testing in the Winnipeg area has indicated that the portion between the Upper and Lower Carbonate aquifers has an exceptionally low frequency of fracture openings and therefore is not a producing zone.

Large solution cavities in the bedrock, typical of karst topography have been encountered. Interception of these solution cavities by wells results in high capacity, whereas, wells that do not intercept these features may have a low specific capacity. As the permeability is highest in the upper part of the bedrock, the slope of the bedrock surface has a controlling influence on the local and regional directions of groundwater movement in the aquifer. Openings along the bedding planes, observed both in outcrops and in excavations, usually do not exceed 1 in. (2.5 cm) in height. Major joint openings strike both northwest and northeast, and vary in size from hairline fractures to openings over 1 ft (0.3 m) wide. The joint blocks are 1 to 10 ft (0.3 to 3 m) wide.

The transmissibility[2] of the Upper Carbonate aquifer (Fig. 11) ranges from under 2000 to

[2]Transmissibility = hydraulic conductivity in gallons/day/square ft multiplied by aquifer thickness in ft.

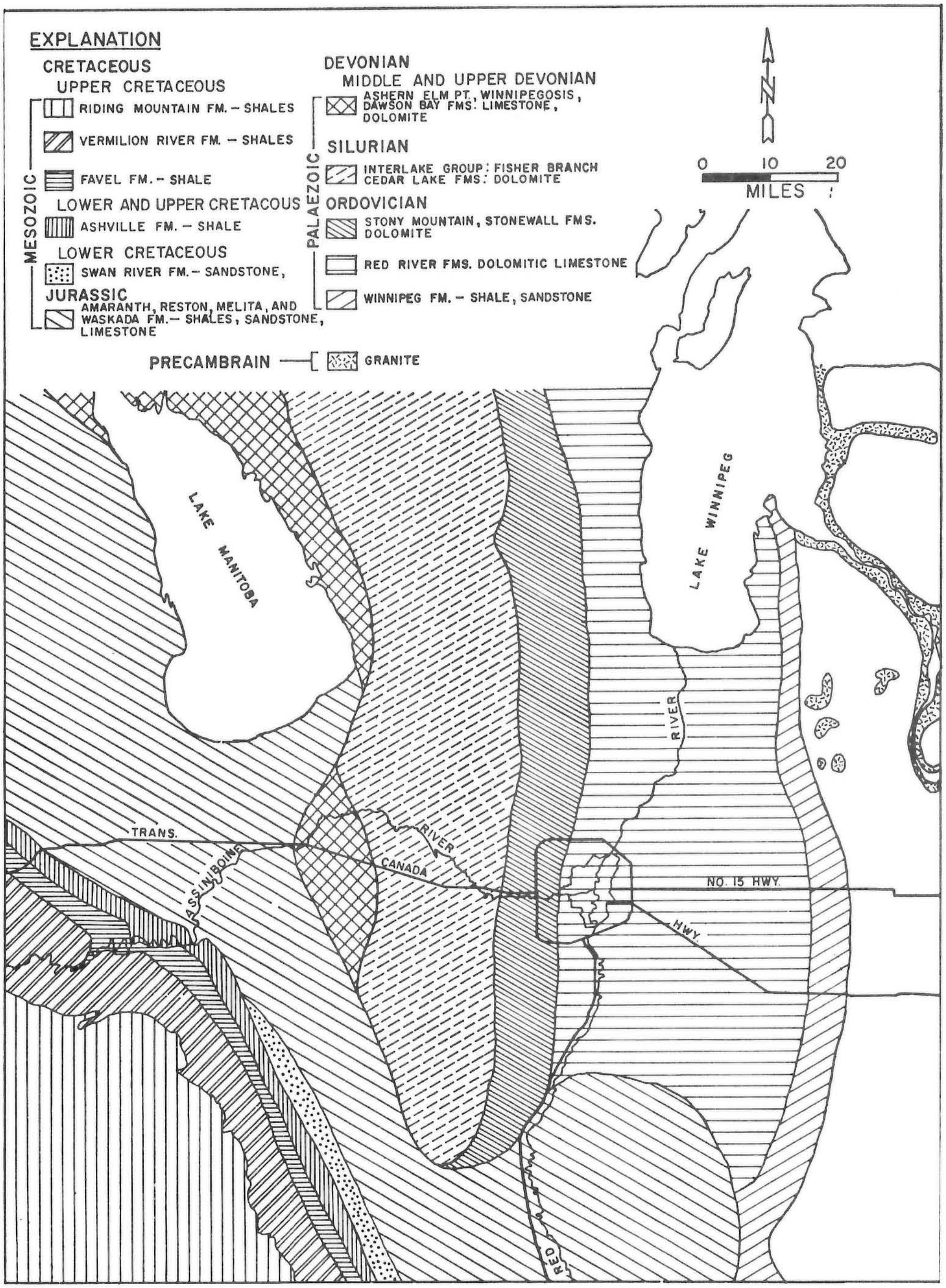

FIG. 5. Bedrock surface geology of south central Manitoba.

over 200 000 gallons (24.8 and 2480 $m^3/m/$ day)/ft/day. The storage coefficient varies from 1×10^{-6} to 1×10^{-3}.

Data from bore-hole water pressure tests and pumping tests indicate that the permeability of the Lower Carbonate aquifer is much less than that of the Upper Carbonate aquifer. The interception of fractures is less frequent and the

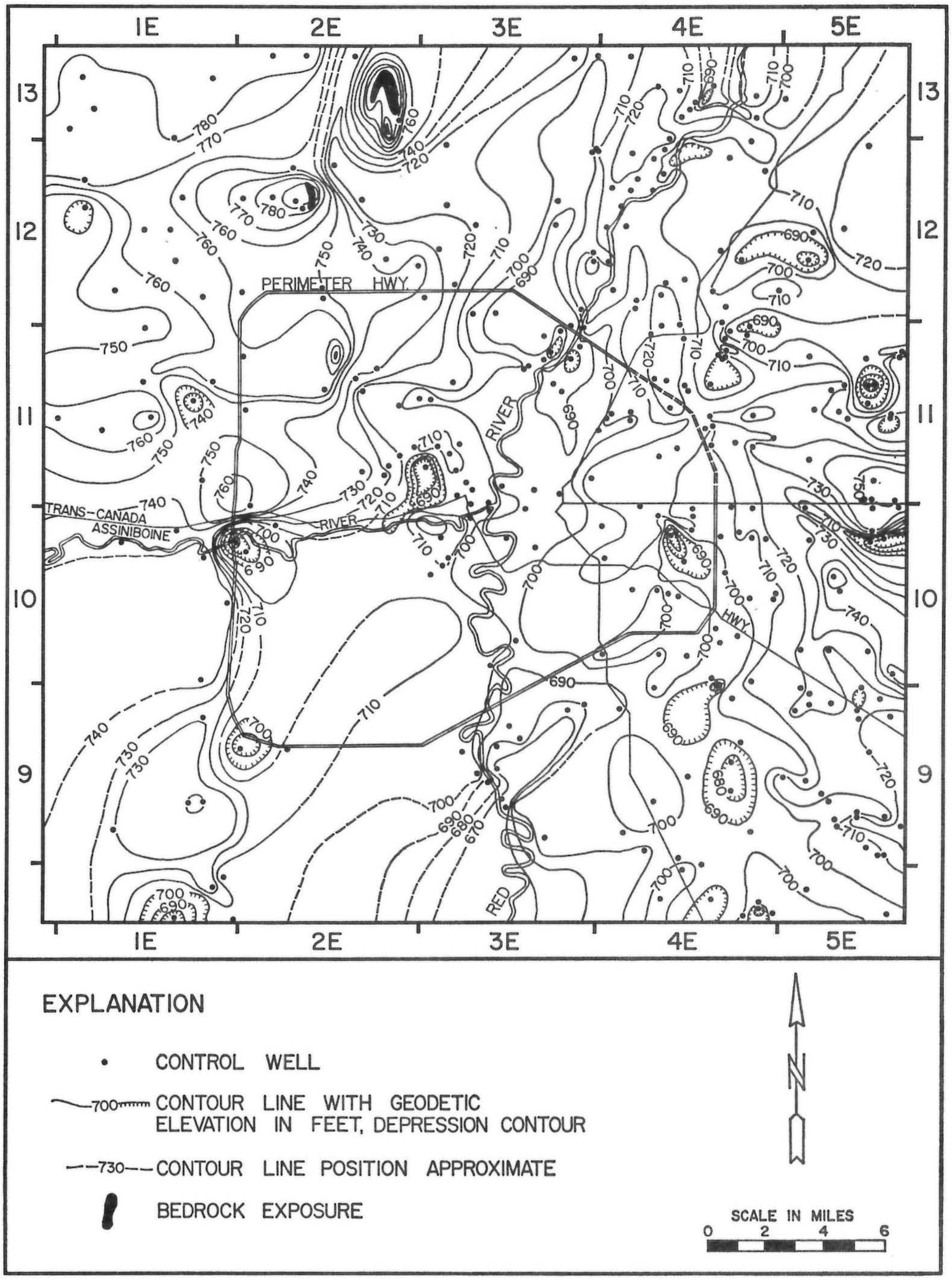

FIG. 6. Topography of the bedrock surface.

groundwater flows are usually small, indicating narrow openings. The maximum transmissibility of this aquifer is probably less than 5000 gallons (62 m³/m/day)/ft/day.

Sandstone Aquifers

The Winnipeg formation contains the Upper and Lower Sandstone aquifers. The 10 to 20 ft (3 to 6 m) thick upper shale unit of the Win-

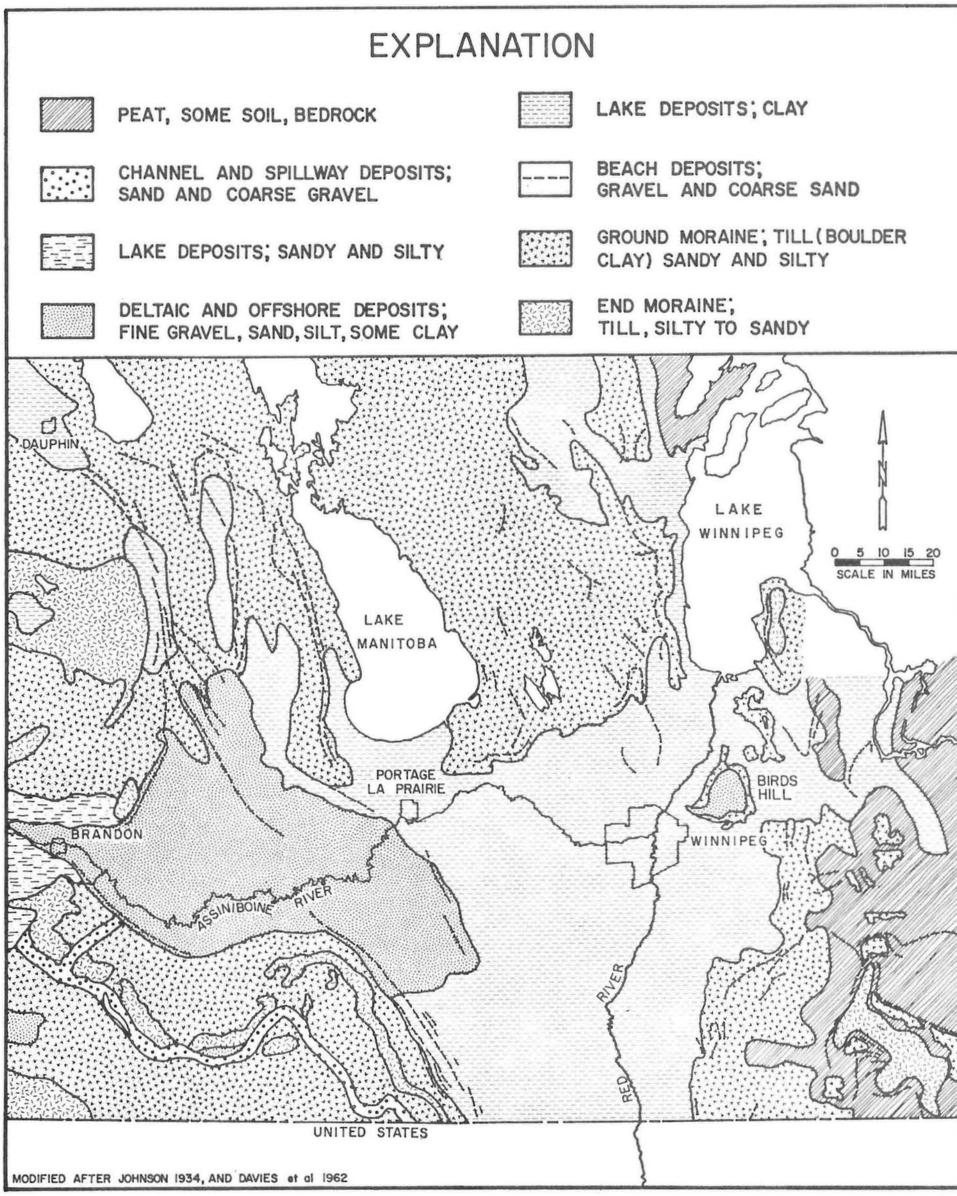

FIG. 7. Surface deposits of south central Manitoba.

nipeg formation is a confining layer for the Lower Carbonate aquifer and acts as an aquiclude between this aquifer and the saline water bearing Upper Sandstone aquifer. Beneath the city of Winnipeg the Upper Sandstone aquifer is 20 to 40 ft (6 to 12 m) thick (Fig. 9) and consists of beds of very fine silicious sandstone interbedded with thin layers of shale. In the metropolitan area this aquifer has a transmissibility of less than 1000 gallons (12.4 m³/m/day)/ft/day. Twenty miles (30 km) southeast of the city, where the sandstone is thicker and coarser grained, the transmissibility is in the order of 10 000 gallons (124 m³/m/day)/ft/day. Thirty miles (50 km) south of Winnipeg this unit thickens to 80 ft. Between this aquifer and the top of the Lower Sandstone aquifer are 60 to 70 ft (18 to 21 m) of shale. Thin lenses

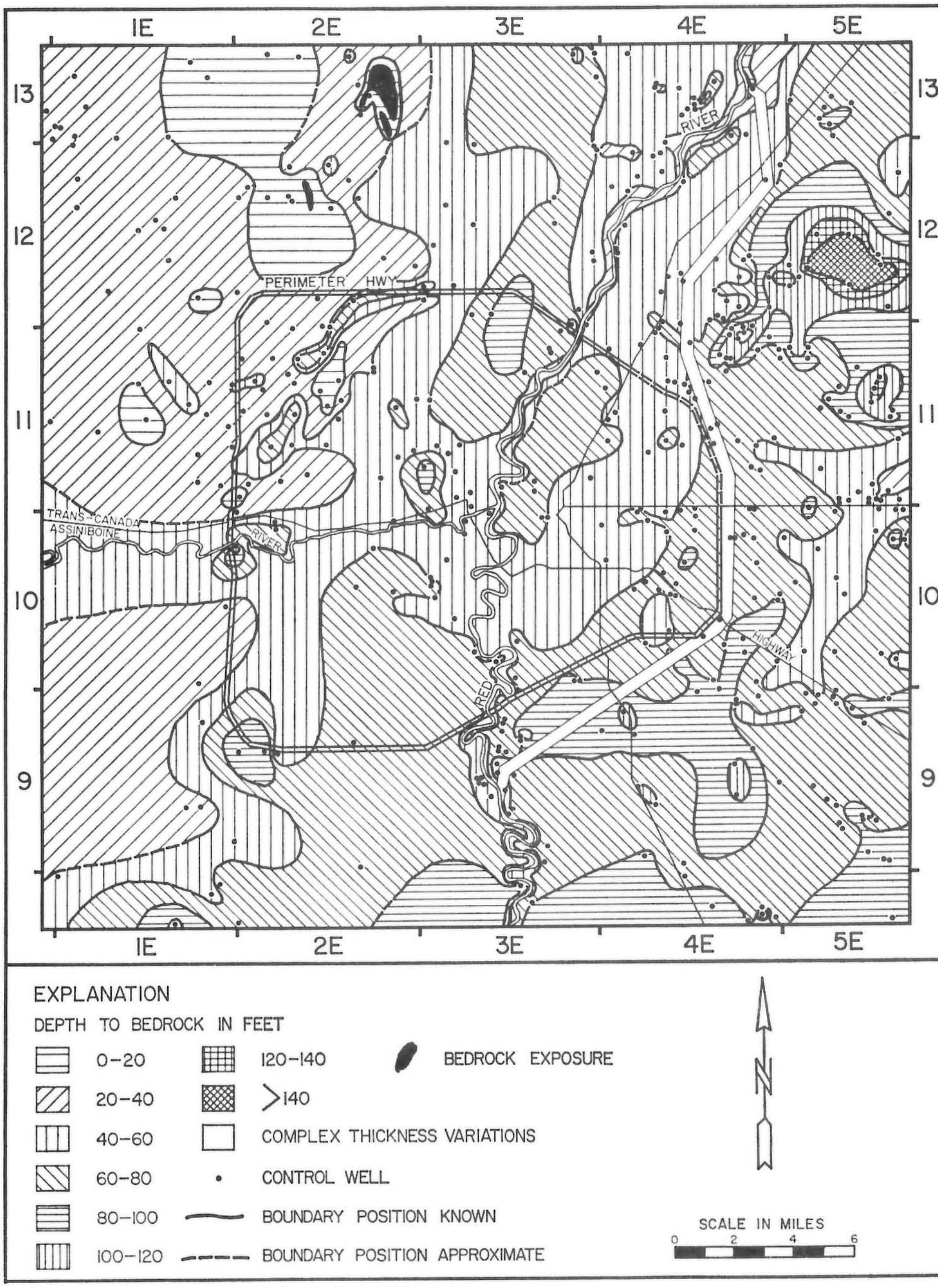

FIG. 8. Thickness of the deposits overlying the bedrock.

of sandstone occur at some places within this shale unit.

Under the city of Winnipeg the Lower Sandstone aquifer is composed of fine grained, silica sandstone. This unit extends down dip and in places along the western border of Manitoba is 40 ft (12 m) thick (Andrichuk 1959). A pumping test on the two sandstone aquifers

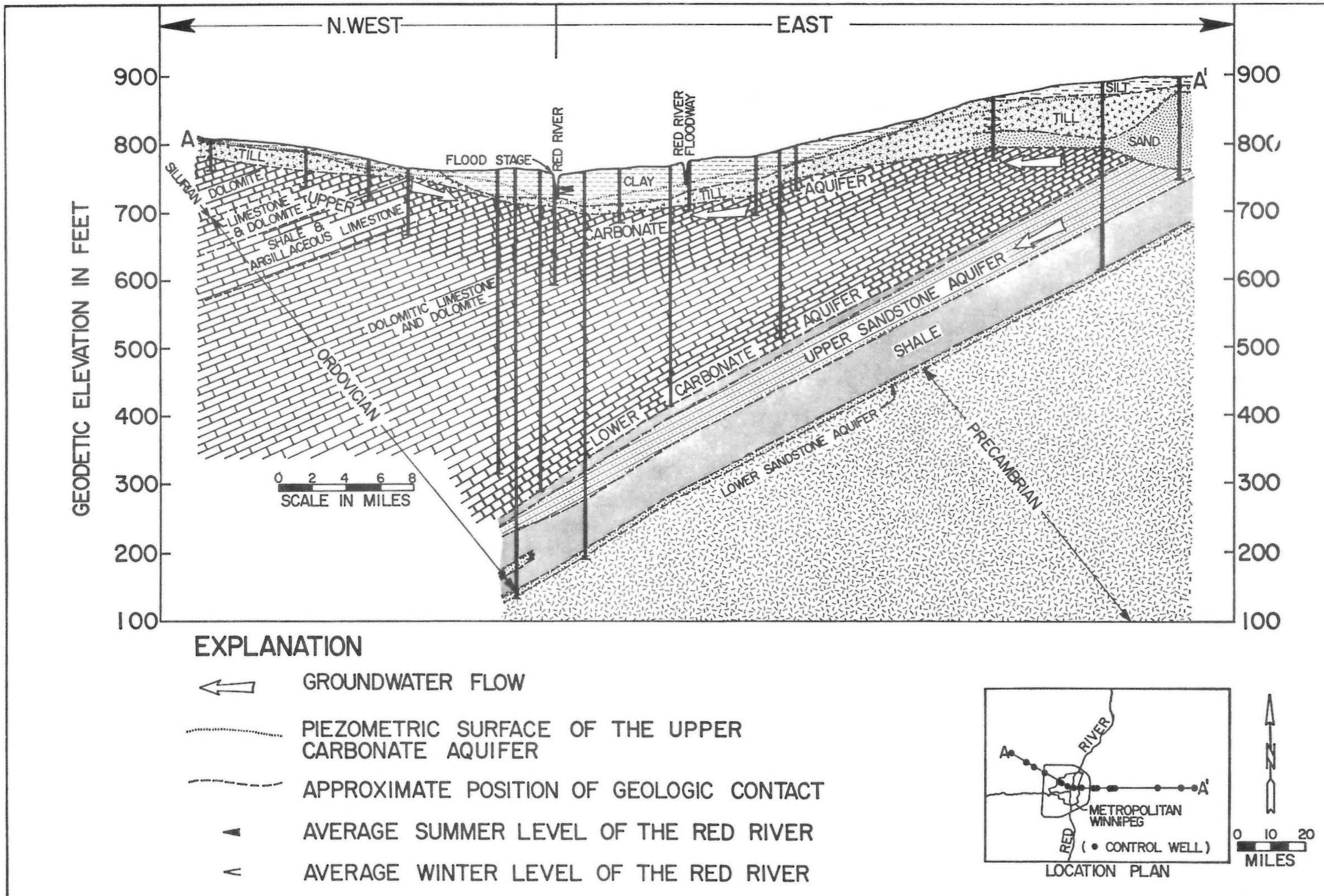

FIG. 9. Hydrogeologic cross section of the Red River Valley through the Winnipeg area.

FIG. 10. Upper bedrock zone under the Red River Floodway Inlet control structure.

under central Winnipeg indicated a combined transmissibility of approximately 1000 gallons (12.4 m^3/m/day)/ft/day.

Surficial Deposits

The Upper Carbonate aquifer is overlain by deposits of glacial drift (Fig. 7). Near the rivers and streams alluvium occurs on the drift. The lower portion of the drift consists of boulder till and associated glaciofluvial deposits. In the central basin the upper part of the drift comprises clay and clayey silts deposited in Glacial Lake Agassiz. Deposits consisting primarily of outwash sand and gravel occur in the Birds Hill area 10 miles (16 km) northeast of Winnipeg.

The bouldery till consists of carbonate rock fragments in a clay-silt matrix. The till thickness under metropolitan Winnipeg averages 20 ft (6 m) and ranges up to 40 ft (12 m). In places, Lake Agassiz sediments rest directly on the bedrock. Under the Winnipeg area the upper part of the till consists of a soft, wet, uncemented zone that ranges in thickness up to 12 ft (3.6 m), and averages 3 ft (1 m). The underlying till is usually highly cemented with calcium carbonate. The author has observed hairline joints in the cemented till which probably account for most of its permeability. Slightly north of the study area field tests using the Hvorslev method (Hvorslev 1951) yield permeability values[3] that average 3×10^{-6} cm/s. Glaciofluvial deposits, such as the Birds Hill complex, considerably increase the overall permeability of the drift.

The Birds Hill glaciofluvial deposits (Fig. 7) underlie an area of some 60 square miles (155 square km) and form an important partially confined aquifer that contributes recharge to the Upper Carbonate aquifer. The deposits are variable in grain size and structure, ranging from massive sections of fine silty sand to cross-bedded coarse gravels. Till occurs discontinuously under the glaciofluvial materials. An upper till usually overlies the periphery of the deposits (Figs. 7 and 12). The discontinuity of

[3]K. Goff, personal communication, 1968.

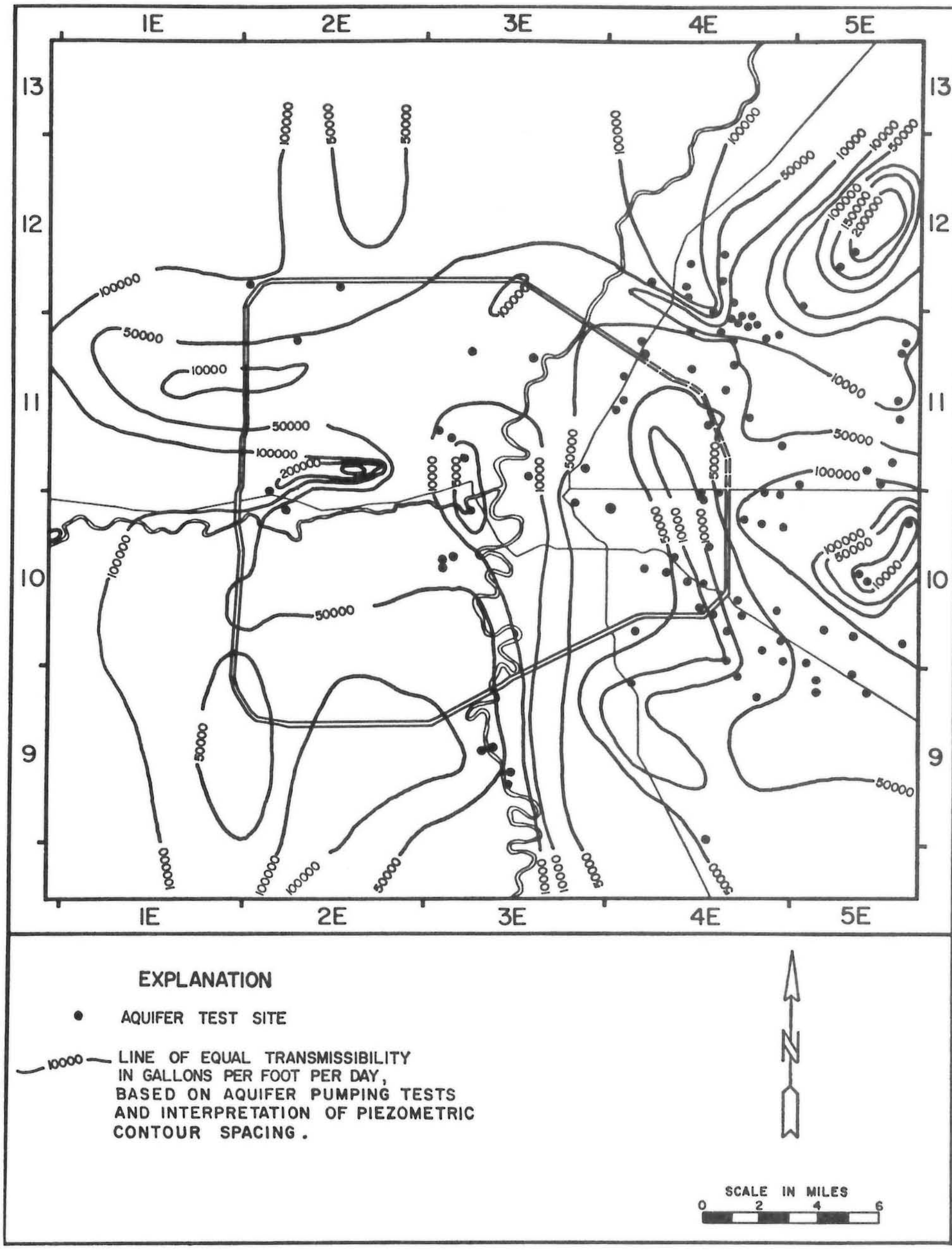

FIG. 11. Transmissibility of the upper carbonate aquifer.

the lower till allows appreciable groundwater recharge from the Birds Hill aquifer into the Upper Carbonate aquifer. The western extension of the hill is a large esker. Pumping tests indicate that the transmissibility of the combined Birds Hill and the Upper Carbonate aquifers ranges between 100 000 and 300 000 gallons (1240 and 3720 $m^3/m/day)/ft/day$. The high transmissibility is primarily due to the Birds Hill aquifer. Other glaciofluvial deposits, deltas, and lake beaches occur along the perimeter and within the Red River Basin (Fig. 7). In general areas of groundwater recharge are associated with these deposits.

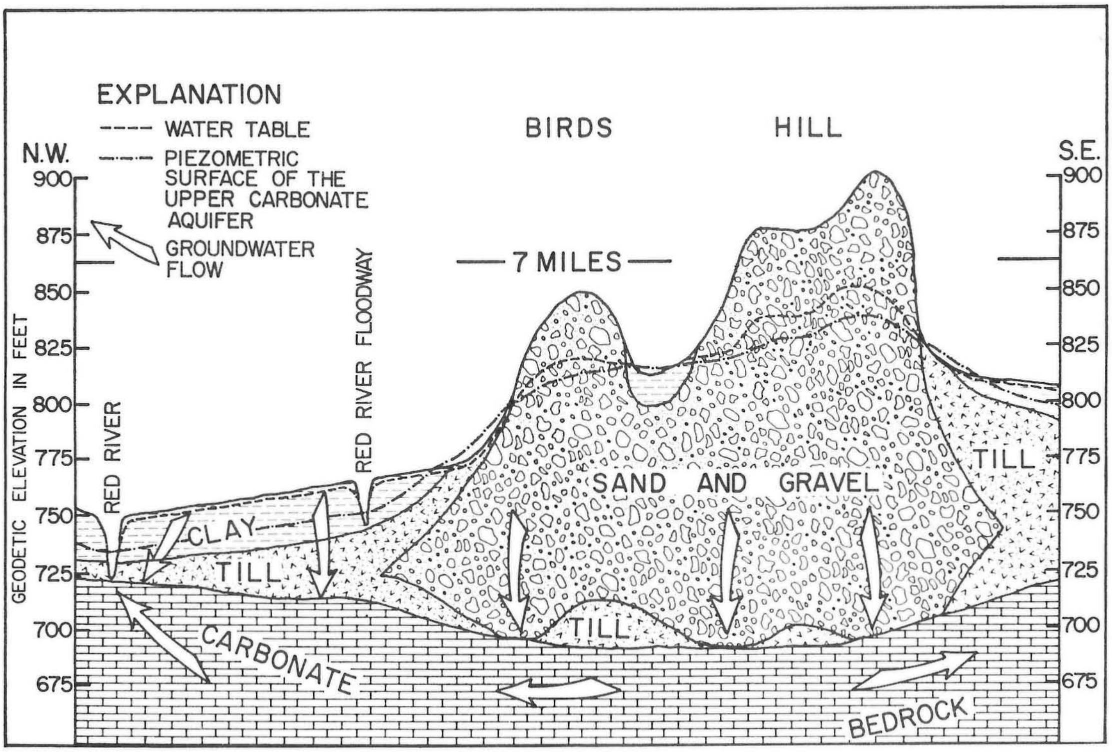

FIG. 12. Schematic geologic cross section of the Birds Hill area.

Lake Agassiz deposits which underlie the central part of the Red River Basin in general consist of two distinct geohydrologic units. The upper unit consists of 5 to 15 ft (1.5 to 4.5 m) of silt and very fine sand interbedded with thin beds of clay. Under Winnipeg the Agassiz sediments have a maximum thickness of 80 ft (24 m) and an average thickness of 40 ft (12 m) (Fig. 13) but thicken westward to over 200 ft (60 m).

Laboratory tests on samples from the lower clay unit indicate an intergranular hydraulic conductivity in the order of 10^{-9} to 10^{-11} cm/s and horizontal permeabilities that are twice the vertical (Baracos 1960, Mishtak 1964). Hairline fractures were observed in the lower clay unit during the floodway excavation. These fractures appear to form a secondary permeability system. Because of the silt and sand beds the upper Agassiz unit has a higher permeability than the underlying clay. The most important hydrogeologic aspects of the lower Agassiz unit is its restriction of recharge to the Upper Carbonate aquifer, and the consequent deterrence of pollution from surface sources.

Groundwater Flow Systems

Groundwater Movement in the Upper Carbonate Aquifer

In the Red River Basin the Upper Carbonate aquifer is the most important part of the extensive zone of groundwater movement that occurs within the upper portion of the bedrock. The groundwater regime in this zone can be divided into three segments of predominantly lateral movement: (1) from the east, (2) from the northwest, and (3) from the southwest (Fig. 14). Infiltration in the glacial till upland east of the lacustrine plain and in the Birds Hill aquifer complex recharge the eastern segment (Figs. 4 and 7). Recharge for the northwestern region occurs in the areas of thin glacial till northwest of Winnipeg. The southwestern system appears to be recharged through the thin veneer of glacial till and fluvial deposits that overlie the Mesozoic shale uplands on the western side of the basin.

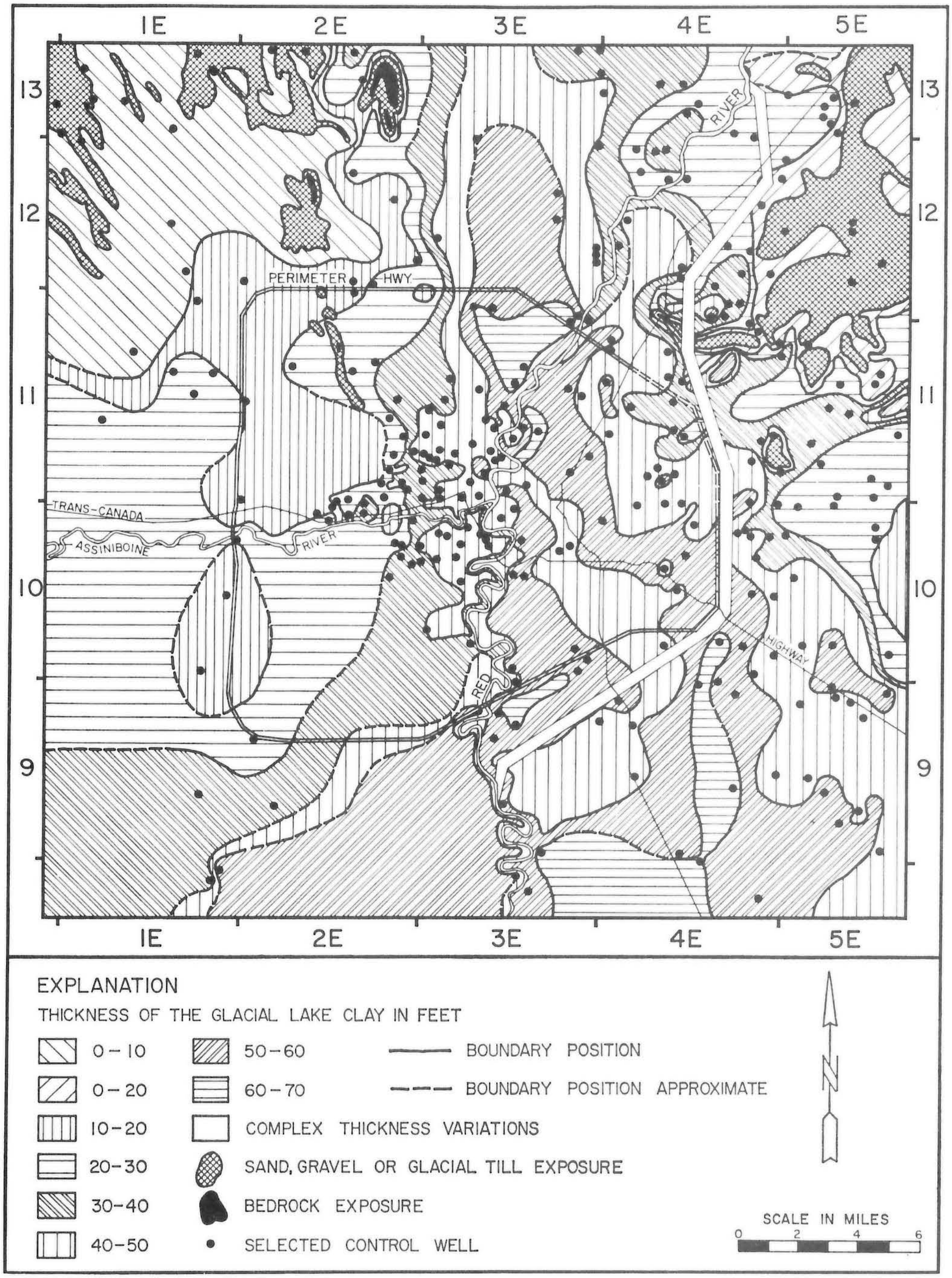

FIG. 13. Thickness of the glacial lake clay.

In 1894 before extensive groundwater pumping occurred, the piezometric surface in the Upper Carbonate aquifer was 1 to 4 ft (0.3 to 1 m) above ground level in northwestern Winnipeg (Johnson 1934). Adjacent to the Red River in north central Winnipeg the piezometric surface was 10 to 20 ft (3 to 6 m) below ground level. Currently in the central part of

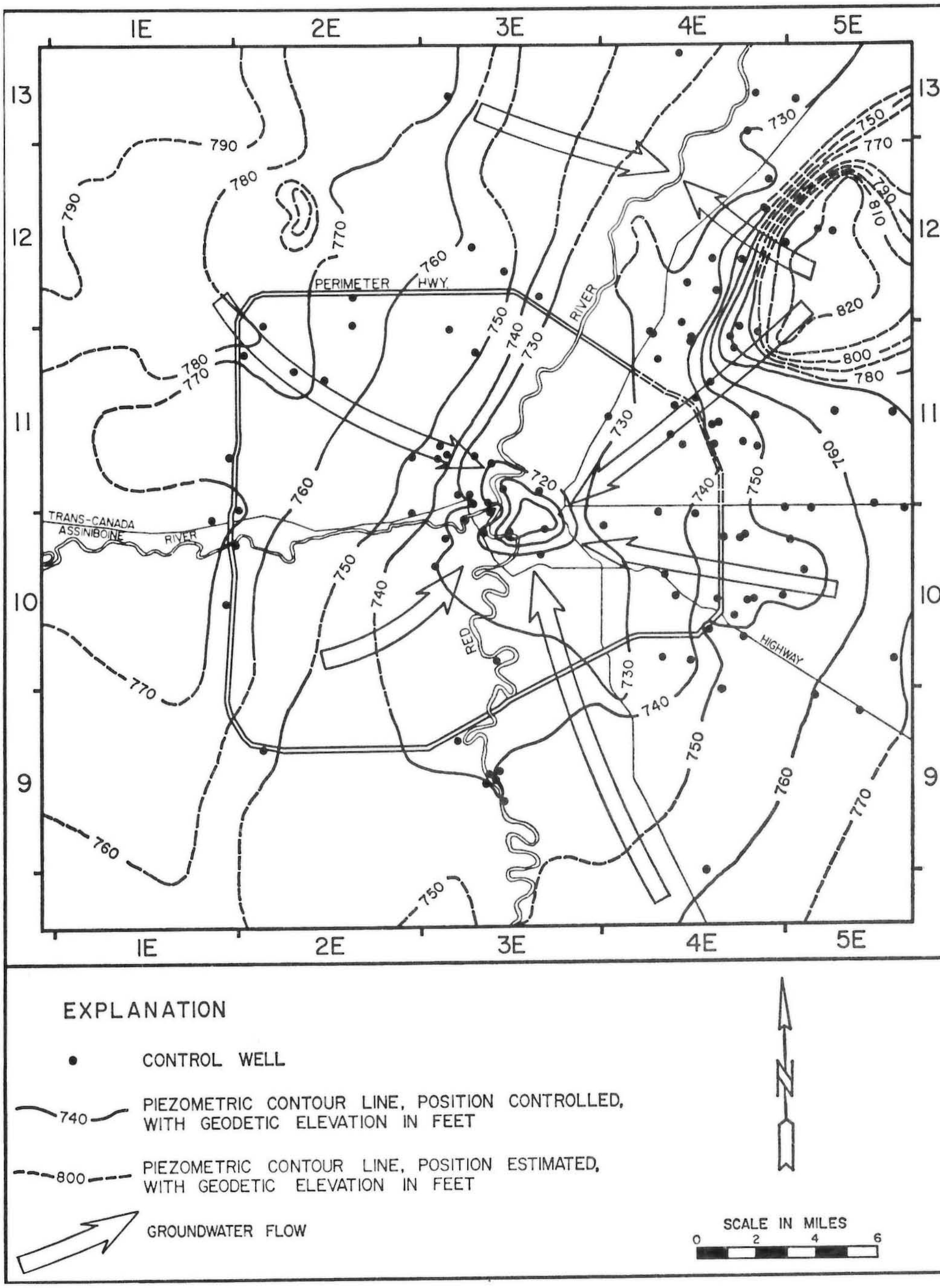

FIG. 14. Piezometric surface of the upper carbonate aquifer, May 1968.

the city, pumping has extensively depressed the piezometric surface. In the central part of the drawdown cone the depths to water range from 70 to 80 ft (21 to 24 m), and the piezometric elevations are at some places below 700 ft (210 m) (Fig. 14 and Hydrograph M-105, Fig. 15). Fluctuations of piezometric levels in the Upper Carbonate aquifer during the past

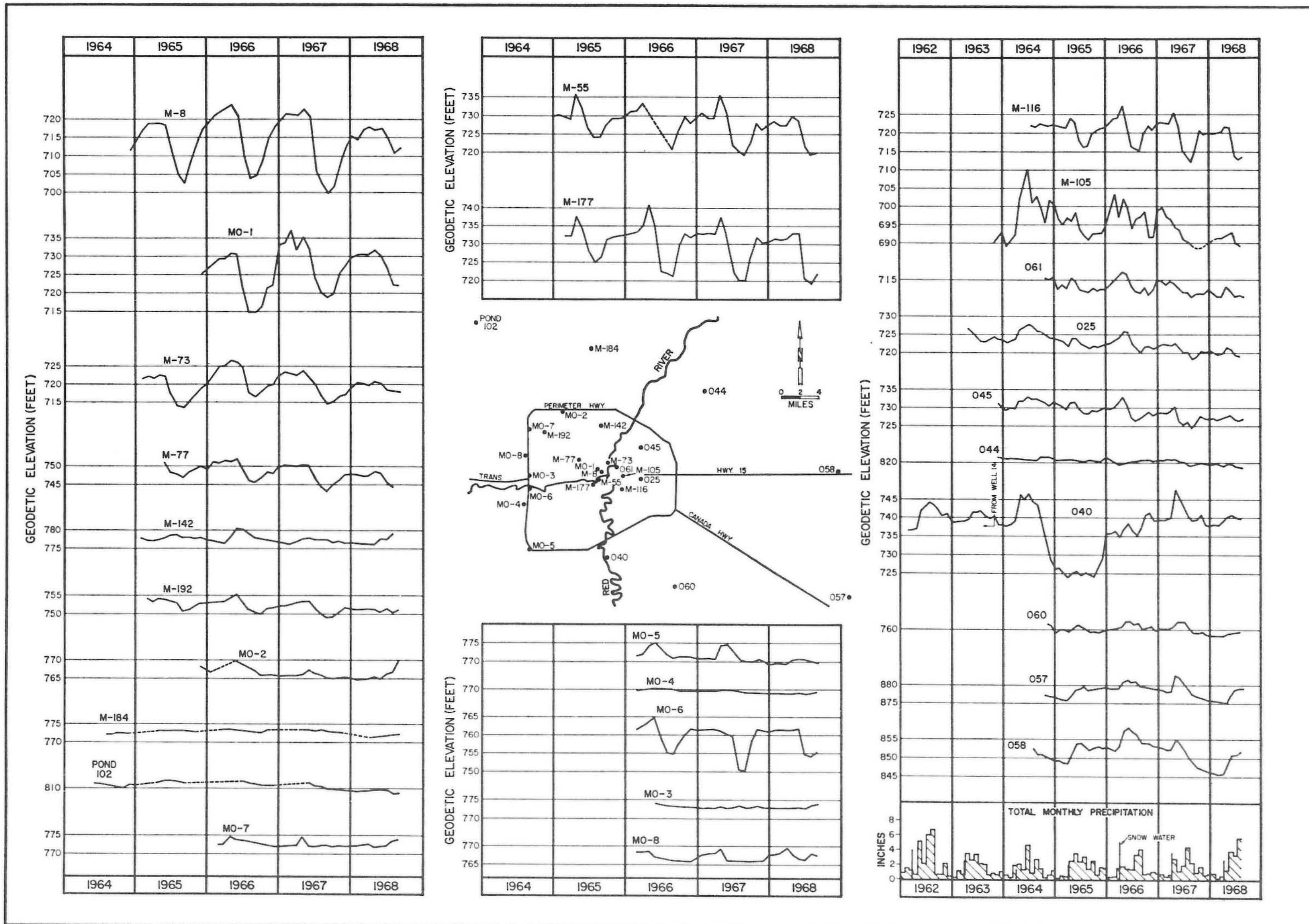

FIG. 15. Selected upper carbonate aquifer groundwater levels.

6 y are shown in the hydrographs in Fig. 15.

On a regional basis the aquifer has been considered to be isotropic and the groundwater flow directions are interpreted as occurring in the direction of the hydraulic gradient (Fig. 14). It is recognized, however, that irregular groundwater flow channels in the joints, fractures, and bedding planes probably created areas of local anisotropy.

Evidence of Aquifer Recharge

Major evidence for recharge is provided by the metropolitan pumpage and water level data. Over the 8-year period of major groundwater development (Fig. 3) at least 130 billion gallons (590 billion l) of groundwater have been withdrawn from the aquifer. Throughout the basin, springs and flowing wells also discharge large quantities of groundwater. The pumpage in the Winnipeg drawdown cone appears to have affected the piezometric surface of the Upper Carbonate aquifer over an area of 1300 square miles (3360 square km). If all the water withdrawn had been produced from storage within the aquifer, the average drawdown over this area, assuming a relatively high storage coefficient of 1×10^{-3}, would have been in the order of 600 ft (180 m). The observed maximum drawdown is approximately 60 ft (18 m). This storage coefficient and the assumption of lateral recharge produced reasonable test results when they were utilized as two of the parameters in a resistor capacitor analogue model (Render *et al.* 1968).

Since 1947, approximately 50 billion gallons (227 billion l) of water have been pumped from the aquifer in the urban area. However, the piezometric surface of the central portion of the drawdown cone has shown only minor fluctuations in elevation. As relatively little water was withdrawn from groundwater storage, the aquifer during this period must have acted primarily as a transmission zone. Another indication that the aquifer is receiving substantial recharge is provided by groundwater data from the floodway area. For over a year, while the floodway has been discharging approximately 3000 gallons (13 600 l)/min, stable water level elevations have been observed in the surrounding observation wells. Furthermore, the line of zero drawdown for the floodway drawdown cone is located near the till upland on the eastern side of the basin. This indicates that there is sufficient recharge available to maintain the draught on the aquifer. Evidence for recharge of the groundwater flow systems in the Upper Carbonate aquifer by precipitation percolating through the glacial till and glaciofluvial deposits located in the uplands along the borders and within the basin is shown by the hydrographs for wells 057 and 058 (Fig. 15). The identification of the Birds Hill as a recharge area is indicated by the dome shaped piezometric surface of the underlying Upper Carbonate aquifer.

Groundwater Geochemistry

The water in the eastern and northwestern flow regions which cross carbonate rock is fresh in the recharge and slightly brackish and very hard in the discharge areas. The values of the total dissolved solids range from 300 to 1500 mg/l and the chloride ion concentrations vary from less than 10 to 500 mg/l (Fig. 16). These two systems are utilized for rural and suburban potable water supplies and for the majority of the urban commercial groundwater pumpage. Only a few miles east of its recharge area the southwestern flow system contains brackish and saline water. The rapid deterioration of the water quality in this system is possibly caused by the water flowing across formations that contain evaporite deposits. Some of the salinity could possibly be due to intermixing with saline waters discharging into the system from a continental flow system (van Everdingen 1968). Within the study area total dissolved solids values in the southwestern system range between 2000 and 10 000 mg/l. As a result of contamination from wells installed into the sandstone aquifers, the chloride ion values under north central Winnipeg are in excess of 500 mg/l (Fig. 16).

The groundwater temperature in the Upper Carbonate aquifer generally varies between 39 and 43 °F. At some sites within the urban drawdown cone the temperatures range up to 50 °F. Available bacterial data indicate the aquifer water usually is pure.

Vertical and River Recharge

In addition to the regional lateral flow systems there are local vertical flow regimes within the overburden that move water stored in the

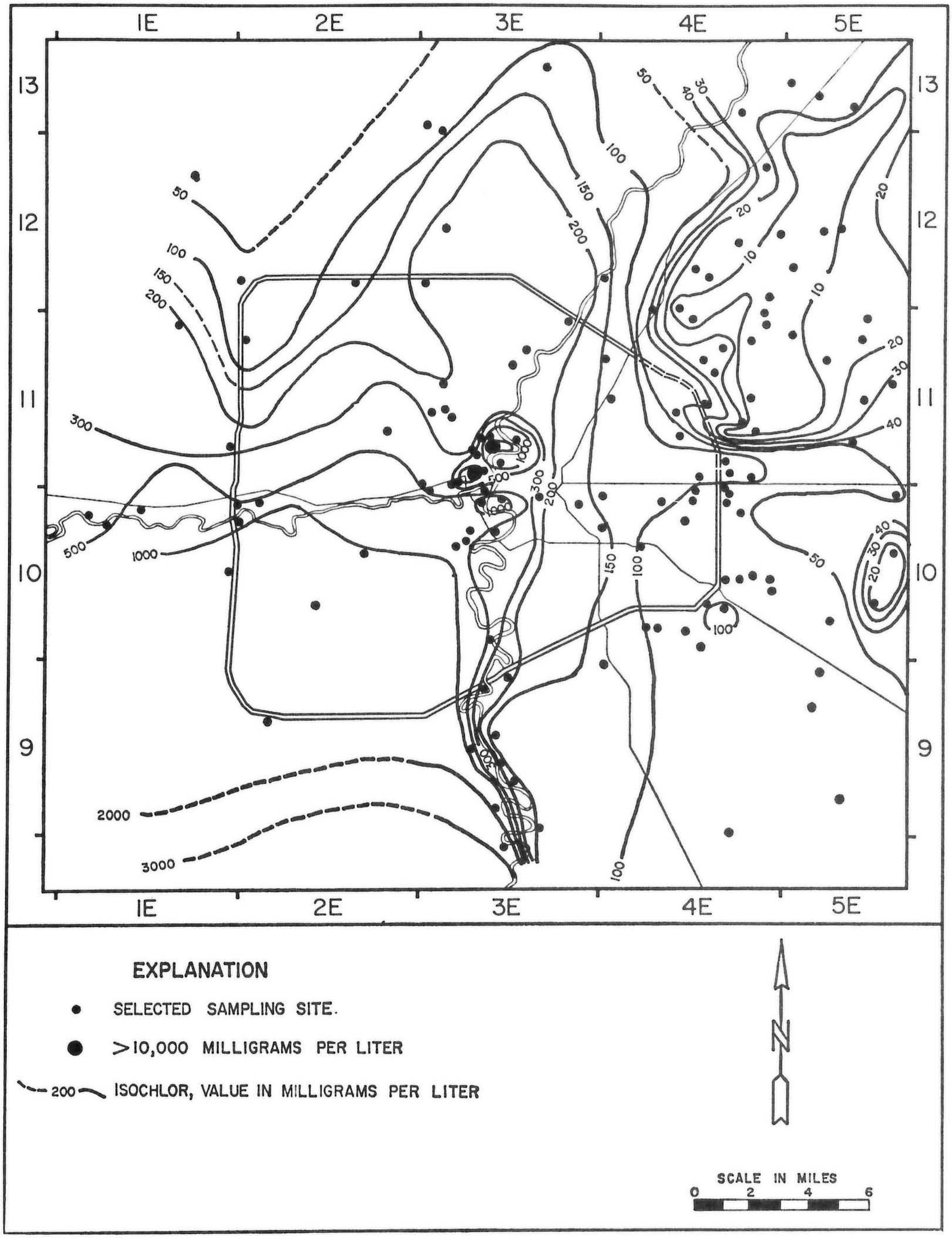

FIG. 16. Upper carbonate aquifer chloride ion concentrations.

Upper Agassiz unit down to the Upper Carbonate aquifer (Fig. 12). Because of the permeability of the Lower Agassiz unit the contributions to the water in the Upper Carbonate aquifer are negligible, probably less than 1% of the summer pumpage.

Where the Upper Carbonate aquifer piezometric surface is depressed below the water levels in the Red River in central Winnipeg (Fig. 9) there is a gradient from the river towards the aquifer. An analogue model study of the effect of floodway groundwater discharge on the piezometric surface of the Upper Carbonate aquifer indicated that the river is at least partially connected with the aquifer (Hobson *et al.* 1964). The analogue incorporated the assumption that the Red River constituted a hydraulic boundary of the aquifer. The assumption was generally verified by the close relationship, in the areas adjacent to the river, of the predicted and observed floodway drawdown cones. The potential difference between the river and the aquifer is greatest during the spring flood period and the summer air conditioning pumpage interval. Within the central Winnipeg area, the quantitative contribution of this flow system appears to be significant.

Groundwater Flow in the Birds Hill Aquifer

The saturated sections of the Birds Hill sand and gravel deposits form an aquifer that is up to 150 ft (45 m) thick. The water table in the aquifer is at higher elevations than the piezometric surface of the Upper Carbonate aquifer (Fig. 12). Thus water moves down to recharge the underlying Upper Carbonate aquifer. The groundwater flows radially out from under the hill with the major flow direction being southwest into the urban drawdown cone. The exposed sand and gravel form excellent water intake areas and as a result of the short contact time with the aquifer materials and the continuous downward movement of fresh water, the water in the aquifer has, as indicated by the isochlors on Fig. 16, a low salinity.

Lower Carbonate Aquifer Flow Systems

Though it possibly receives some downward percolation through the overlying slightly pervious carbonate rock, the Lower Carbonate aquifer is primarily recharged where it subcrops east of Winnipeg under the glacial till (Fig. 9). The direction of groundwater flow appears to be westerly along the top of the upper shale unit of the Winnipeg formation. In the urban area some of the water in the aquifer is discharged through deep wells that penetrate to the top of the Winnipeg formation. The natural discharge area for the aquifer is not known. However, it is possible that vertical discharge occurs through the overlying carbonate rock and glacial drift into the Red River. Chemical tests obtained at three widely separated sites indicate that this aquifer has a significantly higher salinity than the overlying Upper Carbonate aquifer.

Groundwater Movement in the Sandstone Aquifers

The sandstone aquifers are recharged east of Winnipeg where they subcrop under the glacial deposits. The hydraulic gradient is westward towards the Red River Valley. Near the eastern edge of the Agassiz plain the geodetic elevation of the sandstone aquifer piezometric surface is at approximately 890 ft (270 m), while in central Winnipeg the piezometric elevation ranges between 740 and 745 ft (225 and 227 m). The lower values occur under the central section of the drawdown cone in the Upper Carbonate aquifer. The groundwater flows down the dip of the beds at least as far as the center of the Red River Basin. The areas of natural discharge have not been determined. The down dip phasing out of the Upper Sandstone aquifer into shale severely restricts flow in this aquifer. While the Lower Sandstone aquifer thickens down dip the flow in it has not been evaluated.

Artificial discharge from the sandstone aquifers occurs in southeastern Manitoba where the water in the aquifers is fresh. In metropolitan Winnipeg, where approximately six wells have been drilled through to the Precambrian rock, water in these aquifers has total dissolved solids between 30 000 and 80 000 mg/l. The water is generally unsuitable for most industrial and commercial purposes and at present none of the wells are used for water supply.

As part of the study of the hydrogeologic conditions in metropolitan Winnipeg two observation wells were installed in the sandstone aquifers (Fig. 17). In the central area of the Upper Carbonate drawdown cone the hydrographs indicate that the piezometric elevations in the sandstone aquifers are twenty or more feet above the piezometric surface of the Upper Carbonate aquifer. This hydraulic gradient induces saline water from the sandstone aquifers into the carbonate aquifer through open bore holes and abandoned wells. A further indication of the connection between the car-

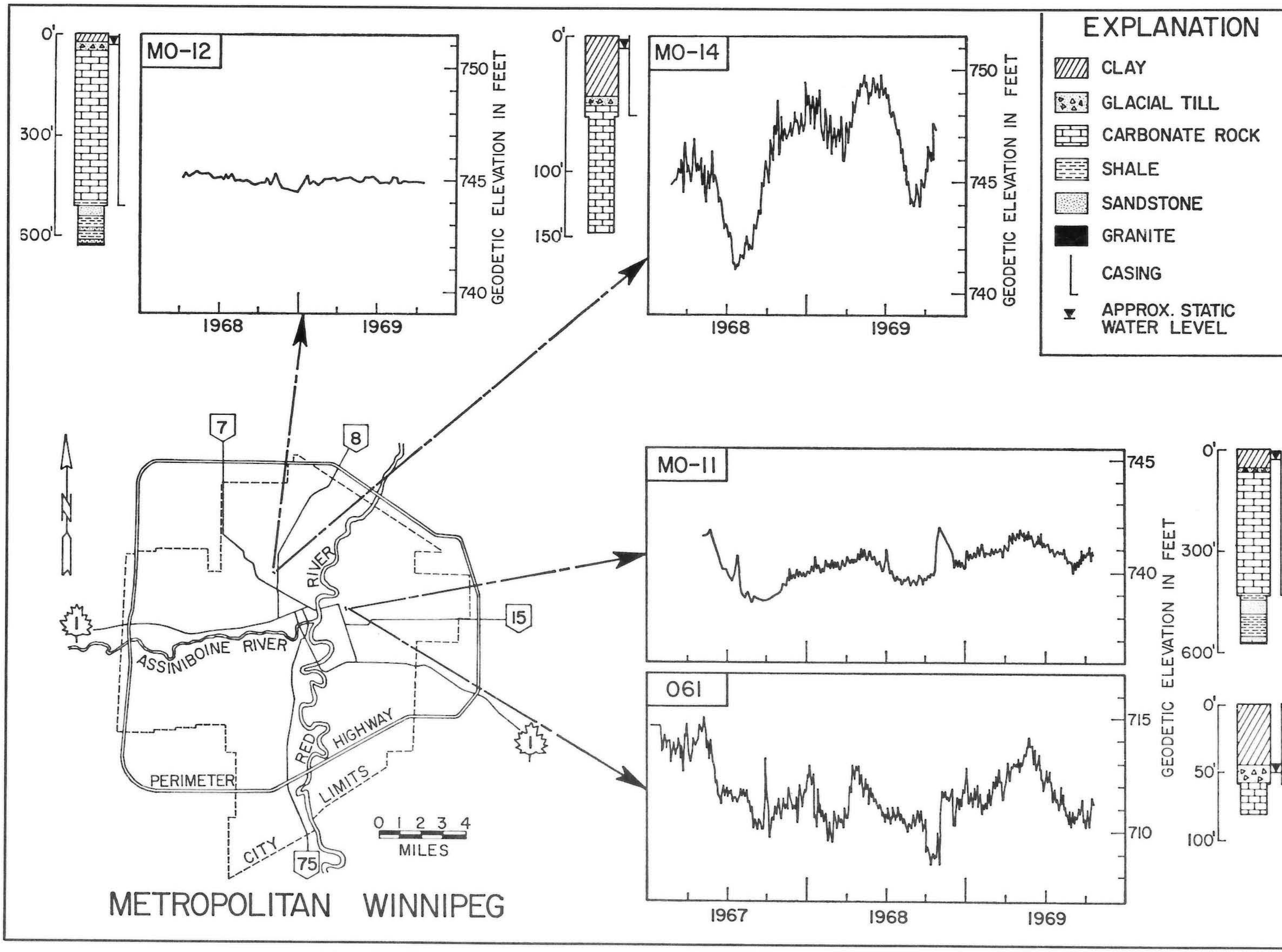

FIG. 17. Comparison of upper carbonate and sandstone aquifer water levels.

bonate and sandstone aquifers in this area is the correlation in the trend of water level fluctuation in the two aquifers (Hydrographs MO-11 and 061, Fig. 17). Conversely, in the northwestern section of the drawdown cone, where no wells have been installed in the sandstone, there is no relationship between the Upper Carbonate and Sandstone aquifer piezometric surface fluctuations. The salinity contamination that has resulted in north central Winnipeg is shown on Fig. 16.

Groundwater Development

During the early development of Winnipeg, the Upper Carbonate aquifer was an important source of municipal and industrial water. From 1900 to 1919 pumpage from the aquifer fulfilled the water requirements of the first city-owned water system. The 1969 estimated annual pumpage of 3 billion gallons (13.6 billion l)/year (Fig. 3) is approximately seventeen percent of the total annual consumption for the metropolitan Winnipeg area. Because of its constant low temperature groundwater is mainly used for commercial and industrial cooling. However, groundwater is also used for irrigation and domestic water supplies. Presently, the groundwater withdrawals in Winnipeg vary from 5×10^6 gallons (22.7×10^6 l)/day in the winter to 10^7 (4.5×10^7 l) gallons during the summer when the air conditioning demand is at a maximum (Fig. 18).

Phase One

The first settlers drew their water from the rivers, however as the settlement moved back from the river, water from individual and community wells was delivered by horse drawn wagons. In 1880 the Winnipeg Water Works Company was enfranchised for a period of 20 y and began operations in 1882 drawing from the Assiniboine River at Armstrong's Point. During the 1800's flowing wells were present in northwest Winnipeg (Johnson 1934) and it is estimated that from 1882 to 1900 the groundwater withdrawal rate was 10^6 gallons (4.5×10^6 l)/day (Fig. 3).

In 1889 the city of Winnipeg purchased the Winnipeg Water Works Company and in October 1900 converted the system from the polluted and sediment laden Assiniboine River water to groundwater from the Upper Carbonate aquifer. From 1890 to 1914 the city of Winnipeg examined as alternate water sources, the Red, Assiniboine and Winnipeg Rivers, the Upper Carbonate aquifer and the Lake of the Woods which was chosen as the supply for the aqueduct system. Immediately prior to completion of the Greater Winnipeg Aqueduct in 1919, a field of 29 wells extending from northwest Winnipeg 10 miles (16 km) north at one-half mile (0.8 km) intervals, to Stony Mountain, Manitoba (Fig. 2) produced 10^7 gallons (4.5×10^7 l)/day. These wells had capacities up to 500 gallons (2270 l)/min and ranged in depth from 85 to 300 ft (26 to 91 m) and in diameter from 1.5 to 15 ft (0.5 to 4.5 m). By 1919, as a result of the municipal pumping, water levels in northwest Winnipeg had declined to approximately 40 ft (12 m) below ground level. During this same interval St. Boniface obtained water from a field of six wells located in the north central part of the city. While some of the original city wells are still maintained for emergency purposes, major groundwater withdrawals ceased following the completion of the aqueduct, and the piezometric surface of the Upper Carbonate aquifer recovered to its natural position close to the ground surface.

The groundwater system was abandoned primarily because of excessive natural hardness and sulfate and because groundwater technology had not become sophisticated enough to allow the long term yield of the aquifer to be predicted. In addition, the maintenance cost of the groundwater system was anticipated to be higher than that of the gravity flow aqueduct. Although groundwater was not satisfactory as a long term water supply, it played an important role by allowing the city to attain the size where financing of the aqueduct was feasible.

Phase Two

A second phase of groundwater development began in the 1920's when commercial centers of pumping were created in the central urban area, and also meat packing plants established high capacity wells in St. Boniface. A substantial drawdown cone developed primarily east of the Red River (Fig. 14) and well productivity decreased because of the decline in the piezometric surface. As the water levels in the St. Boniface area are much the same today as

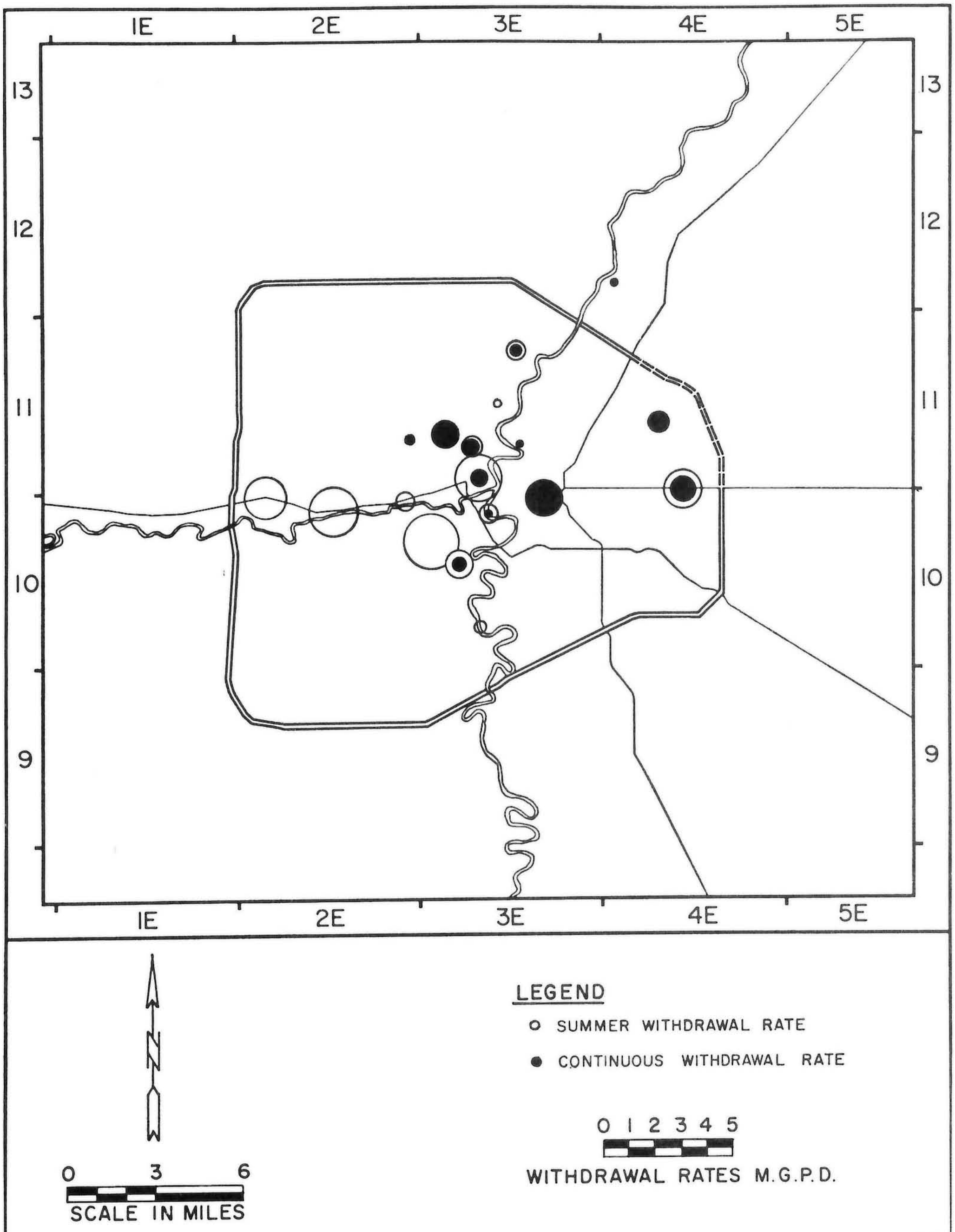

FIG. 18. Upper carbonate aquifer withdrawal rates—1969.

they were in 1947, the drawdown cone appears to have stabilized. In central Winnipeg, wells were installed by theatres and restaurants for air conditioning and by cold storage plants which required large quantities of cold water during their peak operating periods. Another feature of this phase of development was the institution of the groundwater sewage tax by the city of Winnipeg. This tax, which still exists, economically encourages the recharging of spent cooling water to the aquifer and between 1940 and 1960 eight recharge systems came into operation.

During the second phase of groundwater development at least four wells penetrated to the Precambrian. Where these wells were of poor capacity there was little contamination of the carbonate aquifers due to saline water discharge. Also, in areas such as northwest Winnipeg where the hydraulic heads in the aquifers are essentially identical (Hydrographs for wells MO-12 and MO-14, Fig. 17) relatively little damage was done. However, where these conditions did not prevail (Hydrographs for wells 061 and MO-11, Fig. 17) saline water flowed up into the fresh Upper Carbonate aquifer.

Phase Three

Since 1960 there has been an increase in apartment house and hotel construction. The consequent installation of high capacity wells for air conditioning, has constituted a third phase of groundwater development. Some of these units are supply–recharge well installations which eliminate the effluent sewage tax and conserve groundwater. These systems usually operate on a large volume of water which is raised a few degrees in temperature while passing through the cooling unit.

Systems that are adapted to the corrosiveness of the water allow the brackish groundwater that occurs south of the Assiniboine River to be used for cooling apartment buildings. The development of apartment building air conditioning has also created large summer pumpage centers in the suburban areas located along the Assiniboine River in the western sections of the city (Fig. 18). The air conditioning water demand places a short term high capacity stress on the system, as illustrated by representative hydrographs for the urban area (Fig. 15).

Of approximately 200 commercial and municipal wells that have been developed in the Winnipeg area, about 115 are still operating. The estimated annual pumping rates for the operating wells, which draw nearly exclusively from the upper carbonate aquifer, are presented in Fig. 3. In the central section of the area groundwater withdrawals combined with narrow well spacing have lowered the piezometric surface close to the main producing zones of the aquifer so that there is little remaining available drawdown. At some places during the summer period of heavy pumpage, the top of the aquifer is dewatered and the effective transmissibility is reduced.

Well Construction

The construction of most domestic wells consists of 4 in. (10 cm) diameter casing drilled into the top of the bedrock with an uncased shaft extending to the point where sufficient water is encountered. The depth of the domestic wells varies from 25 to 400 ft (7.5 to 120 m), with the average being between 100 and 150 ft (30 to 45 m). The similarly constructed commercial wells are usually of greater diameter and depth, often being extended to the top of the Winnipeg formation. Commercial well specific capacities range between 0.64 (0.095 l/min/cm) and 205 (30.6 l/min/cm) and average 15 (2.24 l/min/cm) gallons/min/ft of drawdown. In constructing a high capacity well the casing must be properly seated in solid rock so that the silt and rock floor in the lower sections of the glacial till does not enter the well. At the same time care must be exercised to ensure that the casing does not block off producing zones in the upper portion of the bedrock.

Groundwater and Construction

Geohydrologic Aspects of Construction in Metropolitan Winnipeg

Excessive discharge from the Upper Carbonate aquifer has frequently interfered with deep excavations in the Winnipeg area. Difficulties of this nature occurred during the construction of the Greater Winnipeg Aqueduct Branch 2 Tunnel (Fig. 2), in 1959 when groundwater flows of 500 gallons/min (2275 l/min) were intercepted in the carbonate rock.[4] The situation at this site contrasted with the conditions at the Aqueduct Branch 1 Tunnel where no significant groundwater discharge was reported (Chase 1920). The writer attributes the difference in groundwater discharge to the higher transmissibility of the aquifer at the Branch 2 site (Fig. 11) and to the fact that during the construction of the Branch 1 Tunnel in 1917 the municipal drawdown cone had

[4]R. C. Sommerville, personal communication, 1963.

lowered the discharge gradients in the aquifer. At the Branch 2 Tunnel site the glacial till, Agassiz deposits, and alluvium ranged in total thickness from 10 to 15 ft (3 to 4.5 m) under the river channel to 50 ft (15 m) beneath the river banks (Bubbis and Sommerville 1960). Groundwater discharge first interfered with construction when the east shaft intercepted the bedrock. Groundwater issuing from fractured rock in the tunnel wall caused the main construction difficulty. The grade line of the 8 ft (2.4 m) diameter tunnel was placed 20 to 25 ft (6 to 7.5 m) below the rock surface. The initial piezometric surface of the aquifer at this site was 45 ft (14 m) above the invert of the shaft. Chemical tests indicated that the water was derived from the aquifer system rather than from river seepage. Because the specifications called for the work to be done "in the dry," the groundwater discharge interfered with the placement of concrete. Remedial measures included a concrete skin wall placed along the fissured lower section of the tunnel and grouting behind this wall until the water was contained.

Groundwater flows from the Upper Carbonate aquifer have also created difficulties at several bridge and building foundation sites in the Winnipeg area. At the Letellier Overpass (Fig. 2) the occurrence of groundwater discharge into pile excavations necessitated a design revision from "poured in place" piles to driven concrete piles.[5] The construction of the river piers for the North Perimeter Highway Bridge involved hydraulic pressure from the Upper Carbonate aquifer which was a factor in maintaining and dewatering sheet pile cofferdams. The solution consisted of flooding the cofferdams, driving the steel H piles, cleaning the excavation to solid material with an air lift pump, and sealing the base of the cofferdam with a thick tremied concrete skin coat.

The pier excavations for the Trans Canada Highway Bridge across the Assiniboine River at the first crossing west of Winnipeg, which was constructed in a diversion channel, intercepted large flows of saline groundwater that discharged from fractures in the weathered bedrock surface.[6] Application of portland cement grout did not seal off the water. The difficulty was controlled by flooding the piers and tremieing a thick concrete skin coat. At the Bristol Aerospace Plant immediately east of Stony Mountain, Manitoba, groundwater discharge at rates up to 3000 gal/min (13 600 l/min) issued from fractures 1 to 3 in. (2.5 to 7.5 cm) wide in the bedrock at the base of a 20 ft (6 m) deep storage tank excavation. Pumps controlled the water while the installation was completed. The springs were then developed as a water supply system for the plant. Groundwater springs in "poured in place" pile borings are a common occurrence during the construction of large building foundations in the Winnipeg area. The occurrence and intensity of the groundwater discharge depends on the transmissibility and piezometric surface elevation of the Upper Carbonate aquifer, and the proximity of the bottom of the excavation to the aquifer.

Fluctuations of the water table in the fine grained deposits of the upper unit of the Agassiz sediments caused by variations in infiltration lead to cycles of shrinkage and swelling of the clay which adversely affect most housing foundations in the Winnipeg area. When saturated, the silt and fine sands in this unit hinder the construction of shallow excavations by impeding the movement of excavating equipment. The thickness of the Agassiz sediments, which restrict the vertical movement of liquid pollutants, is a significant factor in selecting sanitary land fill sites.

Geohydrologic Aspects of the Red River Floodway Project

The hydrogeology of the area was directly affected by and interfered with the excavation of the Red River Floodway channel (Figs. 2 and 19) which has a maximum depth of 60 ft (18 m) and an average depth of 30 ft (9 m). The top widths vary between 750 and 1000 ft (230 and 300 m). The installation also includes an inlet control structure, an outlet spillway, 13 bridges, 2 aqueduct crossings, and crossings for gas, oil, telephone, and electric power lines. The completed channel is now discharging one-half as much groundwater as is annually pumped from the Upper Carbonate aquifer in metropolitan Winnipeg. This discharge has lowered the piezometric surface of the Upper Carbonate aquifer over a 350 square mile (900

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[5]H. Cowley, personal communication, 1963.
[6]G. DePauw, personal communication 1969.

FIG. 19. Floodway outlet looking south towards the Birds Hill Ridge.

square km) area, with maximum water level reductions of 25 ft (7.6 m) occurring near the central reaches of the channel.

Preliminary Investigations

The first extensive detailed groundwater study in the Winnipeg area related to Floodway construction commenced during 1961. The investigation was initiated by the Floodway Division of the Manitoba Water Control and Conservation Branch after test excavation No. 1 (Fig. 2) exhibited hydraulic fracturing in the drift which allowed discharge from the Upper Carbonate aquifer. When the groundwater discharge occurred, the piezometric surface of the Upper Carbonate aquifer was 9 ft (3 m) below the ground surface and the bottom of the test excavation was at the depth of 25 ft (7.5 m). The excavation was completed to the planned depth of 45 ft (14 m) and the groundwater flows increased to approximately 150 gals/min (531 l/min). This discharge lowered the piezometric surface of the Upper Carbonate aquifer 10 ft (3 m) at a distance of 1000 ft (300 m), and the first of a project total of 377 complaints of adverse effects on domestic wells were received from nearby well owners.

The groundwater discharge naturally hindered the movement of rubber tired and tracked excavating equipment, and the lower 10 ft of the test excavation was completed by a dragline. Test drilling of the site prior to excavation had indicated that 60 ft (18 m) of clay and 10 to 15 ft (3 to 4.5 m) of till overlay the bedrock. Investigation since the completion of the channel indicates that over a small area south of the Test Pit excavation, the Agassiz sediments were only 35 ft (10.7 m) thick. A high point in the bedrock topography is likely associated with the thinning of the lacustrine deposits. This feature of the site was likely a contributing factor in the groundwater occurrence, and it is possible that groundwater flows would not have occurred at other nearby floodway sites. The groundwater occurrence at the test excavation laid the framework for the project hydrogeology program and for the contractors' assessment of the difficulties involved in excavating the floodway.

The comprehensive floodway hydrogeologic

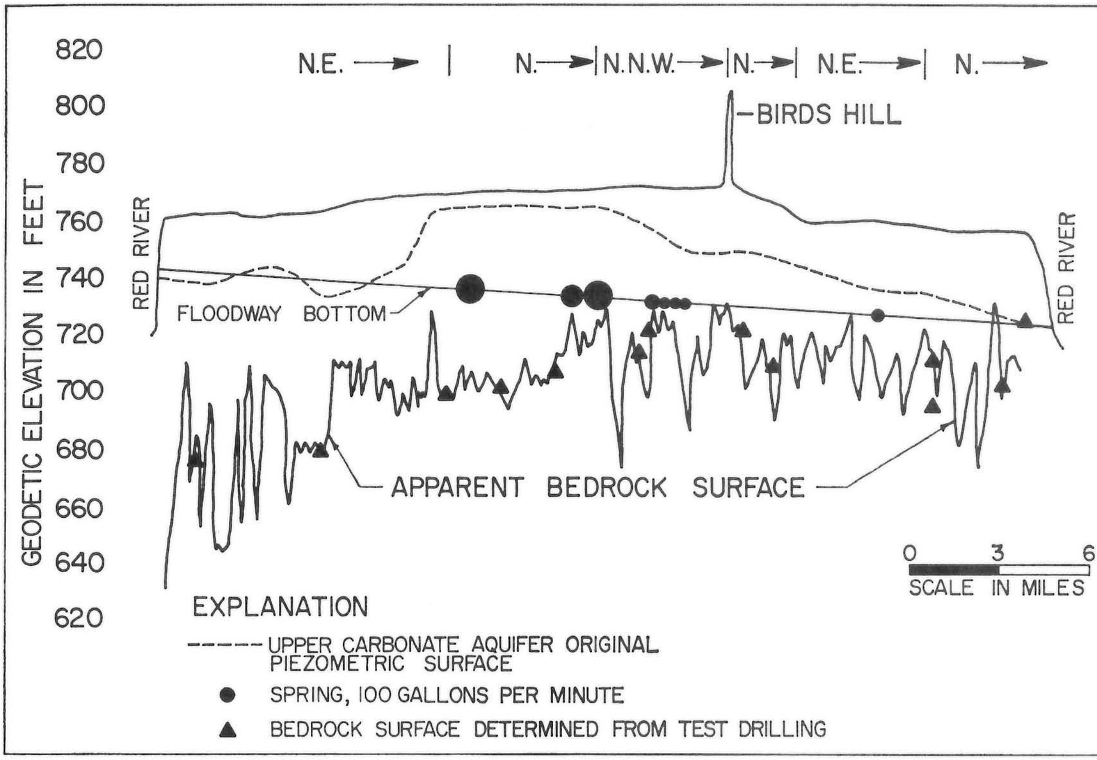

FIG. 20. Hammer seismic section along the floodway centerline.

investigation which followed the experience of Test Pit 1 was undertaken in an area that included the entire length of the floodway and extended laterally from the Red River to points 30 miles (48 km) east. Preliminary aspects of the investigation included: interpretation of aerial photographs, inventory of 3600 wells, test drilling, pumping tests, and the establishment of 200 groundwater observation wells. Following the completion of the preliminary hydrogeologic study a steady state electric analogue model of the groundwater regime was prepared (Hobson *et al.* 1964) using a conducting paper technique. The analogue was used to predict the post-floodway position of the Upper Carbonate aquifer piezometric surface and the magnitude of the floodway groundwater discharge. The predicted line source discharge of 4300 gallons (19 500 l)/min, compares favorably with the present discharge of 3000 gallons (13 600 l)/min. The magnitude of the drawdown of the piezometric surface indicated by the model was generally of the right order, and the predicted time to equilibrium of 400 days was at most places a reasonable approximation. The analogue predictions were valuable in assessing the probable effect of groundwater discharge on construction and Upper Carbonate aquifer piezometric levels.

A hammer seismic investigation conducted in 1962 (Hobson 1964) delineated the apparent bedrock surface along the floodway route and facilitated prediction of the engineering properties of excavation materials. When related to the elevation of the piezometric surface of the Upper Carbonate aquifer, this information aided in the prediction of groundwater discharge zones which were usually associated with apparent bedrock highs (Fig. 20). The hydrogeologic information obtained in these investigations was made available to the prospective contractors in the form of interpretive reports.

Channel Excavation

Groundwater discharge from the Upper Carbonate aquifer had the greatest effect on the excavation of the portion of the floodway between the Trans-Canada Highway and the Birds Hill Ridge (Fig. 2). In this reach the pre-construction elevation of the aquifer piezometric surface ranged 20 to 30 ft (6 to 9 m) above the floodway bottom (Fig. 20) or 10 to 20 ft (3 to 6 m) below ground level. In the central part of this reach the apparent bedrock surface was in close proximity to the channel grade. Groundwater discharge commenced when the channel grade attained 20 to 30 ft (6 to 9 m) below ground surface. The groundwater seepage issued from fractures in both the clay and till. Preferential flow channels evolved and the fracture discharge then became concentrated. During the early stages of excavation discharge from individual springs was frequently in excess of 200 gallons (900 l)/min. In the vicinity of the C.P.R. Keewatin Bridge (Fig. 2), groundwater discharge had the greatest effect on excavation and in some areas the discharges exceeded 1 gallon/minute/lineal ft (15 l/min/m) of channel. In this area draglines had to be used to complete the lower sections of the excavation and final trimming was conducted under frozen conditions.

Before excavation started north of Birds Hill Ridge, the upper till was characterized by upward hydraulic head gradients. Piezometer levels up to 5 ft (1.5 m) above ground surface were observed at several locations. Excavation was interrupted when machines broke through the bottom 2 to 3 ft (0.6 to 1 m) of Agassiz clay into the soft till, often necessitating the use of draglines. Fortunately Test Excavation No. 2 forewarned the contractors of this difficulty.

It was anticipated that the most severe excavation difficulties would occur in the Birds Hill Ridge area. Where observed in gravel quarries adjacent to the excavation, the water table in the Birds Hill surficial aquifer was 20 ft (6 m) above the floodway grade. Initial large groundwater flows occurred in response to the increased hydraulic gradient induced by the excavation. The groundwater flow was greatly reduced when the quarries that extended through the core of the aquifer were backfilled with clay and till. The final groundwater discharge after the excavation was extended through the 1500 ft (450 m) wide ridge was of the same order of magnitude as the 300 gallon (1360 l)/min pre-floodway flow through the aquifer. Awareness by the contractor and the construction engineers of this hydrogeologic situation enabled excavation to proceed unhindered. Preventative measures consisted of the early establishment and maintenance of drainage.

Structures

Severe groundwater problems were encountered during construction of three bridges in the area south of Birds Hill Ridge. For example, at the site of the C.P.R. Keewatin Bridge discharge into the pier excavations attained values of 1800 gallons (8200 l)/min. The discharge was accompanied by continual slumping of excavation walls (Fig. 21). At this site the Agassiz deposits were approximately 40 ft (12 m) thick, with till extending down to the bedrock at 60 to 65 ft (18 to 20 m). The piezometric surface of the Upper Carbonate aquifer was initially 35 ft (10 m) above the central pier bases. The hydraulic gradient either ruptured the bottom of the pier excavations, or the groundwater discharge occurred around H piles driven to the bedrock. Following completion of the structure consolidation grouting terminated the groundwater discharge and stabilized the pier foundation conditions.

An extensive pre-construction exploratory program was undertaken at the inlet control structure (Fig. 2). This investigation consisted of test drilling of the drift and bedrock, pumping tests, and observation well installation. The four geologic units at the site were alluvium, lacustrine clay, till, and carbonate bedrock (Fig. 22). The clay thickness varied from 10 ft (3 m) under the river to approximately 40 ft (12 m) beneath the river banks. The till was 10 to 25 ft (3 to 7.5 m) thick. Under the centerline of the structure 5 to 15 ft (1.5 to 4.5 m) of sand and gravel occurred beneath the till. The structure excavation extended 15 ft (4.5 m) into the bedrock. The preconstruction elevation of the Upper Carbonate aquifer piezometric surface was approximately 60 ft (18 m) above the base of the structure excavation. A 4200 ft (1280 m) grout perimeter reduced the potential regional drawdown by 50% and enabled uplift pressure to be relieved by well pumping. The construction of the curtain required 89 900 ft (27 400 m) of drilling and the injection of 92 800 ft^3 (2630 m^3)

FIG. 21. Pier excavation at the C.P.R. Keewatin Bridge.

of solids (H. G. Acres & Company 1965). Pumping from dewatering wells in the Upper Carbonate aquifer served to lower the piezometric surface to the top of the sand and gravel. Dewatering of these materials was accomplished by an inner ring of well points. When conditions permitted, a portion of the groundwater was returned to the aquifer system by the means of a recharge well. The groundwater control system had the effect of limiting the area over which domestic wells were adversely affected.

Benefits of Geohydrologic Investigations

Channel contractors were able to observe test excavations and were provided with interpretive hydrogeological reports. This enabled bids to be made without resorting to contingency items which would have increased the tendered yardage prices. Tendered prices depended on many factors and the direct cost saving of the hydrogeology investigation is difficult to assess. The hydrogeologic conditions anticipated were certainly one of the main tendering parameters. This was particularly true of the 60 ft (18 m) deep cut through the Birds Hill Ridge. The accepted contractor thoroughly reviewed the hydrogeologic conditions, made a fair and profitable bid and completed the excavation with a minimum of difficulty. Accepted bid prices, as compared to the preconstruction estimated price of 33¢, averaged 29.5¢, and ranged from 18 to 41¢ per yd^3. That the lowest yardage prices were bid on areas where the predicted groundwater difficulties were minimal is a further indication of the value of the pre-tender information. The knowledge of the probable groundwater effects in the contract areas influenced the sequencing of the contracting, and the placement of drainage controls between the individual contracts. The control of drainage was particularly important where groundwater discharge filled a completed excavation while the adjacent areas were still under construction. The groundwater difficulties that occurred at the bridge sites were fore-

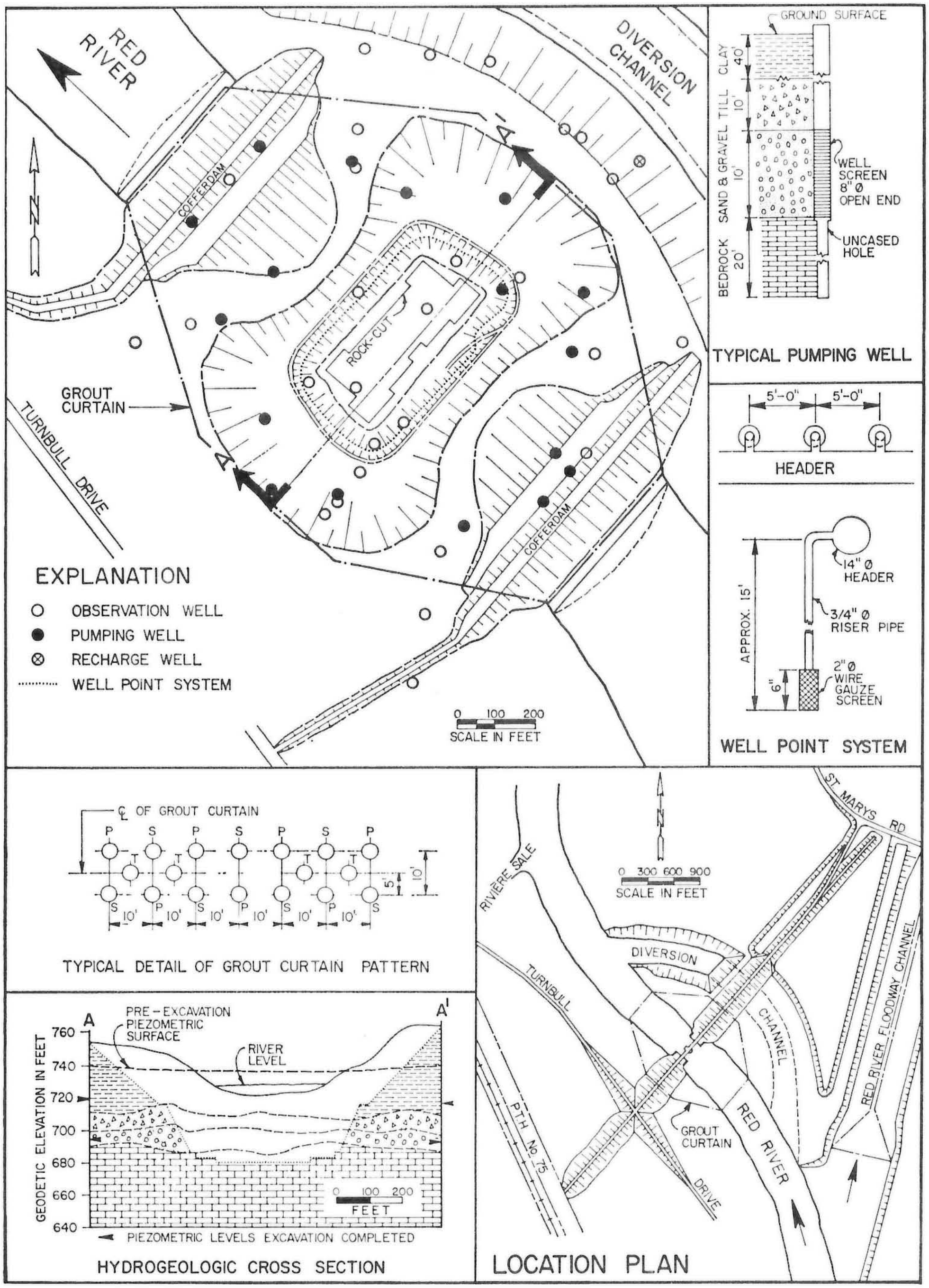

FIG. 22. Red River Floodway Inlet control structure dewatering system.

cast prior to the tenders being advertized and therefore no compensation for changed conditions was considered when groundwater interfered with the progress of the work.

Understanding of the groundwater conditions at the inlet structure site prior to design and construction prevented unanticipated difficulties. The contractors for this structure were provided with displays of the geology and interpretative hydrogeology reports. The contract documents were oriented towards facilitating the management of potential hydrogeologic difficulties.

A quantitative evaluation of the cost benefit of the geohydrology program is not feasible because of the complexity of the floodway project and because major geotechnical difficulties were anticipated. The overall value of the program is evidenced by the fact that claims for unforseen conditions related to groundwater conditions were eliminated.

Summary and Conclusions

The Upper Carbonate aquifer, which acts primarily as a groundwater transmission zone, contributes an estimated 17% of the annual water supply in the metropolitan Winnipeg area, and will be an increasingly important source of commercial water. The summer rate of groundwater pumpage for cooling is gradually increasing; however, the present rates do not appear to be causing more than a seasonal lowering of the piezometric surface of the Upper Carbonate aquifer. The mantle of glacial drift confining this aquifer is a deterrence to pollution from surface sources in most localities in the urban area. It appears that wells and excavations are the most likely mechanisms by which pollution can occur. Similarly, the upper shale unit of the Winnipeg formation prevents natural influx of saline water from the Upper Sandstone aquifer. However, salinity contamination caused by open well bores has been detected in north central Winnipeg. This study supports the concept that local detailed assessment of the major aquifers within a groundwater basin requires cognizance of the characteristics of the basin-wide groundwater system.

Groundwater discharge has interfered with foundation installations in the urban area. During excavation of the Red River Floodway and appurtenant structure excavations, induced groundwater discharge hindered the progress of the excavation, and drew down the piezometric surface of the Upper Carbonate aquifer over an extensive area, thus interferring with domestic groundwater supplies. Within one year following completion of the channel excavation the groundwater system attained a new equilibrium position. The preliminary investigation of the geohydrology was a significant factor in coping with difficulties, reducing yardage prices, and eliminating claims for unforeseen conditions. The steady-state analogue model yielded reasonable predictions of discharge, piezometric surface drawdown, and aquifer response time. The hammer seismic investigation aided in the prediction of many locations of groundwater discharge and provided additional information on the engineering properties of the excavation material. The groundwater regime, as it relates to the engineering properties of earth materials and induced groundwater discharge, will continue to be a major factor during excavation and construction in the Red River Basin. Particularly important is the relationship between aquifer piezometric levels and pore pressures in overlying materials. In this area, a geohydrologic investigation should be an integral part of the preliminary geotechnical investigations for every major construction project.

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Mr. T. E. Weber, Director, Water Control and Conservation Branch, Department of Mines and Natural Resources, Province of Manitoba.

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