INLAND WATERS BRANCH

DEPARTMENT OF ENERGY, MINES AND RESOURCES

Hydrochemical Interpretation of Groundwater Movement in the Red River Valley, Manitoba

J. E. CHARRON

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Abstract

A hydrogeological study of the Red River Valley has been in progress for five years. The hydrochemical approach used in this report is based on the field data accumulated during the study. This is primarily a study of groundwater movement. It demonstrates that the chemistry of the groundwater (hydrochemistry or geochemistry), when applied in conjunction with the geology is an important tool for the hydrogeologist seeking the direction of groundwater movement on a local and regional basis or within an entire drainage basin. Groundwater flow is illustrated by means of semi-logarithmic diagrams, cross-sections, maps, figures, and tables.

The report emphasizes many points that are characteristic of any groundwater body:

1) Most groundwater is saturated or near saturated in $CaCO_3$.
2) Most groundwater is not saturated in $CaSO_4$.
3) The absolute chloride value is the most important indicator of the degree of sluggishness of a body of groundwater.
4) From recharge to discharge the groundwater tends to become more acidic.
5) In a continuous groundwater flow, a change from a positive base exchange index to a negative base exchange index can indicate a reversal of groundwater flow.
6) In unconfined aquifers, groundwater movement is controlled mainly by topography.
7) In confined aquifers, the direction of groundwater movement can be determined from the hydrochemistry of the groundwater.
8) The recharge area for a body of groundwater is often nearby.
9) A flowing artesian zone undermines itself.
10) A salt-water zone may advance at the expense of a fresh-water zone until a new equilibrium is reached.
11) Time is the most important factor in bringing about the hydrochemical changes.

Finally, in a study of this kind there is always the possibility that an understanding of groundwater movement may lead to interesting new mineral discoveries.

Résumé

Une étude hydro-géologique de la vallée de la rivière Rouge, au Manitoba est en marche depuis déjà cinq ans. La méthode hydrochimique dont on préconise l'usage, dans ce rapport, provient des données accumulées au cours des cinq années d'étude. Ce rapport établit tout particulièrement la direction d'écoulement des eaux souterraines. Le rapport démontre que si l'on applique la chimie des eaux souterraines (hydrochimie ou géochimie) en conjonction avec la géologie, ceci ouvre de nouveaux horizons très importants pour l'hydrogéologue qui cherche à établir la direction d'écoulement des eaux souterraines dans les différentes nappes aquifères, soient-elles locales, régionales ou sur toute l'étendue d'un grand bassin fluvial. La direction d'écoulement des eaux souterraines de la vallée de la rivière Rouge est bel et bien illustrée par des diagrammes semi-logarithmiques, des coupes transversales, cartes, figures et par des tables.

Ce rapport dénote plusieurs caractéristiques que l'on pourrait dire être communes à la généralité des bassins aquifères.

1) Dans la majorité des cas l'eau est saturée de $CaCO_3$.
2) Dans la majorité des cas l'eau est non-saturée de $CaSO_4$.
3) La teneur absolue en Cl est le plus important indicateur de la lenteur d'écoulement d'une nappe d'eaux souterraines.
4) D'amont en aval l'eau souterraine tend à devenir acide.
5) Lorsque l'ecoulement continu d'une nappe est établi, un indice d'échange de base positif pour un indice d'échange de base négatif peut signifier un renversement de la direction d'écoulement.
6) Dans les nappes aquifères libres le mouvement des eaux souterraines est dirigé par la topographie.
7) Dans les nappes aquifères captives la direction d'écoulement des eaux souterraines peut être démontrée par l'hydrochimie de ces eaux.
8) La zone d'alimentation d'une nappe aquifère est généralement plus près que l'on pense.
9) Une zone artésienne se fouille d'elle-même.
10) Il existe entre une nappe d'eau douce et une nappe d'eau salée une relation qui entraine un nouvel équilibre, dû à l'avance du front salé.
11) Le rôle du temps en hydrochimie est considérable.

Dans une étude de ce genre il y a aussi toujours la possibilité que le fait de connaitre la direction d'écoulement des eaux souterraines, peut conduire vers de nouvelles découvertes minières très intéressantes.

CHAPTER 1

Introduction

This report of groundwater movement in the Red River Valley, Manitoba, is based on the writer's hydrogeological studies during the period 1959 to 1963. Much of the data collected during this five-year period, together with preliminary conclusions and interpretations, has already been published (Charron, 1961, 1962, 1964 a, b, 1965 a, b).

In the report, the writer has collected the main data in the form of semi-logarithmic diagrams, cross-sections, maps, and tables, and discusses their significance in terms of the groundwater movement in the Red River Valley. He has also endeavoured to show the applicability of hydrochemistry in following the flow of groundwater in aquifers, and to demonstrate that the chemistry of groundwater (hydrochemistry or geochemistry) is an important tool for the hydrogeologist seeking to discern the direction of groundwater movement on a local and regional basis or within an entire drainage basin. It is hoped that the report will create more interest in the use of hydrochemistry in hydrogeology.

LOCATION

The area is part of the Red River basin in southern Manitoba and is approximately 6,900 square miles in extent, covering the entire map-area 62 H of the NTS system. The limits of the area studied are: in the west, range 5 W (inclusive); in the east, range 11 E (inclusive); in the north, township 12 (inclusive); and the International Boundary to the south (Map 1).

PHYSIOGRAPHY AND GEOLOGY

The Red River Valley, Manitoba, is situated at the extreme southeastern end of the western plains, where it lies below what is commonly known as the first prairie step. It is characterized by a broad, flat expanse of terrain consisting mostly of lacustrine clay and till (Fig. 1). The clay is a homogeneous deposit that contains very few pebbles and it can vary in thickness from a few feet to more than 150 feet. The till was deposited principally as ground moraine and, like the clay, it can vary in thickness from a few feet to more than 240 feet. Underneath these unconsolidated surficial deposits are found the shales, dolomites, limestones and sandstones that make up the western plains sedimentary rocks (Fig. 2). The average 12° dip of these rocks is generally southwestward. In turn they lie unconformably on the Precambrian basement (Fig. 2).

At its lowest elevation, about 715 feet above mean sea-level, The Red River Valley is the lowest area of that part of the western plains. Therefore theoretically, it should be an area of discharge for waters of the western plains; such is indeed the case for the surficial water, but not for all groundwater. This study of groundwater movement can be better understood if a picture of the entire area can be visualized emphasizing the following three points.

First, the area studied is only part of a large hydrological basin (Red River drainage basin). As a matter of fact the area studied is only part of a large valley. It is a slice of the Red River Valley, 96 miles from east to west and 72 miles from north to south, but this is believed to be sufficiently large to show a true cross-section of the entire valley. Actually the only part of the area studied that is not completely known from north to south is the west side, where the western limits of the valley are mostly out of the area studied except in the extreme southwestern corner. Therefore the understanding of the west side of the valley in the area studied should not be as clear or complete as in the remainder of the area described in this report.

Secondly, the area studied should be seen as a broad and flat valley with a maximum relief of 650 feet between the highest and lowest points. Of great importance especially is the west-central part, comprising more than 3,400 square miles of extremely flat, thick lacustrine clay which, for purposes of this study, is considered uniformly impermeable throughout its entire extent. This means that groundwater recharge within this map-area has to occur in the east and north and on the western margin of the area (Fig. 1).

Thirdly, this area covers a part of the eastern margin of the sedimentary rocks of the western plains, unconformably overlying the Precambrian rocks of the Cambrian Shield. This is extremely important because various geological zones and lithological units will affect the chemical composition of the groundwater flowing through them. The fact that the area is located at the beginning of these rock formations should simplify the chemical composition of the groundwater, as the mixture and chemical changes of the groundwater should be at a minimum. Also, the fact that the structural geology of these sedimentary rocks (Fig. 2) is fairly simple means that the chemical composition of the groundwater should be truly a reflection of the sediments or rocks through which the groundwater flows.

These three points together facilitate the application and interpretation of the ideas presented in this report.

Water Infiltration

Figure 1 is called an infiltration map instead of a surficial geology map to emphasize the groundwater aspect of this study. This map clearly brings out three facts: 1) it shows how little bedrock outcrops within the area; 2) it emphasizes the extent of the clay and till plains; and 3) it illustrates how little of the entire area can actually constitute an area of recharge.

Bedrock exposures are so limited (they collectively occupy less than half a square mile) that for the purposes of this study, they can be considered as non-existent. Bedrock aquifers, however, are more important than the other types of aquifers in the area; they occur as confined aquifers underneath the clay and till mantle. Figure 2 gives a complete picture of the bedrock configuration underneath the clay and till mantle.

The clayey surface (outlined on Fig. 1) is considered to be homogeneous throughout and impermeable. Its total area is 3,400 square miles, or approximately 49 per cent of the entire study-area.

Unconfined aquifers are present in the other half of the area studied, where they provide an important source of water for individual farms and homes, but they are too local and too shallow to influence the regional groundwater picture significantly. Because of this, the writer concentrated his hydrochemical studies of the groundwater on the confined aquifers.

The till surface (ground moraine) comprising in all some 2,351 square miles, mainly in the eastern half of the area, is here considered to be semi-permeable. Its effect on recharge of the aquifers below it could be considered as long-term and indirect. Bogs and marshes cover about 600 square miles of the till plain in the eastern half of the area. The water from these bogs and marshes slowly seeps downward in the till and this is the long-term recharge referred to above. Because the process is slow, it is also constant or continuous. The flow of the groundwater within the till should be predominantly downward, as has been suggested by Meyboom (1962). This vertical movement can be explained by low relief and extremely slow groundwater movement, thus establishing gravity as the predominant force.

Only 17 per cent of the total area studied can be considered as truly permeable. Of this 17 per cent, only the gravelly areas and some parts of the sandy zones are known to recharge the confined aquifers directly. Good examples of recharge areas are the area of gravel known as Birds Hill, and the large sandy area of Sandilands Forest Reserve. Many ridges of sand and gravel are also shown on Figure 1, but they have not been differentiated into sandbars, eskers, drumlins, beaches, etc. Where the sand or gravel is of considerable thickness, the movement of the groundwater in it, as compared to that in the till, should be horizontal and even upwards in some cases, depending on the head relationships, in agreement with Meyboom (1962).

Thus, only a very small part of the entire map-area can be truly defined as an area of recharge. Even the largest of these areas of coarse sand, which is a part of Sandilands Forest Reserve, is not all it would seem to be at first glance. The coarse sands of this reserve were originally thought to be entirely a direct recharge area for the confined bedrock aquifers, but this line of thought is now changed. Only in rare instances does direct recharge occur and then only where the sand has great depth. One such area may exist in 6–2–11 E, where a drill-hole yielded about 150 feet of sand and gravel; another similar zone could possibly be located southeast of Marchand, Manitoba, although no drill-hole data are available to prove it. But in general, the sand of this area is only surface cover overlying the semi-permeable till. Because of this, recharge is available only to unconfined aquifers (at the water-table level) and the groundwater flow is controlled by the topography of the land. This control can be either local or regional or both. The bogs and marshes surrounding the highlands are indicative of the groundwater flow in that region. The groundwater flows down the highlands through the top or surface layers of sand until it encounters the semi-permeable till at the foot of the highlands. Because the permeability of the till is less than that of the sand, it cannot absorb all the groundwater. The groundwater which is not absorbed is brought to the surface (because of a head difference at the source), where it forms bogs and marshes on top of the till. Airphoto mosaics demonstrate this very clearly.

Similarly, the sandy sediments on the western margin of the map, those of the large silty area in the southwest and of the small one in the north, as well as the silty sand meanders found in the floodplain of the Assiniboine River, are all lying above the lacustrine clay sediments and help to recharge only the unconfined or water-table aquifers.

CLIMATE

The climate of the area is continental. The average annual precipitation over the entire area is 20 inches, of which 1.6 inches has been calculated as runoff feeding the rivers of the area (Water Atlas of the U.S.A., 1963). The remaining 18.4 inches is returned to the atmosphere through evapo-transpiration, or infiltrates the ground as groundwater. Exact figures are not available, but from what has already been said on infiltration, it is probable that less than 0.4 inches eventually enters the ground to become groundwater.

GROUNDWATER SAMPLING

Standard groundwater sampling procedures (Thomas, 1953) were employed throughout the study, and the samples taken in the field are believed to be representative of both the region and the aquifer from which the groundwater came. In the writer's experience, a sample of groundwater obtained from a flowing well is generally better than samples obtained from wells which have to be pumped. Almost without exception, the analysis of a sample derived from a flowing well fitted the chemical picture easily and could be interpreted clearly, whereas analyses of samples obtained from artificially-pumped wells had to be scrutinized deeply before they could be fitted into the picture; in some instances they remain ambiguous. There are two important reasons why a groundwater sample from a flowing well is more representative of the rock formation it comes from than samples from pumped wells. These are: 1) the flow of the well is related to the natural pressure of the groundwater in the aquifer from which it originates; therefore, it should not appreciably affect the pressure in the aquifer (a change in pressure affects the free CO_2 in the water); 2) there is a better chance that the sample will yield a homogeneous representative analysis, the chemical composition of which will be truly expressive of the aquifer through which it flowed. This is mainly due to the steady continuous flow which is characteristic of flowing wells. The water from a pumped well, on the other hand, may have been in the casing for a considerable period of time, and even though the well is pumped for a long time before taking the sample, the natural phenomenon is never quite achieved.

There is nothing to indicate that the accumulation of a large number of samples is necessarily of particular value; frequently, too many analyses tend to confuse rather than clarify. The objective should be quality rather than quantity, and quality in this context should be taken to mean that the sample is representative of many wells in a particular region and that the analysis will yield reliable information.

CHAPTER 2

The Presentation of Chemical Analyses of Groundwater Samples

To interpret and correlate the analyses of some 162 groundwater samples collected within the area, the writer has used, during the course of the study, three different methods of presentation. These are: 1) the Stiff diagram (Stiff, 1951); 2) the Palmer-Piper geochemical diagram (Palmer, 1911; Piper, 1944); and 3) the semi-logarithmic diagram by Schoeller (Schoeller, 1962).

The Stiff diagram, which is easy to use, is particularly helpful in correlating or comparing various groundwater analyses, especially the analyses of samples obtained from unconfined aquifers. In general, the chemical composition of groundwater derived from unconfined aquifers is unstable and variable, whereas the chemical composition of the water at greater depths in confined aquifers is more uniform because it has had more time to become established. Nevertheless, even at this variable stage of the groundwater, correlation by the Stiff method will give surprisingly good results.

The Palmer-Piper geochemical diagram has the advantage that a large number of analyses can be classified quickly on one diagram; on the other hand, the necessity of reducing the elements to percentages is a disadvantage. This method throws some light on the chemistry of the groundwater but is not of much help in its interpretation.

Despite their shortcomings, these two methods are helpful in the correlation of various groundwaters. As the Schoeller method was found, however, to be the most useful of the three, the writer has included only a few brief remarks on the Stiff and Palmer-Piper methods and the interested reader is referred to the literature on the subject.

SCHOELLER'S SEMI-LOGARITHMIC DIAGRAM

Schoeller's Semi-logarithmic Diagram, by far the best of the three methods for presenting chemical analyses, is the one used in this report. It is particularly useful in scrutinizing groundwater samples from the deep confined aquifers where the chemical composition of the groundwater is closer to equilibrium. It is less satisfactory for groundwater samples from unconfined aquifers. The use of all three methods in this type of study, however, may give even better results, because in many cases the three methods complement one another.

The construction, description, and interpretation of the semi-logarithmic diagram was published originally by Schoeller in French in 1935; only a resume of his work appeared in English (1959). The writer suspects that the resumé was too brief, and consequently never fully understood. To illustrate the great potential Schoeller's method in the field of hydrogeological studies, the basic facts in Schoeller's work are described here in detail.

In the semi-logarithmic diagram, the values of the elements are absolute values and not percentages, and it is thus possible to allow for the fact that the solubility of some elements is more limited than others. In this report, the unit used in the construction of these graphs is the equivalent per million (e.p.m.). Schoeller used milliequivalents. The two units are identical if it is assumed that 1 ml. of water weighs 1 gram.

In general, these graphs have many advantages: (1) many analyses can be plotted on one graph; (2) the graphs show not only the absolute values of each element but also the relative values, which are ratios of the elements in a given type of water, e.g. (rSO^4/rCl, rMg/rCa) (see footnote 1); (3) they indicate whether or not the saturation point of the various chemical compounds has been attained (4) because of the logarithmic scale of the paper, if a straight line joining the points for two elements A and B in one type of water is parallel to another straight line joining the parts for the same elements A^1 and B^1 in another type of water, the ratio of these elements is the same in either case, that is, $A/B = A^1/B^1$. The slope of these lines indicates the ratio between those elements of prime importance; (5) if the waters have different concentrations, they will appear on the graph one above the other, thus indicating relative movement of the groundwater between the points of origin of these analyses (the flow being from a lower concentration to a higher concentration). If the analyses are from sites located close together on a map the flow could be termed local; (6) the analyses can be plotted in groups showing various types of waters; for instance, according to the Chebotarev (1955) sequence

$$HCO_3^- \rightarrow HCO_3^- + Cl^- + HCO_3^- \rightarrow Cl^- + SO_4^= \text{ or } SO_4^= + Cl^- \rightarrow Cl^-$$

thus illustrating the direction of groundwater flow by zones, on a regional or basin-wide basis. The last two advantages are considered by the author to be extremely important.

[1] The prefix r denotes that the value is in e.p.m.

Graph Construction

The procedure for constructing a Schoeller diagram is as follows. Using semi-logarithmic paper (Fig. 7), and scaling from left to right on the abcissa, plot at regular intervals the radicals rCa, rMg, rNa, rCl, rSO_4, and $rHCO_3$. The intervals must be equal or the purpose of the graph will be defeated. The order of the radicals indicated above is logical, at least from a chemical point of view, especially because it enables determination of the various ratios deemed important, such as rMg/rCa, rSO_4/rCl, etc. The relatively constant radical $rHCO_3$ is placed at one extreme, thus helping to keep the graph neater.

On the ordinate, graduated on a logarithmic scale, are plotted the values of the radicals in equivalents per million; the points thus plotted are joined by straight lines. This gives the graphic pattern. The whole graph is symmetrical, in a logical chemical order, with respect to an imaginary vertical axis (centre line) placed between rNa and rCl. This centre line is called the pH-of-equilibrium line.

The Saturation Point of $CaCO_3$

These graphs can be used to determine whether or not the groundwater is saturated with the various salts, information which helps the hydrogeologist understand more easily the causes that change the chemical composition of groundwater as it flows through the aquifers.

The amount of $CaCO_3$ dissolved in water can be determined by comparing the pH of the water with the pH of equilibrium. The pH of equilibrium is the pH corresponding to the saturation point at the CO_2 of equilibrium of the water. To find the pH of equilibrium, a straight vertical line is drawn halfway between rCa and $rHCO_3$ (Fig. 7). This vertical line, called the pH-of-equilibrium line, is the centre line placed between rNa and rCl as previously mentioned. Along this line a point exists which corresponds to the saturation of $CaCO_3$ for the pH of equilibrium of the water; the point can be determined for each H^+ -ion concentration and thus can be found for each pH. A second straight line is then drawn from the absolute value of rCa to the absolute value of $rHCO_3$. Now the pH of equilibrium of the water is that point where the second line intersects the vertical line or pH-of-equilibrium line. The pH-of-equilibrium value can then be read directly on the graph in equivalents per million (e.p.m.). Figure 8A, called a solubility scale of the pH of equilibrium, is used to convert the pH-of-equilibrium value from e.p.m. units (as given on the graph) to the common numerical value for pH, which is the negative exponent of the logarithm of the hydrogen-ion concentration. The solubility scale could be incorporated in the graph, but this would involve a lot more work. Because the pH of equilibrium is a function of the ionic strength and temperature of the water, slight corrections have to be made to the pH-of-equilibrium value established from the graph. The values to be added for various ionic strengths and temperatures are shown in Table III. Now if the corrected pH of equilibrium is inferior to the true pH of the water, the water is supersaturated. If, on the other hand, the pH of equilibrium is superior to the true pH of the water, then saturation has not been reached and the water is still aggressive and can dissolve more $CaCO_3$. Generally the water is found to be saturated.

A second vertical line drawn between rCa and $rHCO_3$, two thirds of the way from rCa, is called the Kr-of-equilibrium line (Fig. 7). The straight line joining the absolute rCa value with the absolute $rHCO_3$ value will cut the vertical Kr-of-equilibrium line at a point that will be the Kr of equilibrium of the water. This Kr represents the amount of $CaCO_3$ in e.p.m. that the water can dissolve. Again, correction has to be made for the ionic strength and temperature of the water. In most cases the groundwater is saturated in $CaCO_3$ and here the Kr-of-equilibrium value takes on great importance, because it then represents the value of free CO_2 dissolved in the water. This is important, because the free CO_2 in the water is the principal active chemical agent in the decomposition of rocks, especially limestone rocks.

Keeping in mind that the pH of equilibrium is equivalent to the CO_2 of equilibrium in a water, and that the Kr-of-equilibrium value represents the free CO_2 dissolved in the water, the following can be said: If the value of the CO_2 of equilibrium (the value of the pH of equilibrium on each individual graph pattern) is larger than the value for free CO_2 (the value of the Kr of equilibrium on the same graph pattern), then the solution is not in equilibrium, which will cause $CaCO_3$ to precipitate. On the other hand, if the value of CO_2 of equilibrium is less than the value for free CO_2, the water can still be considered as aggressive, even though it is already saturated. The excess of CO_2 can then be called aggressive CO_2 (see Fig. 7).

The Saturation Point of $CaSO_4$

The degree of saturation of $CaSO_4$ is found by drawing a vertical line half-way between rCa and rSO_4 (Fig. 7). This line is called the sulphate solubility line or S line. A straight line joining the absolute values of rCa and rSO_4 will cut the vertical S line at a point S_1. This point S_1 is to be kept in mind for the moment, for two more steps are required to determine whether or not the water is saturated. First the NaCl content of the groundwater sample is found [this can be done quickly by dividing the chloride value of the water on the graph by 0.6 (Fig. 7)]. Then a solubility scale of $CaSO_4$, $2H_2O$ is used. Such a logarithmic scale, for various NaCl concentrations at 20° C, is shown in Figure 8B. It gives the points of saturation concentration of gypsum, ranging from 30.8 e.p.m. for pure water, up to 107.0 e.p.m., representing the maximum solubility of gypsum in

salt water (at 2,250 e.p.m. NaCl) (Schoeller, 1955). It should be remembered that the solubility of gypsum increases with an increase in NaCl, up to an NaCl content of 2,250 e.p.m., beyond which the solubility of gypsum decreases. Even though the solubility of SO_4 is a function of the ionic strength and temperature, these two factors play a minor role compared to the NaCl, concentration of the water. The small corrections due to ionic strength or temperature are used only to get more exact figures and are disregarded in this study.

Therefore, knowing the NaCl content of the groundwater and using the solubility scale of $CaSO_4$, $2H_2O$ (Fig. 8B), it is easy to derive the saturation point of the water for the given NaCl concentration. If the value of S_1 (Fig.7) is above the saturation point, the water is supersaturated; if below it,saturation has not been reached.

CHAPTER 3

Interpretation of Groundwater Analyses

For this report, 162 groundwater samples were collected for analysis over a period of five years: 19 in 1959; 19 in 1960; 42 in 1961; 38 in 1962; and 44 in 1963. A few more samples might have helped to clarify some points; on the other hand, some of the samples taken are of almost no value. All 23 groundwater samples derived from unconfined aquifers are of very little value in this study, as we are primarily concerned with groundwater from confined aquifers.

The 162 analyses were made by the Industrial Minerals Sub-Division, Mines Branch, Department of Mines and Technical Surveys, Ottawa. Eleven more analyses are included in this report to further facilitate interpretation. Seven of these eleven analyses are from outside the area investigated, some 125 miles to the west in the oil fields of the Virden area, Manitoba. The other four analyses are from within the area, but were analysed by the Manitoba Health Laboratory. All 173 analyses of groundwater samples are illustrated in Figures 9 to 39. Table I (in pocket) shows the analytical values of the six ions used in the construction of each graph, the relative values of some of their ratios, and the mathematical values of the various salt concentrations in each groundwater sample. Figure 3 illustrates the location where each groundwater sample (166 within the map-area) was taken. Figure 3 also shows that the largest concentration of samples was taken from the large flowing artesian zone, outlined on Figure 4. This reflects the fact previously mentioned, that samples taken from flowing wells in an artesian zone are considered by the writer to be more reliable and hence better suited to interpretation.

A GENERAL CLASSIFICATION OF THE SEMI-LOGARITHMIC GRAPHIC PATTERNS

The graphs of analyses of groundwater fall into three large categories. They are the analyses derived

(1) from unconfined aquifers in surficial deposits;
(2) from confined aquifers in till or bedrock (limestone, dolomite, and sandstone);
(3) from confined aquifers in shale.

Each category in turn contains several groups of analyses.

The Graphic Pattern of Groundwater from Unconfined Aquifers: Category I, Groups 1, 2, 3 and 4

Most of the analyses in Category I are derived from wells located on the western margin of the area (Fig. 3). In general, the graphs for this category have a concave pattern, with some exceptions on the rCa, rMg side (Figs. 9 to 12). This pattern is understandable because groundwater of this type is still close to the surface and has not had time to dissolve even the more soluble salts such as NaCl or $CaSO_4$. Because of the resulting low values for rNa, rCl, and rSO_4, the pattern will obviously be concave or U-shape. This type of water should be predominantly a bicarbonate water, because the unconfined aquifer from which it was obtained can be considered as a recharge area. Such aquifers are recharged directly by precipitation. However, the graphs do not show this groundwater to be mainly a bicarbonate (HCO_3^-) type of water, but rather a $HCO_3^- + SO_4^=$ type. This reflects the origin of the surficial deposits through which this groundwater flows. These surficial deposits were derived primarily from the shale bedrock underlying that part of the area. The shale bedrock, in turn, is closely associated with anhydrite and gypsum beds, accounting for the rSO_4 value being generally larger than one equivalent per million, which is the basis for calling this groundwater a $HCO_3^- + SO_4^=$ type of water.

The graphs of Category I have been divided into 4 groups (Figs. 9 to 12). Even though this groundwater near the surface has not had much time to associate itself chemically with the aquifer, it can be said that Groups 1, 2 and 3 (Figs. 9 to 11) have a common characteristic in the U-shape of their patterns. Group 4 has a similar pattern, with the exception of the high chloride value. No explanation can be given for this relatively high rCl value of the analyses of this group; but one thing common to all of them (except #47) is a high nitrate value (140 to 490 p.p.m.).

As already mentioned, precipitation directly recharges these shallow water-table aquifers, and the time factor, which is important in this study, has not had too much effect on the results. Nevertheless, by looking at the diagrams (Figs. 9 to 12) and Table I, these generalities are obvious; in this category the rMg/rCa ratio is greater than one, fifty per cent of the time, the rSO_4/rCl ratio is greater than one most of the time, and the rNa/rCa ratio is less than one all the time.

Even though the average value for total dissolved solids in parts per million [Aver. T.D.S. (p.p.m.)] for each group (Figs. 9 to 12) is larger than for the previous group, there is

no continuity shown here between the groups of this first category. This means that, for unconfined aquifers, groundwater studies can be only local in scope. Another fact established at this point is that hydrochemistry is of no help in determining the direction of movement of groundwater in unconfined aquifers. The movement of groundwater in this type of aquifer can be said to be controlled by topography. To conclude, a better correlation between the analyses of this category can be achieved with the Stiff diagrams.

The Graphic Pattern of Groundwater from Confined Aquifers in Till, Limestone, Dolomite and Sandstone: Category II, Units A and B

The graphs of Category II are the heart of this study. They will therefore be discussed in greater detail later. For the moment it can be stated that the general pattern of the analyses is convex except in Groups 1, 2, and 3 (Figs. 16 to 22), originating in or near the recharge zone, which gives them a V-shaped pattern (somewhat similar to the U-shape patterns for unconfined aquifers) due to a low salt content. Time once more is the principal factor. The groundwater of the analyses included in Groups 1, 2, and 3 is still near the recharge point, and thus it has not had enough time to dissolve the more soluble salts certainly not much more time than the groundwater in unconfined aquifers. Consequently, a high salt value in groundwater in the recharge area would be abnormal and could mean a high salt concentration in the aquifer rocks. The convex pattern of the remaining eight groups of unit A and three groups of unit B of Category II is due to high salt values, accumulated by the groundwater as it follows its path.

In this category, the relative rCa and rMg values may have some significance when we are dealing with groundwater from the rocks of the Red River Formation. A higher rCa value may indicate that the aquifer consists of limestone, while a higher rMg value may indicate that the aquifer is predominantly dolomitic.

There is no doubt that in this category more than one aquifer is involved. The analyses derived from these different aquifers could have been interpreted separately. But there is one factor common to all of them, namely artesian pressure. Because of this pressure, it is believed that groundwater from the bedrock infiltrates upwards, even into the till. This single factor causes similar graphs for many analyses derived from different aquifers. On this basis then, all the analyses in this category are presented as if only a single aquifer existed. The existence of artesian pressure was proved by the United States Geological Survey in a detailed piezometer study in the Red River Valley south of the International Boundary. The piezometer batteries there indicated upward flow gradients, which means that the deeper the well the higher will be the static water level. This is in complete agreement with the writer's findings in the Red River Valley north of the border. This category is divided into two units. One unit (A) combines the westward and eastward flow of the groundwater, while the second unit (B), separated for clarity, represents the southward flow of groundwater.

Therefore, considering the various aquifers as a single very large aquifer, the most striking point illustrated by the graphs (Figs. 16 to 34) is a consistent similarity within each group and a continuous similarity between the various groups. Each group is related to the one before and the one after it. The continuity between the groups shows that, at depth and given enough time, the groundwater will establish chemical equilibrium within an aquifer or system. The continuity of the graphic patterns makes it possible to follow the steady movement of groundwater through that system. Studies of groundwater movement can then be regional, basin-wide, or even continental in scope.

The Graphic Pattern of Groundwater from Confined Aquifers in Shale: Category III, Groups 1, 2 and 3

The pattern of the graphs for Category III is entirely different from the patterns of the two categories previously described. The main characteristic of the pattern is the relatively high rSO_4 value. In Groups 1 and 2 (Figs. 13-14) of this category, the high rSO_4 value is accompanied by a relatively high rMg value. All the samples of these two groups, (except #7) were taken on the east side of the Red River Valley, and the relatively high rMg value reflects the dolomitic character of the rocks of the Red River Formation in this area. On the west side of the valley, the relatively high rSO_4 value is accompanied by a relatively high rNa and rCa value, as shown in Group 3 of this category (Fig. 15). The bedrock on this side of the valley underlies the surficial deposits that form the unconfined aquifers.

The relatively high SO_4 value of the analyses of this category reflects the association of anhydrite and gypsum with the shale formations, as mentioned previously in the discussion of unconfined aquifers, but to a stronger degree. This is demonstrated by analysis #72, of water from the red shale of the Amaranth Formation. The high chloride value of this analysis is due to the fact that evaporite beds form part of the rock formation. The rSO_4 value (36.89 e.p.m.) of analysis #72 is not extremely high, but it can become so if one considers that it is found immediately after the groundwater has gone through a sulphate-reduction zone, which will be discussed later. As the Amaranth Formation contains gypsum some 100 miles to the northwest, this was interpreted by the writer (Charron, 1965a) as an indication of the possible existence of gypsum beds in the area. Subsequent drilling 2 miles to the east of where sample #72 was taken confirmed that possibility. The core obtained from the drilling showed a 48-foot section of gypsum

intermingled with red shale of the Amaranth Formation. The results of the drilling combined with the analysis #72 indicate the direction of the horizontal component of groundwater movement in this area, because the drilling was carried out east of where the water sample was obtained. This proves that the groundwater movement is from east to west. It also indicates the upward component of the groundwater movement, because the gypsum occurs at a depth of 95 feet in the drill-hole, whereas the depth of the well from which sample #72 was obtained is only 60 feet.

Some patterns of the third group in Category III can be interpreted as good examples of a mixture of groundwater from two different aquifers. A typical shale-water pattern from the western margin of the map-area is that of sample #3 (Fig. 15). The pattern of this analysis was chosen as the model for the shale waters of this area for two reasons: (1) the shale bedrock outcropped a few feet away from the well where the groundwater sample was taken for this analysis; (2) the characteristics shown by the pattern of the analysis are conspicuous. Therefore, a high rNa and rSO_4 value accompanied by a low rCl value were taken as the main characteristics of this type of water. Knowing that the shale is overlain by till, and using the analysis of sample #3 as a type analysis, the water of analysis #18 (Fig. 15) can be described as a mixture obtained mainly from a shale aquifer and partly from a till aquifer. Similarly, the water of sample #21 (Fig. 15) is a till-shale mixture, but here more of the mixture is derived from the till than from the shale aquifer.

Even though groundwater is encountered in shale formations in the Red River Valley, as described in the previous paragraphs, the shale formations will be considered as aquicludes and not aquifers throughout the remainder of this study. The writer believes that, wherever groundwater occurs and a shale formation is in evidence, the contact zone of that shale with the gravelly till above it, or with the limestone, dolomite, or sandstone below it, is the true aquifer and not the almost impermeable shale itself. Although it is certain that fractures in the shale carry some groundwater, the amount is considered by the writer sufficiently small that the shale formations can be regarded as aquicludes.

Groundwater Mixture

A pattern change that is at variance with the normal trend of patterns displayed by the water of a groundwater basin can indicate many things. It may be that the groundwater is derived from a different aquifer, as shown by the analyses in Category III. It may be that the groundwater originates in a different groundwater basin. It may also be due to a mixture of water. The mixture in the simplest form may consist of waters from two unconfined aquifers or from two confined aquifers. The latter case has been illustrated in the discussion of the analyses of Category III. It may also be a mixture of water from an unconfined aquifer with water from a confined aquifer, or of water from two groundwater basins.

As mentioned before, all the analyses presented here have been divided in three categories. At one time the writer contemplated establishing a fourth category to illustrate the occurrence of mixtures of groundwater; as such mixtures were certain to occur almost anywhere, however, he decided against it. It should be noted that a mixture of groundwater is in most cases caused by vertical leakage, either from unconfined aquifers near the surface into the confined aquifer below, or vice versa under the influence of artesian pressure.

The comparatively low total dissolved solids (T.D.S.) value of analyses #92 (Fig. 9) #116 (Fig. 14) can be used as examples of the statement in the previous paragraph. It seems logical to assume that analyses #92 and #116 should have a higher T.D.S. value if only because of the depth of the well in each case, 250 feet and 236 feet respectively, and their location in the area (Fig. 3). Only a mixture with a groundwater having a lower T.D.S. value could bring about this dilution. The cause here may very well be found in the gravel aquifer of Birds Hill (Fig. 1) with its own local recharge. Water from this source mixing with water from the east could result in a relatively low T.D.S. value for the two analyses in question. The possibility of direct leakage right at the well site should not be overlooked.

Finally, the lack of a definite trend in some patterns such as those displayed by analyses #85 #87 (Fig. 14) and #88, #89 and #112 (Fig. 35) can also be interpreted as a mixture of water. The values of all six radicals of these analyses fall within the same log cycle, between 3 and 10 e.p.m. If grouped together, these analyses could be interpreted as a mixture of water from two groundwater basins. However, a short hydrochemical sequence is available to help illustrate the existence of a southern flow of groundwater within the map-area (Fig. 3), as will be shown later in this report. Thus it was thought more appropriate to present these analyses in their respective groups, rather than use them to illustrate mixture of groundwater. It is also possible that both causes mentioned work together.

Because the main purpose of this report is to illustrate groundwater movement, the most important analyses used to describe this phenomenon will be those of the second category.

CHAPTER 4

A Detailed Hydrochemical Interpretation of the Analyses of Category II

UNIT A (GROUPS 1 TO 11)

The groundwater analyses representing Unit A are divided into eleven groups, each group and sub-group being characterized by samples with a similar graphic pattern. Although it might have been possible to reduce the number of groups, there are enough differences between the groups to warrant separation, and this separation has been maintained to facilitate presentation and interpretation of data. It may be argued that a particular analysis could or should be placed in a different group without creating any discrepancy. This is true, particularly where groundwater samples are transitional between one group and another or are on the borderline of two chemical zones. So many variables which have an effect on groundwater come into play that only the most important ones are now mentioned. They are: (1) the absolute values of the six radicals; (2) the relative values of the ratios which are deemed characteristics, such as rMg/rCa, rSO_4/rCl, $\frac{rCl - rNa}{rCl}$; (3) the type of aquifer; (4) the depth of the aquifer; (5) the modifying phenomena of reduction, concentration and base exchange; (6) the time factor.

The method used here to form these various groups is as follows. First, all analyses with the same obvious basic patterns are grouped together. The analyses whose patterns are less obvious are scrutinized to decide into which group they will fit best. This means that waters from different aquifers can end up within the same group. Secondly, each group can also be subdivided for classification (e.g., Groups 4a, $4a_1$, 4b, 4c and 4d, Figs. 23 to 25). Thirdly, the order of grouping is such that the average value for total dissolved solids of successive groups increases from Group 1 to Group 8, as does the base exchange index[1], to be discussed later in this report. Illustrated in this way, the basic pattern of each group has something in common with the group preceding or following, exceptions being, of course, the first and last groups. Actually very little knowledge of the aquifers is needed to obtain a sequence, such as here presented, which will point out the direction of groundwater movement. The sections which follow present an analytical description of the eleven groups that form Unit A of Category II.

[1]The index is negative when rCl < rNa and positive when rCl > rNa. See also "Three Modifying Phenomena", Chapter 8.

Groups 1a and 1b

Basically Group 1 (Figs. 16 and 17) is typical of a bicarbonate type of water. The patterns resemble that of groundwater in unconfined aquifers, in that they have a concave shape. This, combined with the low T.D.S. value, places the groundwater near the recharge area.

Group la is characterized by the lowest average T.D.S. value (246 p.p.m.) of any group. The group is basically a Ca, Mg, HCO_3 type of water, like all the groups near recharge, and like almost all groups originating from the unconfined aquifers previously described. The base exchange index is strongly negative, much more so than for unconfined aquifers (Table 1), and this is due to the extremely low rCl value. From Figure 3 it is readily seen that the analyses forming Groups la and lb completely surround the highlands of Sandilands Forest Reserve. This area is considered to be the main area of recharge for the aquifers on the eastern slope of the Red River Valley. In Group la, calcium predominates over magnesium, but the ratio rMg/rCa is very near 1. The value of rMg/rCa can either be larger or smaller than 1, but except for very rare instances throughout the entire study, it will be near unity.

Group lb is practically the same as Group la, but differs in that the rMg/rCa ratio is always greater than 1. The predominance of magnesium over calcium in this sub-group reflects either a dolomitic composition of the surficial deposits in the area or an absence of carbonate rocks, which is the case where the surficial deposits are underlain by the sandstone of the Winnipeg Formation. This is best shown in this group by analysis #131 (Fig. 17), particularly because of the low rCa value.

Groups 2a, 2b, 2c, 2d and $2d_1$

Group 2 is also considered to be in the bicarbonate zone. In the first group, the groundwater was at the heart of the recharge area. In the second group, the groundwater has started to move away from the main recharge area, which is the highlands of Sandilands Forest Reserve. Nevertheless, in Group 2a, recharge seems to be local (Figs. 3 and 4) in the case of analyses #119, #122, and #135. The fact that this group is very much like Group 1a may be due to local recharge. Otherwise the patterns of Group 2a would resemble more closely the patterns of analyses farther downstream.

Group 2b starts a trend that will be characteristic of the whole of Category II. So far, in the first group and in Group 2a, the V-shaped pattern of the bicarbonate type of water has had a sulphate value greater than the chloride value. But for Group 2b the chloride value, as shown on Figure 19, is beginning to increase and succeeds in surpassing the sulphate value. This is as expected because of the greater solubility of the chlorides. Therefore, the rSO_4/rCl value is generally smaller than 1 and it will remain this way throughout the rest of Category II. Group 2b is also the last group of this category in which the rNa value is smaller than one equivalent per million.

Group 2c (Fig. 20) is basically similar to Group 2b. The sodium value (rNa) is now permanently larger than 1 e.p.m. The change of the value of the rSO_4/rCl ratio is now complete, and for the rest of the groups in Category II, it will remain smaller than one. The abnormally-low sulphate value of the analyses can be explained by the sulphate reduction phenomenon, which will be discussed later in this report. Although the rMg/rCa ratio has been either larger or smaller than one in the previous groups, in this group it is generally larger than one, and it will remain so in the subsequent groups, except in rare instances. This indicates that the Red River Formation, consisting of dolomitic limestone, exists underneath the surficial deposits. This group is the only one in which the average T.D.S. value (359 p.p.m.) is larger than that of the following group; this is mainly due to the high individual T.D.S. value of analysis #134.

In Groups 2d and $2d_1$ (Fig. 21) the rNa value is larger than 2 e.p.m. for the first time. Otherwise this group is very similar to the previous one. The sulphate reduction phenomenon is still evident. Therefore, if one looks at the groups already mentioned, it can be seen that, on the whole, the increase in the overall T.D.S. value is due mainly to an increase in the rNa and rCl values.

The cut-off line used to separate Group 2 and Group 3 is the value of rCl. In Group 2, with the exception of analysis #143, the chloride value was smaller than 1 e.p.m., whereas in Group 3, the rCl value is generally larger than 1 e.p.m. Where the rCl value is smaller than 1 e.p.m., the analysis is placed in Group 3 only if the rNa value was considered high enough to warrant such a classification.

Groups 3a and 3b

The average T.D.S. value of this group is 468 p.p.m. The sulphate reduction phenomenon is still evident for the whole group. The V-shape or concave-type pattern is now changing, owing to the considerable increase in the rNa and rCl value. The typical V-shape will slowly give way to a convex pattern.

The rNa/rMg *ratio,* which until now has been smaller than unity, is increasing, to the extent that, in Group 3b (more than 4.0), it was the basis for dividing Group 3 into two sub-groups 3a and 3b (Fig. 22). This ratio will continue increasing (see Table I). The base exchange index (b.e.i.) is also increasing rapidly, as can be seen when its value in this group is compared with that in Group 2. Nevertheless, it is still negative. The groundwater is still slowly moving westward, farther away from the recharge area. In Groups 1 and 2 the water was said to be in the bicarbonate zone (HCO_3^-); it is now in the transition stage into the bicarbonate chloride zone ($HCO_3^- + Cl^-$). These chemical zones will be discussed in detail later.

A slight decrease in the absolute values of rCa and rMg is noticeable in Group 3. Until now the calcium and magnesium values have been generally above 2 e.p.m. in the bicarbonate groups and much more so in Groups 3 and 4 of the first category, which consisted of groundwater from unconfined aquifers. In Group 3 of the second category, the calcium and magnesium values have decreased to less than 2 e.p.m. in all analyses but one. This decrease is also noticeable in the following two groups. This may be due to an infiltration of groundwater from the sandstone aquifer of the Winnipeg Formation into the dolomitic limestone of the Red River Formation, or it may be due to a base exchange of Ca and Mg for Na.

Groups 4a, $4a_1$, 4b, 4c and 4d

The diagrams of Groups 4a, $4a_1$, and 4b (Fig. 23) continue the flow sequence as shown by the chemistry. In general, the main points of this group are the visible increase in the sulphate value, and the fact that the chloride value is now larger than 1 e.p.m. in every analysis but one. In many cases, the sulphate value is still smaller than 1 e.p.m. but it is now increasing normally and not being held back by the sulphate reduction phenomena.

For the first time in the confined aquifer groups, we have a positive base exchange index (b.e.i.) value and this factor has placed the two analyses #93 and #102 with a positive b.e.i. in Group 4b (Table I).

Groups 4c (Fig. 24) and 4d (Fig. 25) are in the same chemical zone, that is $HCO_3^- + Cl^-$, as are the analyses of Groups 4a, $4a_1$, and 4b, but the difference in their patterns warranted the further sub-division of Group 4. No concrete explanation can be given for the change in pattern of these two sub-groups.

Analysis #89, although it is believed to belong to the northern groundwater basin (Fig. 3), which means that it should be in Category II, Unit B (Table I) and should be Group 1 of that unit, is placed in Group 4d (Fig. 25). Because it is alone and fits the pattern of the other two analyses of Group 4d, it seems more appropriate to place it in this group rather than form a new Group 1 in Unit B of Category II. In its present place it shows that in different

groundwater flows the same chemical properties can occur as long as the conditions are similar.

Groups 5a and 5b

With this group (Fig. 26) we have again moved farther downstream from the main recharge area. The groundwater is now in the $Cl^- + HCO_3^-$ zone (Fig. 3). The convex pattern has become prominent.

So far no attention has been paid to the three vertical lines (the sulphate-solubility line S, the pH-of-equilibrium line, and the Kr-of-equilibrium line), which form part of the diagrams we have been using. The grouping of the analyses in Group 5 is considered to be very good (Fig. 26). It is easily seen on Figure 26 that the lines intersecting the three vertical lines are also well grouped. It should be stated now that the writer has made continuous use of the slope of these intersecting lines and their location on the graph in the correlation and grouping of the analyses. Looking at the S line in Group 5, it can be seen that the $CaSO_4$ concentration is still far below the saturation point and also that the slope of the intersecting lines has changed. The change has been progressive. In the previous four groups, these intersecting lines on the S line were strongly inclined to the right. The inclination was stronger for greater reduction in sulphate, because in most cases the rCa value was fairly constant. In Group 5 these intersecting lines are almost horizontal. This is true also of the eastern limit of the clay plain.

All the analyses in this group are in the $Cl^- + HCO_3^-$ zone, which is considered to be completely outside the main recharge area. The infiltration map (Fig. 1) is used again to explain and prove this point. If Figures 1 and 3 are superimposed, it is seen that the chloride-bicarbonate zone coincides with the eastern limit of the clay plain on Figure 1. Because the clay was said to be impermeable, it is reasonable to assume that from that point on, no more direct recharge from above can possibly penetrate to the confined aquifers underneath the clay, at least right up to the western limits of the clay plain. Thus an imaginary line along the general trend of the $Cl^- + HCO_3^-$ zone indicates the western limit of the recharge area in the eastern part of the valley. The depth of the deepest aquifer, which at that particular point happens to be the sandstone of the Winnipeg Formation, would therefore be the maximum depth at which topography could have any influence on groundwater movement. This depth appears to be 400 feet.

Whether this is reflected in the chemistry of the water by the slope of the intersecting lines becoming horizontal at that point is a question which cannot be answered. But the idea developed in the foregoing paragraph originated because of that fact. In other words, in the interpretation of the intersecting lines, the writer was trying to find more applications than simply the fact that they help to establish whether or not the water is saturated in $CaSO_4$ and $CaCO_3$. Disregarding analysis #57 (Fig. 26), which still shows the influence of the sulphate reduction phenomenon, we can conclude the discussion of Group 5 by stating that the increase in sulphate in this group (rSO_4 has reached 1 e.p.m.) is interpreted as an increase in concentration of that salt in the aquifer through which the water flows.

Group 6

Group 6 is basically the same as Group 5 and, although it does not break up the sequence other than by having a higher average T.D.S. value than Group 7, it nevertheless does not properly form part of the sequence. This is because the groundwater analyses forming Group 6 are derived from the sandstone aquifer as compared to the groundwater of Groups 5 and 7, which is derived from the limestone of the Red River Formation. To the writer Group 6 is proof of the extraordinary relationship existing between the groundwater of various aquifers. It also demonstrates the fact that chemistry can sometimes complement geological knowledge and vice versa.

Before this five-year study was completed, it was thought that the analyses forming this group were derived from the dolomitic limestone of the Red River Formation and these analyses were therefore regarded as perfect examples of ionic base exchange. It may very well be that base exchange does occur between the calcium and sodium ions especially in the case of analysis #142, but the new line of thought is that the rCa values of these analyses are low simply because the groundwater is derived from the sandstone of the Winnipeg Formation. The low calcium and magnesium value (lower than normal at less than 1 e.p.m.) shown by the diagrams of this group (Fig. 27) are now considered to be the main characteristic of groundwater derived from this aquifer.

Because of the very low rCa value, the lines intersecting the three vertical lines (S, pH eq., and Kr eq.) all slope to the left, almost parallel to one another. For the first time the average T.D.S. value is larger than 1,000 p.p.m.; this is not because we are any farther from recharge in a horizontal plan, but because we are farther from recharge in a vertical sense as a result of the greater depth of the aquifer. This confirms that chemical changes will take place over a shorter distance in a vertical direction than in a horizontal direction. In other words, to change chemical zones or to increase the content of total dissolved solids, groundwater must travel a shorter distance in a vertical direction than in a horizontal direction.

This study has substantiated that almost all groundwater is saturated in $CaCO_3$ because only one analysis (analysis #121 of Group 6, Fig. 27) shows otherwise. The calcium value of that analysis is the lowest (0.08 e.p.m.) in the entire report.

The six chemical analyses of this group are all the data available on this sandstone aquifer. Consequently, the groundwater movement or the direction of flow of groundwater within this aquifer cannot be illustrated except by the fact that the groundwater represented by these six analyses traverses three chemical zones (Fig. 3). Nevertheless, it is felt that this group of analyses fits well enough within the general sequence to warrant calling it Group 6. In this way, the analyses of this group become a part of the chemical sequence caused by the groundwater movement that is being evaluated in the study.

Groups 7a and 7b

With Group 7 we continue the sequence as we had left it in Group 5 (Fig. 26). The two sub-divisions of this group are based on the difference between the rMg/rCa ratios of each sub-group. In Group 7a, the ratio is larger than 1, whereas in Group 7b it is smaller than 1.

The sulphate value of this group exceeds both the rCa and rMg values, as in the case of Group 6. Thus Group 7 is not only a continuation of the sequence in Group 5, but also follows Group 6 without disturbing the sequence. This is another reason why Group 6 was introduced with the other groups of this category.

An increase in calcium and magnesium values is a new trend which is discernable in Group 7. The peculiarity of this increase lies in its association with the rSO_4 value. That is, for each increase of rSO_4 there is a comparable increase in the rCa and rMg values. This increase will continue in all the subsequent groups of Category II, Unit A. Also, from Group 7b to Group 11, the rMg/rCa ratio will generally be less than 1.

Even though analysis #71 (Fig. 29) has the highest rSO_4 value yet encountered in this category, the saturation point of $CaSO_4$ is far from being reached. As a matter of fact, no groundwater saturated in $CaSO_4$ has been found anywhere in the area of the Red River Valley studied by the writer. This is almost the opposite of what has been stated for the saturation point of $CaCO_3$. Finally, the base exchange index of this group is still negative, but it is slowly approaching zero.

Groups 8a and 8b

In Group 8 (Fig. 30) the rNa and rCl values are high; consequently a high average T.D.S. value (5,190 p.p.m.) is found. This value is the highest for any group within the area studied. Apart from this, there are many new characteristics in the diagrams for Group 8: (1) the high rCa and rMg values (above 10 e.p.m.); (2) the base exchange index is almost nil as indicated by the line joining rNa and rCl, which is almost horizontal and, in one analysis #82, is positive; (3) the sulphate value has surpassed the bicarnonate value; (4) the low bicarbonate value; (5) the change in slope of the lines intersecting the pH-of-equilibrium and Kr-of-equilibrium lines. With this group, the groundwater has entered a new chemical zone called the $Cl^- + SO_4^=$ zone (Fig. 3).

First, it should be stated that each water sample in Group 8 is derived from a till bedrock contact and that, as far as the till aquifer is concerned, this is the beginning of the discharge area for the westward flow of groundwater in the Red River Valley. Therefore, the new $Cl^- + SO_4^=$ zone shown in Figure 3 is justified only if the groundwater is considered to be derived from a bedrock aquifer. If the groundwater is considered to be derived from the till aquifer, then this same $Cl^- + SO_4^=$ zone becomes the ultimate and last zone and should be called the Cl^- zone, because the discharge area has been reached.

It should be noted that the analyses of this group are the last available in this area pertaining to bedrock, even though they are not analyses of true bedrock water. In Groups 9 and 10, the analyses are all derived from the till aquifer with the possible exception of #30. The movement of groundwater in the bedrock from here westward might be regarded as doubtful, because no more analyses are available from the bedrock aquifers in this area. This is one of the reasons for adding Group 11 (Fig. 34) to the sequence of this category.

The values of rNa and rCl of Group 8 seem to have increased rather abruptly and the feeling is that under normal circumstances the increase should have been gradual as it has been throughout the previous groups. The cause of the sharp increase is believed to be the occurrence of anhydrite and gypsum beds in the Amaranth Formation. Thus we would have here a case of concentration by dissolution.

So far, the most stable radical, the bicarbonate, has generally maintained a value between 5 and 10 e.p.m. But now that the groundwater has entered the $Cl^- + SO_4^=$ zone, the bicarbonate value is decreasing and in analysis #82 (Fig. 30) it reaches its lowest value at 2.43 e.p.m. This low bicarbonate value accompanied by a relatively high calcium value changes the slope of the line intersecting the vertical lines for the pH of equilibrium and the Kr of equilibrium. These intersecting lines are sloping to the right for the first time and thus the pH-of-equilibrium value exceeds that of the Kr of equilibrium. As mentioned earlier, this means that the water is saturated in $CaCO_3$ and because there is no excess CO_2 it cannot dissolve any more $CaCO_3$, causing it to precipitate. This can all be deduced from the diagrams (Fig. 30), which show clearly that, in two analyses, the pH of equilibrium is greater than the Kr of equilibrium.

Category II, Unit A has now been followed through eight groups. The gradual changes from one group to the next tend to convey a sense of motion, which has been translated by the writer into groundwater movement. The writer has no doubt that groundwater movement can be

discerned simply by looking at the diagrams and noting the changes in the concentration of each radical as expressed by the patterns of each group. But this sequence of eight groups, which has been used to describe groundwater movement throughout the entire aquifer system of this area, ends here. In Group 9, the sequence will continue in a westerly direction but only for the groundwater in the till aquifer.

Groups 9a and 9b

The analyses in Group 9 all pertain to groundwater obtained from the till aquifer. This group is undoubtedly in the discharge zone of the westward flow of groundwater in the till aquifer. This is best illustrated by the truly positive base exchange index and the low bicarbonate value. At the start, in Group 1, the bicarbonate value was the highest value on the graph; now, in Group 9, it is the lowest for Category II. Similarly at recharge, the base exchange index was strongly negative; now it is strongly positive.

In every analysis, the values for the first four radicals exceed 10 e.p.m. The high calcium value indicates that the water is becoming more and more saturated with $CaSO_4$, as compared to previous groups, but it is still far from being saturated.

In the previous groups, the rNa/rMg ratio had been increasing and values exceeding 10 were not uncommon. In Group 9, however, the value of this ratio has decreased and is barely more than 1. The relatively low rNa value and the high rCa and rMg values are a direct result of the base exchange phenomena, which will be discussed in detail later.

The fact that the value of the pH of equilibrium is larger than that of the Kr of equilibrium may also be used as an indicator that the groundwater has entered a discharge zone. This first became apparent in two analyses #82 and #170 of Group 8. To conclude, Group 9 is the end product of the westward flow of the groundwater in the till aquifer.

Groups 10a and 10b

Group 10a is comparable to Group 9 simply because it is the mirror image of that group; it represents the groundwater on the west side of the valley, which is flowing eastward. For the same reason, Group 10b is similar to Group 8, but the groundwater movement is now eastward, from Group 10b to Group 10a. Using the same criteria as before, this groundwater movement from Group 10b to Group 10a is clearly shown by the base exchange index, which is mainly negative or very nearly so in Group 10b (Fig.33) and totally positive in Group 10a (Fig. 32).

As with the analyses for Group 9, the analyses in Group 10 are derived entirely from groundwater of the till aquifer. If the flow of groundwater is from Group 10b towards 10a, we are faced with the question of why the average T.D.S. value is so much larger for Group 10b (4,408 p.p.m.), than for Group 10a (3,627 p.p.m.). This can be answered on the basis of Figure 4. As shown on this figure, the movement of groundwater in the sandstone of the Swan River Formation (Dakota Sandstone) is up-dip, owing to artesian pressure. The groundwater in this sandstone has a very high sodium chloride content (10,000 p.p.m.). The strong artesian pressure pushes this saline groundwater upwards into the sand and gravel lenses of the till aquifer; this is reflected by the unusually high sodium chloride values of analyses #6, #9 and #10 (Fig. 33), which in turn account for the high average T.D.S. value of their Group 10b. If it were not for the influence of the groundwater from the Swan River Formation, the average T.D.S. value of Group 10b would be less than that of Group 10a and everything would be in order.

The presentation of Group 10 as given here may seem ambiguous. Had it been discussed separately, however, as was done for Unit B of the same category, it would not have been possible to present a complete picture from east to west across the entire width of the Red River Valley, as has been attempted in this chapter and also in Figure 3.

Groups 11a, 11b and 11c

The samples of this group were obtained some 120 miles west of the western margin of the area being studied. The seven analyses are introduced here in Category II to show the continuous flow pattern of the groundwater in the limestone aquifer of the Red River Formation and to some extent also in the sandstone aquifer of the Winnipeg Formation.

If Groups 9 and 10 are for the moment eliminated from the sequence formed for the groups of Category II, Unit A, a certain relationship between Group 11 (Fig 34) and Group 8 (Fig. 30) is immediately apparent, particularly for analysis #82 of Group 8a (Fig. 30). The relationship is so strong that if analysis #82 is taken from Group 8a (Table I) and placed at the top of Group 11a (Table 1), it fits perfectly in all respects. Similarly if the pattern of analysis #82 is taken from Figure 30 and placed with those of Group 11 in Figure 34, it would not seem out of place. If this apparent continuity between the two groups is real, and the writer has no doubt that it is, then this would prove that, below a certain depth, groundwater movement is no longer influenced by the topography of the land.

In Group 11, the very high NaCl values, the very high average T.D.S. value (141,551 p.p.m.), the positive base exchange index, the supersaturation in $CaSO_4$, and the extremely low bicarbonate value are all indicative of a discharge area. This then is a true Cl^- zone. This zone can thus be called the ultimate stage in the flow of the groundwater in the limestone of the Red River Formation and the sandstone of the Winnipeg Formation.

One more fact remains that is worth mentioning. So far, only Group 6 (Fig. 27) has been representative of groundwater from the sandstone of the Winnipeg Formation and the main characteristic of the analyses of that group was the low value of rCa and rMg. Analysis #169 of Group 11 (Fig. 34) is the only analysis of that group for which the sample was obtained from the sandstone aquifer of the Winnipeg Formation, and surprisingly enough the main characteristics that differentiate analysis #169 from the six others of that group is the low value of rCa and rMg.

The main question at this point is: where does the groundwater go from here? There is as yet no answer to the question.

Unit A of Category II forms without doubt the core of the present study, for even without further analyses and discussion the presentation of the analyses in groups forming a definite sequence, as is done here, undoubtedly proves the occurrence of groundwater movement from group to group throughout the entire sequence. In this case the groundwater movement is from Group 1 to Group 8 and possibly as far as Group 11.

UNIT B (GROUPS 1 TO 3)

The sequence shown by the groups of Unit B is not as elaborate nor as complete as that just shown by Unit A. Nevertheless Unit B can be divided into three groups. The groundwater of this unit is basically a till-bedrock contact type of water, at the discharge end of a groundwater flow-system.

Group 1

This group is the least demonstrable of any group yet mentioned. It has not a single basic characteristic ion, in that all the values of the six radicals here used are of almost equal value. This observation, however, may be the characteristic for this group. The particular pattern displayed may also be indicative of a mixture of groundwater. So far, no other explanation can be given. It should be noted that analysis #112 does not properly belong in this group but it has been included because it seems to belong here more than in any other group.

Groups 2a and 2b

This group has a negative base exchange index in Group 2a and a positive base exchange index in Group 2b. This, plus the fact that it is already in a $Cl^- + SO_4^=$ zone, places the group well towards the discharge end of a groundwater basin.

Groups 3a and 3b

Group 3 shows most of the characteristics of the patterns described for Groups 8, 9, and 10 of Unit A, and all these groups are known to be in the discharge end of a groundwater basin.

It is obvious that the general and individual characteristics of the three groups of Unit B are similar to those described in Unit A of Category II. They will not therefore be repeated here.

Even though only three groups are available and only four chemical zones can be derived from these groups, it is nevertheless possible to show a flow pattern or direction of groundwater movement, as illustrated in Figure 3.

It is now time to explain the role played by Table I in sorting out the different groups.

Explanation of Analytical Data, Table I

All of the 173 analyses are represented on Table I. This table gives the absolute values of the six radicals, the numerical value of the relative ratios, the base exchange index value and the calculated values of S_1, pH of equilibrium, Kr_1 of equilibrium, ionic strength (μ), and temperature (θ); the corrected pH of equilibrium, which is also given as derived from the solubility scale; and finally the total dissolved solids value. The last two values were the most important in establishing the various groups.

From the T.D.S. column in Table I, it is readily seen that the analyses were placed so that there is an increase in the T.D.S. value from each analysis to the next within each group, as well as an increase in the T.D.S. value from group to group within a category. The T.D.S. value as presented in this column is the sum of the six radicals mentioned in the table. Therefore, if a discrepancy occurs in that a higher T.D.S. value precedes a lower T.D.S. value (as is the case for example in Category I, Group 1, analyses #28, and #29), then a check should be made in the remark column to see the true T.D.S. value of the analysis, which is taken from a complete analysis and given in parts per million. Because the T.D.S. value is increasing, it follows that all the absolute values should also be increasing, and this is true in a general way; an exception must be made, of course, for the bicarbonate value, which was shown in the discussion of the semi-logarithmic diagrams to be decreasing from recharge to discharge area.

The table reveals also that a certain relationship exists between the T.D.S. value and the corrected pH of equilibrium value. In other words, just as the T.D.S. value increases from one analysis to the next within a group, so does the corrected pH of equilibrium value. It is obvious that, at the same time, the corrected pH-of-equilibrium value, as read on the solubility scale (Fig. 8, A 1), decreases.

So the grouping of the analyses, as illustrated in Table I and in Figures 9 to 37, is based first on the patterns of the analyses as shown by the semi-logarithmic diagrams, and secondly on the criteria explained in the previous paragraph. Analysis #57 (Fig. 26) will be used as an example to demonstrate this. At first, analysis #57 was included with the patterns of Group 3a and 3b (Fig. 22), because of the similarity of the patterns. Yet, as soon as the three values for T.D.S., corrected pH of eq., and solubility scale value (called pH scale in Table I) of analysis #57 are checked against the similar values of the other analyses in Groups 3a and 3b, there is a break in the sequence (see Table II). From this abbreviated table it is clear that analysis #57 does not belong either in Group 3a, nor in Group 3b, except in the T.D.S. column. But as soon as it is placed in Group 5a, as is done in Table I, it fits perfectly. Therefore, analysis #57 was placed in Group 5a.

In some instances an analysis will fit equally well in one group or in the one next to it, even when the method described above is used. It is then that the other values such as the relative ratios, the base exchange index, etc., become important and are used to decide on the right grouping. In Table I, the base exchange index value of a group is generally negative or positive.

Table II

Comparison of analyses

Sample No.	Group 3	T.D.S. e.p.m.	pH eq. corr e.p.m.	ph Scale
77	3a	12.76	3.16	7.2
54	"	13.79	3.55	7.1
157	"	15.29	4.21	7.0
"57"	?	26.32	"2.36"	"7.5"
59	3b	14.35	2,34	7.5
66	"	20.94	2.43	7.5
55	"	25.79	3.41	7.2
"57"	?	26.32	"2.36"	"7.5"

The grouping of the 173 analyses as presented here was arrived at by using both the diagrams and the numerical values given in Table I. All except four analyses, #155 (Cat. II, Unit A, Group 2b), #104 (Cat. II, Unit A, Group 4a), #14 and #6 (Cat. II, Unit A, Group 10a and 10b respectively) follow the sequence in their respective groups. These four analyses are marked "irregular" in the remarks column.

CHAPTER 6

Absolute Values

$rHCO_3^-$ – Bicarbonate

The $rHCO_3^-$ value is generally fairly constant as it is governed by the pressure of CO_2 in the soil and air, which varies very little. Therefore, the bicarbonate value is the most consistent of the six radicals used in the plotting of the graphs.

The $rHCO_3^-$ value is usually high at recharge and low at the discharge end of a groundwater system. Only in five analyses does the value of $rHCO_3^-$ fall outside the log cycle bounded by the values of 1 e.p.m. and 10 e.p.m., and in four of these five cases the groundwater was derived from unconfined aquifers; consequently, for these four values, the $rHCO_3^-$ values were larger than 10 e.p.m.

A large bicarbonate value in a discharge zone, like the one recorded in analysis #163 (Cat. II, Unit A, Group 11), could be interpreted as an indication of leakage from a surface aquifer into the deeper confined aquifer.

$rSO_4^=$ – Sulphate

No extremely high concentrations of sulphate occur in the area studied (maximum value being 29.65 e.p.m.). Therefore, saturation for this salt is not attained in any of the analyses. To find an example of saturation in sulphate one has to go outside the area and look at Group 11 (Fig. 34), where even supersaturation is illustrated by analysis #165.

Ordinarily the rCa value increases with an increase in sulphate or vice versa and this is best illustrated by the diagrams of Figure 23, analyses #93 and #102, or by Table I, Cat. II, Unit A, Group 4b. In this study, the rSO_4 value at recharge was found to be much smaller than the rCa value. Only rarely did the rSO_4 value surpass appreciably the rCa value.

In the study of this area the most striking observation about the rSO_4 value is the sulphate reduction phenomenon that will be discussed later.

rCl^- – Chloride

The rCl^- value was found to be the most important of the absolute values. In Category II, the chloride content clearly increases within each group. It increases also from Group 1 to Group 8. This means that the chloride content of the groundwater increases from east to west, and also from north to south in Unit B of the same category. An increase in rCl automatically causes an increase in the T.D.S. value; this is the basis from which the groundwater movement as shown in Figure 3 was derived.

A sharp increase is noticeable in the chloride values of samples #31, #32, #33, #36, #97, #98, #82, #83, and #84 (Fig. 3) obtained along a line formed approximately by the junction of the Assiniboine and Red Rivers. This line extends some 20 miles west and 30 miles south of Winnipeg. The sharp increase in chloride value is attributed to evaporite beds in the bedock. Therefore, a line joining the analyses mentioned, along the two rivers, defines the limit of the evaporite beds in this area. The increase is believed by the writer to be too sudden to warrant any other explanation, such as time, distance travelled by the groundwater in the aquifer, etc., although of course these other factors will also have contributed somewhat to the increase in chloride content.

The chloride value is extra important because it controls the solubility of $CaSO_4$. As stated before, the solubility of $CaSO_4$ increases with an increasing value for NaCl to a maximum of 2,250 e.p.m. of NaCl, after which it decreases.

All that has been said about the chloride value can be summarised as follows: the absolute chloride value is one of the most important indicators of the degree of sluggishness of a body of groundwater and therefore of its time of contact with the aquifer, and of the distance it has travelled in the aquifer. Thus the groundwater represented by the analyses of Group 11 (Fig. 34) can be considered as stagnant or as having a minimum amount of movement. Similarly, the groundwater in the till, which is illustrated by the $Cl^- + SO_4^=$ zone (Fig. 3) and the analyses of Groups 9 and 10 (Figs. 31 to 33), can be considered as stagnant or as having a minimum amount of movement. Both of these groundwater zones can thus be considered, in their respective rights, as the discharge end of a body of groundwater.

rCa, rMg, rNa

The absolute values of rCa, rMg, and rNa usually depend on those of the anions, and on base exchanges. Generally, an increase in rCl will cause an increase in rNa, just as an increase in rSO_4 will bring about an increase in rCa and rMg. These facts are well demonstrated by the analyses of Category II.

Relative Values

rSO_4/rCl

Where the mineral concentration is very low, as was found near the recharge area, the ratio rSO_4/rCl tends to vary either way and can be either smaller or larger than one, simply because very small increases in rSO_4 or rCl cause a very large variation of the ratio value.

In confined aquifers this ratio, as shown by the study, generally is less than one; Category III is the exception to this rule. The opposite is generally true in unconfined aquifers.

In general, the rSO_4/rCl ratio decreases from recharge to discharge area, owing to the higher solubility of the chlorides, unless a very high concentration of SO_4 is obtained through the dissolution of a gypsum deposit. The trend mentioned is again reflected in a general way by the analyses of Category II.

rMg/rCa

The rMg/rCa ratio is sometimes characteristic for a body of groundwater. The rMg and rCa values generally increase with increasing rSO_4 and rCl contents. The ratio at the discharge end of the sequence, as shown by the analyses of Category II, Unit A, is usually smaller than one, while at recharge it tends to vary either way. In this study, the ratio was found to be more useful because it indicated whether the water was derived from a dolomitic rock rather than from a limestone rock. It was assumed that the aquifer was dolomitic if the ratio rMg/rCa for the water was larger than one, and limestone if the ratio was smaller than one.

rNa/rMg

The rNa/rMg ratio can also be characteristic for a body of groundwater. But in this study, only the following generalizations can be made. The ratio is usually smaller than one in unconfined aquifers, and in confined aquifers near the recharge end. At discharge it is almost always larger than one. The rNa/rMg ratio is usually much larger than one if the value of rSO_4/rCl ratio is very small and the rMg/rCa value is close to or larger than one. Groups 5, 6, 7, 8, and 11 of Category II (Table I) are good examples of this.

Base Exchange Index

The chemical phenomenon known as base exchange can modify the ratios existing between the cations of Ca, Mg, and Na. This phenomenon is here expressed or characterized by a base exchange index (b.e.i.).

If the rCl value is smaller than the rNa value, the b.e.i. is considered to be negative, whereas if the rCl value is larger than the rNa value the index is considered positive. A more complete discussion of base exchange is presented later.

For the present, as far as Table I is concerned, the b.e.i. value of each analysis is calculated from $\frac{rCl - rNa}{rCl}$ In this study, all the analyses in one group usually have either a positive or negative b.e.i. Generally, however, the b.e.i. is negative at recharge and positive at discharge. This fact should be kept in mind as it will be used later to determine groundwater movement and even to define groundwater flows.

There is also the possibility that a relationship exists between the base exchange index and the sulphate reduction phenomena, especially if the b.e.i. is negative. No explanation for this is available, but the fact remains that the sulphate reduction phenomena is most complete when the b.e.i. is strongly negative. This is illustrated by the diagrams of Figures 19 to 22.

Solubility Value of $CaSO_4$

The solubility value of $CaSO_4$ is represented on the semi-logarithmic graph by the value indicated by the intersection of the vertical (S) line with a line joining the rSO_4 value and the rCa value of the analysis in question.

In Table I, the numerical value of S_1 is arrived at by taking $\sqrt{(rCa)\,(rSO_4)} = S_1$.

Using analysis #171 (Fig. 25) as an example, we have a value of 1.95 e.p.m. for S_1 on the graph (Fig. 25) and in Table I. Knowing that the solubility of $CaSO_4$ is controlled by the concentration of NaCl in the water, we must determine the NaCl value of the water. The chloride value of analysis #171 is given as 2.54 e.p.m. (Table I). So the NaCl value is approximately 2.54 ÷ 0.6 or 4.23 e.p.m. Using the solubility scale of $CaSO_4$ (Fig. 8B), we find that the $CaSO_4$ saturation point for an NaCl concentration of 4.23 e.p.m. is between 31 and 32 e.p.m. Therefore the low value of 1.95 e.p.m. which we have calculated for S_1 is far below the saturation point. In other words, the groundwater of analysis #171 is not saturated in $CaSO_4$.

Kr of equilibrium

The Kr of the water is the amount of $CaCO_3$ (in e.p.m.) that the water can dissolve. In other words, it gives the solubility of $CaCO_3$ in the water. As the groundwater is generally saturated in $CaCO_3$ the Kr_1 value of a water becomes the free CO_2 value of the water.

The Kr_1 value of each analysis is found on the graph as the e.p.m. value given by the intersection of the vertical line (Kr eq.) with a line joining the absolute $rHCO_3$ and rCa values of the analysis in question.

In Table I, the calculated numerical value of Kr_1 is derived from the equation:

$$\sqrt[3]{(rHCO_3)^2\ (rCa)} = Kr_1$$

Using analysis #114 (Fig. 28) as an example, we have for Kr_1 a value of 3.58 e.p.m. on the graph (Fig. 28) and on Table I.

The water can still be considered as aggressive, if the CO_2 of equilibrium (value of pH of equilibrium, in e.p.m.) is less than the free CO_2 (Kr_1 value of water in e.p.m.), even though the water may be saturated in $CaCO_3$. This surplus of CO_2 is then called aggressive CO_2. In the case of analysis #114 (Fig. 28), we know that the water is saturated in $CaCO_3$, and yet the Kr_1 value of 3.58 e.p.m. (Table I) is larger than the pH of equilibrium value of 2.90 e.p.m. (Table I) and also larger than the value of the corrected pH of equilibrium of 3.57 e.p.m. (Table I). Therefore, the groundwater represented by analysis #114 can still dissolve $CaCO_3$ even though it is saturated in $CaCO_3$. It will then become supersaturated.

The diagrams of Category II, Unit A, show that, at the recharge end of the sequence (Figs. 16 to 29), the Kr_1 value of the analyses is larger than the value of the pH of equilibrium. Consequently, $CaCO_3$ is still being dissolved in all the waters represented by Figures 16 to 29. For the remaining diagrams the opposite applies. At the discharge end of the sequence (Figs. 23 to 27), the pH-of-equilibrium value is larger than the value of the Kr_1 equilibrium and, because the solution is no longer in equilibrium, the $CaCO_3$ will precipitate. This is clearly reflected on the diagrams (Figs. 30 to 34) by a decrease in the $rHCO_3$ value. The farther the groundwater is from recharge, the lower is the bicarbonate value.

pH of equilibrium

This value is important because it shows whether or not the water is saturated in $CaCO_3$. Besides, from this value is derived the corrected pH of equilibrium (in e.p.m.), which is used in this report to help in the grouping of the 173 analyses.

The pH-of-equilibrium value can be found on the graph as the value indicated by the intersection of the vertical line (pH eq.) with the line joining the $rHCO_3$ value and rCa value of the analysis in question (and used earlier for the determination of the Kr of equilibrium). The two intersecting lines can be made simultaneously on the graph to save time.

In Table I, the pH-of-equilibrium value (pH eq.) is derived from

$$\sqrt{(rCa)\ (rHCO_3)} = \text{pH eq.}$$

Analysis #60 (Fig. 28), with a pH eq. value of 2.40 e.p.m. on the graph (Fig. 28) and in Table I, can serve as an example. Allowance has to be made for the temperature (θ) at which the analysis of the groundwater was carried out and for the ionic strength (μ) of the water. The two correction values for θ and μ are added to the pH-of-equilibrium value of the water to give the corrected pH eq. of the water.

The value of μ for analysis #60 is 0.22 e.p.m. as shown in Table I. It is derived from the equation (Schoeller, 1961):

$$\mu = \tfrac{1}{2}\,[2rCa + 2rMg + rNa + rCl + 2rSO_4 + rHCO_3] \times 10^{-3}$$

Therefore the ionic strength of analysis #60 equals

$$\mu = \tfrac{1}{2}\,[(2 \times 1.16) + (2 \times 1.49) + 15.83 + 10.46 + (2 \times 3.44) + 4.97] \times 10^{-3}, \text{ or } \mu = 0.22$$

The Δ pH for various values of μ (ionic strength) are

Table III

Values to be added to the pH of equilibrium
(after Schoeller, 1961)

μ	Δ pH	μ	Δ pH	T°C	θ	T°C	θ
0.001	0.12	0.017	0.48	0°	+ 0.50	16°	+ 0.18
0.002	0.16	0.018	0.49	1°	+ 0.48	17°	+ 0.16
0.003	0.20	0.019	0.51	2°	+ 0.46	18°	+ 0.14
0.004	0.23	0.020	0.52	3°	+ 0.44	19°	+ 0.12
0.005	0.26	0.021	0.53	4°	+ 0.42	20°	+ 0.10
0.006	0.28	0.022	0.55	5°	+ 0.40	21°	+ 0.08
0.007	0.31	0.023	0.56	6°	+ 0.38	22°	+ 0.06
0.008	0.33	0.024	0.57	7°	+ 0.36	23°	+ 0.04
0.009	0.35	0.025	0.58	8°	+ 0.34	24°	+ 0.02
0.010	0.37			9°	+ 0.32	25°	+ 0.00
0.011	0.39			10°	+ 0.30	26°	− 0.02
0.012	0.40			11°	+ 0.28	27°	− 0.04
0.013	0.42			12°	+ 0.26	28°	− 0.06
0.014	0.44			13°	+ 0.24	29°	− 0.08
0.015	0.45			14°	+ 0.22	30°	− 0.10
0.016	0.47			15°	+ 0.20		

derived from the following equation (Schoeller, 1962):

$$\Delta \text{ pH} = 3.618 \sqrt{\mu}$$

Table III gives the various values of Δ pH and θ to be added to the pH of equilibrium for different values of ionic strength and temperature.

Knowing $\mu = 0.022$, the Δ pH of analysis #60 is 0.55 while θ is + 0.02. Therefore, the corrected pH of equilibrium of analysis #60 is 2.40 + 0.55 + 0.02 = 2.97 e.p.m. Using the solubility scale of the pH of equilibrium (Fig. 8A), we find that 2.97 e.p.m. equals 7.3 + on the analytic scale. The analytic pH of the water or the pH of the water determined during the analysis of the groundwater sample in the laboratory is 8.1. This last value is larger than the corrected pH of equilibrium value which is 7.3 +, which means that the water is supersaturated in $CaCO_3$.

The opposite is true of analysis #121 (see Fig. 27 and Table I). The corrected pH of equilibrium is calculated as 1.12 e.p.m. which, converted by the solubility scale of the pH of equilibrium, gives an analytical pH of 8.1 +. At the same time, the analytic pH of the water is given as only 7.8. Consequently, the water is not saturated and is still aggressive towards $CaCO_3$.

It is stressed again that in most cases groundwater is saturated in $CaCO_3$ or is very near the saturation point. The 173 analyses in this report substantiate this.

In general, the analytic pH decreases as the groundwater progresses from recharge to discharge. At recharge, pH values of 8 or more are not uncommon (Table I), whereas by the time the water has reached the conditions shown by Figures 19, 21, 22 and 23 in Category II, Unit A, the analytic pH value drops to 7.8. In the chloride zone, as shown by Group 11, of Category II, Unit A (Fig. 34), the only analytic pH value available is 6.0.

This agrees with statements made earlier, that at recharge the groundwater is predominantly a bicarbonate type of water, therefore the pH should be basic, and from there the groundwater tends to become more acidic.

CHAPTER 8

Three Modifying Phenomena

As demonstrated in the foregoing paragraphs, the chemical composition of groundwater changes as the groundwater travels through the aquifers. This change in chemical composition is mainly brought about by dissolution. But other chemical phenomena can also change the chemical composition of groundwater and three which are considered most important will be discussed. They are: reduction; ion exchange; concentration.

REDUCTION (SULPHATE)

The sulphates are most strongly affected by reduction, a fact that is believed to be well illustrated in this study of the Red River Valley. Therefore, only sulphate reduction will be here considered. First, the known facts concerning sulphate reduction will be outlined and then applied to the area.

1) Some analyses of groundwater yield abnormally low sulphate values as compared to other analyses taken from the same aquifer.

2) The low rSO_4 content is always associated with the presence of organic matter.

3) The sulphate reduction is not caused by the organic matter itself, but by a very specific anaerobic micro-organism, *Sporovibrio desulfuricans,* and its varieties.

4) The reduction is accompanied by oxidation of the organic compounds, by the production of CO_2, which in turn will produce large quantities of HCO_3 and H_2S.

These four points pertaining to the phenomenon of sulphate-reduction are well illustrated in this area, and are regarded as evidence for the occurrence of sulphate reduction in the area under study. First, it is obvious that the sulphate value of the groundwater in unconfined aquifers is low (see Figs. 9 to 12), but this low value is not believed to be due mainly to sulphate reduction. Therefore, the analyses of Category II, Unit A, will be used to demonstrate how this sulphate reduction takes place.

1) The low sulphate values were first encountered by the writer in 1961, east of St. Pierre, Manitoba (see Fig. 38). In some cases the sulphate value was nil (e.g. analyses #54, #56, and #78), and in a dozen more analyses it was less than 0.09 e.p.m. Figure 38 shows the area where abnormally-low sulphate values were found in the Red River Valley. All the wells concerned are believed to yield groundwater from a confined aquifer; they vary in depth from 18 feet to 400 feet. The writer believes that once the groundwater in this area has reached depths of 100 or more feet, the sulphate content of the groundwater should have increased similar to the values for the other salts in the water. This should be especially so in Groups 3a and 3b (see Fig. 22) and analysis #57 of Group 5a (see Fig. 26).

2) At recharge, the surface water lying above the till in the bogs and marshes is believed to infiltrate slowly, first into the semi-permeable till and eventually into the bedrock aquifers below it. Therefore, the peat bogs form the required source of organic matter in the groundwater.

3) Because the water has first gone through the peat bogs, which are the source of organic matter, it is only a matter of time for the sulphate-reduction process to be carried out by the micro-organisms as the groundwater flows through the aquifers.

4) The region from La Broquerie to St. Pierre has many flowing wells (see Fig. 4); in every case where abnormally low sulphate values occur the smell of H_2S was detected at the well site at the time the groundwater sample was taken.

Figure 4 was made to illustrate groundwater movement in the area, and amongst other things helps to explain the following point. The writer makes use of the sulphate reduction phenomenon in the investigation of groundwater movement. He believes that the groundwater flow that starts in the highlands of Sandilands Forest Reserve should be directed (on the west side of the highland area at least) predominantly towards the southwest, as indicated by a large arrow on Figure 4. But no strong flow does exist there. Instead, it is assumed that the direction of the *main* flow of groundwater coming from the highlands is to the northwest, following a line passing through La Broquerie, Steinbach, and St. Pierre. If this assumption is valid, then the aquifers along that flow path must be more permeable, and the path itself should then be viewed as a porous channel. All of this becomes understandable if explained by sulphate reduction. It has been well established that the groundwater must be in contact with organic matter before the phenomenon can occur. In this case, the peat bogs at the foot of the highlands are the necessary contact zone. If the groundwater in the aquifers downstream from and underneath these peat bogs has a low sulphate value, this means that infiltration of the surface water from the peat bogs is taking place. It was shown (Fig. 38) that low sulphate values do exist near St. Pierre. These low values

have been explained by sulphate reduction. Therefore, it is assumed that infiltration does take place along the path previously described and the zone must then be considered more porous and permeable than the area surrounding it.

In summary it can be stated that sulphate reduction causes an increase in CO_2, reflected by an increase in the $rHCO_3$ value. This is apparent on the graphs of Figures 19 to 22. There is a simultaneous production of H_2S, which was detected at the time of sampling. In addition, a decrease takes place in the values of rCa and rMg, as shown by analysis #57 (Fig. 26).

Schoeller (1955) has classified the sulphate-reduction phenomena as to time, as actual and ancient phenomena. The actual phenomenon takes place at the present time and is mainly characterized by an absence of sulphate and a presence of H_2S. This is the situation prevailing in the Red River Valley. On the other hand, the ancient phenomenon took place long ago. It is characterized by the absence of sulphate in combination with the absence of H_2S. The latter would be valid in oil fields at the discharge end of a groundwater system.

To conclude, it is believed that the low sulphate values of the analyses taken near St. Pierre, Manitoba, are due to sulphate reduction.

ION EXCHANGE (BASE EXCHANGE)

Although anion exchange is possible, we are dealing strictly with cation or base exchange in this discussion. The base exchange phenomenon can completely change the ratios between the cations Ca, Mg, and Na. It can also change the total concentration value, either by increasing it or by decreasing it.

Clays are known to give positively-charged colloids, which are able to fix and exchange cations. This is especially true of sodium montmorillonite, which is known to have a high exchange capacity. The infiltration map (see Fig. 1) reveals that 49 per cent of the area under study is covered by such a clay. In this report the clay is regarded as an aquiclude. But it is known that the presence of clay in an aquifer can change the permeability value of that aquifer, to an extent depending on whether the water is fresh or saline. The fresher the water, the more the clay will swell, reducing the permeability. Consequently, the high ion-exchange capacity of sodium montmorillonite clays may have a great influence on the permeability of the various aquifers in the area.

In this study, the base exchange phenomenon is characterized by a base exchange index (b.e.i.). The fact that each analysis shows a base exchange index does not necessarily mean that base exchange has actually taken place; this is especially true when the base exchange index is negative.

The exchange index is indicated on the graphs by the unequal value of rCl and rNa, that is, by an oblique line joining rCl and rNa. The index is positive when the line dips to the left and negative when the line dips to the right. The dip of the line is more pronounced if the exchange index has a larger absolute value.

The negative base exchange tends to diminish the rCa and rMg values while it increases the rNa value (see Figs. 20 to 24). The rMg/rCa ratio is usually larger for a negative base exchange than for a positive exchange, because of a decrease in rCa which may in turn be due to sulphate reduction. Because rCa diminishes, the CO_2 of equilibrium also drops while aggresive CO_2 increases. Consequently the $rHCO_3$ value goes up (see Figs. 20 and 21).

The positive base exchange tends to increase the rCa and rMg values while it diminishes comparatively the rNa value (see Figs. 12, 31 and 32). In this study, it causes an increase of the rMg/rCa ratio for water from unconfined aquifers (see Fig. 12), whereas it causes a decrease of the ratio in confined aquifers (see Figs. 31 and 32). The more rCa increases, the more $rHCO_3$ will decrease (see Figs. 31 and 32), because the groundwater is saturated in $CaCO_3$. Although the rCa value increases, the increase in rSO_4 is not so evident, because the saturation point for $CaSO_4$ is gradually being approached.

Much has been said about ion exchange but it is still difficult to determine whether or not the phenomenon has taken place. The best examples of base exchange among all the analyses displayed in this report seem to be given by the analyses shown in Figures 31 and 32. Comparing the diagrams in the two figures with those of Figure 33, it seems obvious that the b.e.i. line of the analyses in Figures 31 and 32 should be almost horizontal, as it is for the analyses in Figures 30 and 32. But instead of this, the b.e.i. is strongly positive. In other words, the rNa value has decreased while the rCa and rMg values have increased. Adding the fact that these analyses were derived from till that basically consists of sodium montmorillonite clays, it seems reasonable to explain the peculiarity of the analyses in Figures 31 and 32 by base exchange.

The only other group of analyses that displays a strong positive b.e.i. is Group 4 in Category I (see Fig. 12). In almost every case, the groundwater represented by the analyses in this group was derived from unconfined aquifers in silty clay. The peculiarity of these analyses is a high rCl value. No explanation can be given for this relatively high chloride value other than that these same analyses also have a high nitrate value. It seems more than a coincidence that the common anions in clay minerals are $SO_4^{=}$, Cl^-, PO_4^{3-} and NO_3^-. This has been mentioned to indicate that these analyses may be a good example of anion exchange. The exchange, if it does occur, would be between the Cl^- and NO_3^- ions.

Figure 39 shows eleven analyses with a low total hardness value (#57, #59 to #63 and #65 to #68) from the

vicinity of St. Pierre, Manitoba. This groundwater, with the possible exception of #57, is believed to be obtained from the dolomitic limestone aquifer of the Red River Formation. Instead of having a total hardness between 200 and 400 p.p.m., as is generally encountered in the groundwater of the other wells of the region, it has a total hardness of less than 134 p.p.m., so it must be considered as soft water. The location of these soft-water analyses on Figure 39 indicates that they occur at the extreme western tip of the sulphate-reduction zone previously described on Figure 38. On Figure 39 two values are given for each analysis. The top value is the total hardness and the lower value is the sodium-bicarbonate content of the water. In every one of these analyses, non-carbonate hardness is absent. Consequently, the total hardness is all carbonate hardness (or temporary hardness) and the difference between the alkalinity value and the total hardness value is all sodium bicarbonate. Sodium bicarbonate waters are generally soft (Thomas, 1953). As a matter of fact, the higher the sodium bicarbonate value, compared to the total hardness as shown on Figure 39, the softer the water.

To find an explanation for this soft-water zone, three ideas were followed.

First, when the area around St. Pierre, Manitoba, was studied by the writer in 1961, it was thought that the eastern limit of the rocks of the Red River Formation may not extend as far east as was assumed initially, as shown on Figure 2. Moving the linestone contact farther to the west was believed to be adequate to solve the soft-water phenomenon at St. Pierre. If the groundwater did not come into contact with the limestone aquifer so far to the east, then it would not be able to dissolve the Ca and Mg salts and would therefore be classified as soft water. Further studies to the east of this area in 1963, however, showed that wells to the east of the soft-water zone yield hard water instead of the soft water that would be expected if the absence of limestone were regarded as the cause of the soft water. Therefore, this idea was abandoned as a solution to the soft-water phenomenon at St. Pierre, Manitoba. Nevertheless, the assumed eastern limits of the rocks of both the Red River Formation and the Winnipeg Formation have been shifted westward because of the accumulation of new geological data since the start of the study.

Secondly, it was thought that upward movement of soft groundwater from the sandstone of the Winnipeg Formation into the Red River Formation could occur, possibly through the well represented by analysis #57, causing the soft water which occurs near St. Pierre. But this could not be proven and did not seem very probable.

Thirdly, it seemed possible to explain the occurrence of the soft water by base exchange and on this basis was assumed to be a good example of base exchange with a negative base exchange index. The remarks made previously in this report about negative base exchange hold true for the eleven analyses considered here as representative of soft water. The decrease in rCa and rMg may be partly due to sulphate reduction, because the analyses are at the western end of a reduction zone, but if these decreases are largely due to base exchange between Ca, Mg, and Na, then the softening of the water would occur naturally in the same way in which it is done commercially with the use of zeolites. This third line of thought seems to be the best explanation for the soft-water zone occurring near St. Pierre.

The discussion of ion exchange illustrates the possibility of ion exchange under three different aspects; a cation and anion exchange with a positive base exchange index; a cation exchange with a negative base exchange index.

From the semi-logarithmic diagrams, one can see that if the analyses are plotted by their rCl value, the low rCl values correspond to a negative base exchange index (see Figs. 16 to 22), whereas the high values of rCl correspond to a positive base exchange index. Knowing that the general direction of groundwater movement is from low T.D.S. values to high T.D.S. values, it follows that groundwater movement will also be from low rCl values to high rCl values and consequently from a negative exchange index to a positive exchange index. The latter part of the statement will be useful later on in this report to show the direction of groundwater movement, as illustrated on Figure 3. It will be especially useful to distinguish the different groundwater flows.

CONCENTRATION

Changes in mineral concentration of water can be caused by evaporation and dissolution. Evaporation, mainly a surface phenomenon, will not be discussed here.

Dissolution is increased or decreased depending on many factors, such as temperature, pressure, type of aquifer, rate of flow, and time of contact. Higher temperatures and pressures increase the concentration of minerals in groundwater by dissolution. Similarly, if the rate of movement of a groundwater is slow, due to low porosity and poor permeability, then the long period of contact of the water with the aquifer will also cause an increase in the concentration of minerals in the groundwater. The factors mentioned are all known, but exact figures on the influence of each individual factor are not available in this study.

Nevertheless, because it is known that the groundwater in the area under study is generally saturated in $CaCO_3$, it seems logical to assume that the salts of NaCl and $CaSO_4$ should be affected most strongly by dissolution. It is also known that the concentrations of these salts in a groundwater have a tendency to increase with their concentrations in the rock or aquifer. It is thus safe to state that groundwater passing through saliferous beds or gypseous formations will contain an increased concentration of these salts.

In this report, dissolution of NaCl and $CaSO_4$ seems to take on great importance. Figure 3 shows that the total dissolved solids values of the analyses actually increase with 1,000, 2,000, 3,000 and even more parts per million from the $SO_4^{=} + Cl^-$ zone to the $Cl^- + SO_4^{=}$ zone. This increase occurs in a distance of approximately 3 miles. The higher T.D.S. values of the analyses in the $Cl^- + SO_4^{=}$ zone is due mainly to NaCl and $CaSO_4$ increases by dissolution (Figs. 30 to 33 and 37). The bedrock geology map of the area (Fig. 2) indicates the presence of the Amaranth Formation in the south-central part of the area studied. This formation is known to be associated with evaporite and gypsum beds. Therefore, it may be assumed that the phenomenon of concentration of these salts in the groundwater, by dissolution, is possible in this area, because of the occurrence of the beds. This fact led the author to the discovery of a gypsum bed, as was mentioned earlier. The phenomenon of concentration by dissolution may also be used to outline the eastern limit of the evaporite beds, something which as yet has not been brought out by the geology. This limit could be approximated by joining the location points of analyses #170, #84, #83, #82, #98, #97, #31 and #36. The eastern and northern limits of the evaporite beds should be found somewhat east and north of the line (Fig. 4) if the direction of groundwater flow has a westerly and southerly component, as indicated on Figure 3.

The relatively high NaCl concentration of these analyses causes the groundwater found in that zone to be classified as not potable. This saline zone has another long-range effect in this part of the Red River Valley. It is common knowledge that the "mining" of fresh groundwater that is in contact with saline water tends to lead to a new equilibrium, which is normally reflected by an advance of the salt water zone at the expense of the fresh water. zone, as the density of salt water is greater than that of fresh water. This phenomenon is actually taking place in this area, as was demonstrated by the author in a previous report (Charron, 1965b). The rate of advance of the salt-water zone will grow if the rate of mining or withdrawal of the groundwater is increased. Based on a constant recharge rate, the rate of advance of the salt water in this region has been calculated to be 175 to 525 feet per year, depending on the locality (Charron, 1965b).

Thus far, all the hydrochemical ideas used in this report, have been those presented by Schoeller (1962) in his book "Les eaux souterraines". The present writer has taken these ideas and applied them to the study of the Red River Valley. The idea of presenting the analyses in groups, however, by using both diagrams and Table I so that a sequence was formed, is new. On the basis of all of these data, the writer has constructed two maps (Figs. 3 and 4) to further illustrate groundwater movement and its direction of flow. A dissertation of these two maps and their accompanying sections will follow.

But before going on to a discussion of the two maps, it should perhaps be pointed out that the semi-logarithmic diagrams alone, arranged in groups as illustrated, convey the impression of groundwater movement as well as the direction of flow of that groundwater. This is best shown by the analyses of Category II, Unit A, Figures 16 to 31 (and possibly also including Figure 34). When these figures are placed in that order, from left to right, it is easy to visualize the increasing T.D.S. value, from group to group and from chemical zone to chemical zone. The chemical changes tend to give a continuity to the series of diagrams, which shows that the direction of groundwater movement is from Figure 16 to Figure 31 and maybe as far west as Figure 34 or from east to west as illustrated in Figure 3.

CHAPTER 9

A Hydrochemical Interpretation of the Direction of Groundwater Movement, as shown by Figure 3

The base of Figure 3 is the same as that used for Figures 1, 2, and 4. The location points of all 166 groundwater samples obtained for analysis from wells within this area are indicated in Figure 3.

The groundwater sample of each analysis marked "U" was obtained from an unconfined aquifer, while those marked "T" or "B" came from confined aquifers. "T" stands for a confined aquifer in till while "B" stands for a confined aquifer in bedrock. No differentiation is made here between the various bedrock aquifers, such as the dolomitic limestones of the Interlake Group and Red River Formation, or the sandstone of the Winnipeg Formation.

At most of these location points, the following information is available: (1) the number of the analysis, corresponding to a similar number in Table I and on the semi-logarithmic diagrams; (2) the value for total dissolved solids (T.D.S.) of the analysis, in parts per million (p.p.m.); (3) the depth of the well in feet; (4) the sign of the base-exchange index (b.e.i.); (5) the chemical zone in which the analysis falls shown by a colour.

With the data on this map, the writer wants to illustrate, on a horizontal plan, the direction of groundwater flow or movement. It is regarded as relative groundwater movement, as related to the T.D.S. value, to the depth of the well from which the groundwater sample was obtained and therefore to the type of aquifer and to the geochemical zones.

The smaller arrows illustrate the direction of groundwater flow between two analyses. They point from an analysis of a lower T.D.S. value to one with a higher T.D.S. value, keeping in mind depth, aquifer, etc. There are arrows of two colours, green and blue. These distinguish the groundwater flowing in the till aquifer (small green arrows) from that flowing in the bedrock aquifers (small blue arrows). It should be pointed out here that in some cases the arrows seem to indicate upstream flow, as for instance the arrow between analyses #81 and #82. This does not necessarily mean that the actual direction of groundwater movement is from analysis #81 towards analysis #82, but rather that, relative to these analyses the groundwater flow should be in the upstream direction. It should be noted that these upstream arrows are generally confined to one chemical zone. In reality, the general direction of groundwater movement is a composite of all these small arrows and this is indicated by the three larger arrows.

ZONATION

In the natural flow of groundwater, as depth increases and as the groundwater moves farther downstream away from recharge, a change in the predominant ions will take place, which can be summed up as follows: at recharge, groundwater has a bicarbonate character, but during its progress downstream, changes take place, that ultimately change it to a chloride character at discharge. Two full sequences of changes in the predominant ions are given here. The first one, Ignatovitch-Souline, in Siline Bektchourine (1952):

$$HCO_3^- \rightarrow HCO_3^- + SO_4^= \rightarrow SO_4^= \rightarrow SO_4^= + Cl^- \rightarrow Cl^- + SO_4^= \rightarrow Cl^-$$

The other is a sequence given by Chebotarev (1955):

$$HCO_3^- \rightarrow HCO_3^- + Cl^- \rightarrow Cl^- + HCO_3^- \rightarrow Cl^- + SO_4^+ \text{ or } SO_4^= + Cl \rightarrow Cl^-$$

The zones as shown here are plotted on Figure 3, with the use of colours. The location point of each analysis is coloured depending on the predominant ion or ions of that analysis. For example, all analyses of the $HCO_3^- + Cl^-$ zone were coloured red. Figure 3 shows that a complete sequence is rare, but a complete sequence is not necessary to establish the direction of groundwater movement.

The western groundwater flow (flowing east to west), which is the main groundwater flow in this area, gives the following sequences, depending on the region where it is taken. In the southern part of the map, if a line is followed from east to west, in the centre of Township 2 and parallel to Township 2, the sequence is

$$HCO_3^- \rightarrow HCO_3^- + SO_4^= \rightarrow HCO_3^- + Cl^- \rightarrow Cl^- + SO_4^=$$

If another east-west line is drawn farther to the north in Township 4 and parallel to that township, the sequence becomes

$HCO_3^- \rightarrow HCO_3^- + SO_4^= \rightarrow HCO_3^- + Cl^- \rightarrow Cl^- + HCO_3^- \rightarrow Cl^- + SO_4^=$

Similarly a line in Township 6 gives

$HCO_3^- \rightarrow HCO_3^- + Cl^- \rightarrow Cl^- + HCO_3^- \rightarrow SO_4^= + Cl^- \rightarrow Cl^- + SO_4^=$

This last sequence is very similar to Chebotarev's sequence, and it is also the most complete sequence available in the area. Also shown on Figure 3 to describe the direction of groundwater movement in the westerly flow, are various bicarbonate zones (different shades of green), proving that differentiation is possible even in a recharge area where salt concentrations are at a minimum.

As for the eastward flow (flowing west to east), the zone sequences are not as complete. A west to east line in Township 5 gives only

$$HCO_3^- + SO_4^= \rightarrow Cl^- + SO_4^=$$

while a line in the extreme southwest corner in township 2 will give

$$HCO_3^- + SO_4^= \rightarrow SO_4^= + HCO_3^- \rightarrow Cl^- + SO_4^=$$

One more variety in the sequence is available with a line in Township 4 or 7

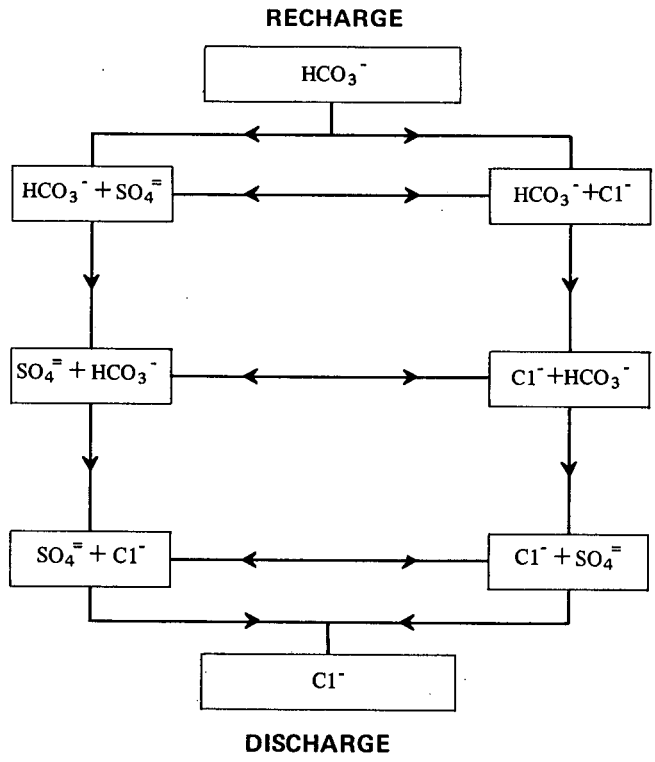
$$HCO_3^- + SO_4^= \rightarrow SO_4^= + Cl^- \rightarrow Cl^- + SO_4^=$$

The southern flow (flowing north to south) is also not very descriptive if compared to the western flow. The main zonal sequence of the southern groundwater flow is

$$HCO_3^- + Cl^- \rightarrow HCO_3^- + SO_4^= \rightarrow SO_4^= + Cl^-$$

Therefore, the writer believes that a complete sequence would be a combination of the two theoretical sequences, that of Ignatovitch - Souline and that of Chebotarev. That being the case, the full sequence of changes in the predominant ions should then be as shown in the diagram (the display of the sequence as a flow-sheet is more realistic because no chemical reaction or equation is implied).

The hydrochemical zonation as explained by Schoeller (1962) is called a vertical zonation. It is based principally on the depth of the aquifer. Vertical zonation, as such, does exist in this area, as is shown in Figure 6, but in general in this report, more use is made of these chemical zones on a horizontal basis as is well illustrated by Figure 3. The direction of the groundwater movement, as shown by the chemical zones, follows in a general way the large arrows, which in turn represent a composite of all the smaller arrows. Thus the direction of groundwater movement can



be derived from the hydrochemistry of the groundwater.

In the chemical zones represented on Figure 3, certain irregularities occur, such as the $Cl^- + SO_4^=$ zone based on the analyses #114 and #117 (in Twps. 9, 10, 11, Rges. 4, 5E). This zone does not fit into the sequence. The irregularity can be used to illustrate the vertical zonation mentioned in the previous paragraph. The groundwater represented by analyses #114 and #117 comes from a depth of 360 feet and 379 feet, respectively, which is considerably deeper than the 236 feet of analysis #116 and the 65 feet of analysis #85, both of which belong downstream from the two analyses in question. If the writer's conclusion that in general the groundwater flows from east to west is correct, then the $Cl^- + SO_4^=$ zone at a greater depth will occur farther to the east than it would at a shallower depth. This is illustrated again on Figure 6.

The last point to be explained on Figure 3 is the groundwater-dividing lines that indicate three sections of the groundwater basin in this area. Surface water divides exist on all hydrological maps, separating the various surface drainage basins. It is believed that similar basins exist for underground water.

The groundwater "divides" were derived as follows. It has been shown by Schoeller (1962) that, for rCl values above 500 e.p.m., the base exchange index is almost always positive. In other words, once a groundwater has reached 500 e.p.m. for its rCl value, its base exchange index is positive and cannot become negative again. If such a change

is found between two points of analysis, it is an indication of a reversal in the direction of the groundwater flow.

The high concentrations encountered by Schoeller do not exist in this map-area, because they are usually restricted to oil fields, as is shown by the semi-logarithmic diagrams in Figure 34. Nevertheless, assuming the same criterion can be applied at low chloride concentrations, like the ones in this area, then a return to a negative base exchange index should indicate that we have left the discharge zone and are approaching the next divide, as indicated by a reversal of groundwater flow. The analyses on the eastern margin of Figure 3 have a negative base exchange index; as one progresses westward, downstream so to speak, the base exchange index becomes positive just beyond a line formed by the Red River in the north-central part of the map-area, and somewhat east of the Red River in the south-central part of the map-area. Based on the foregoing paragraphs, it would be reasonable to assume that, from this line westward, the base exchange index should remain positive. But this is not so, and many analyses on the western margin of the map-sheet have a negative base exchange index. This therefore indicates a reversal in the direction of flow.

In the next example we will follow an imaginary line on Figure 3 from east to west, which approximates the line separating Townships 3 and 4. In the bicarbonate zones, all the analyses in the vicinity of the line have a negative base exchange index. The same applies to analyses #79 (-b.e.i.) and #51 (-b.e.i.). Then we reach analyses #47, #48, and #49, all of which have a positive base exchange index. Going downstream in a westerly direction we come upon analysis #74 (+ b.e.i.), which is situated approximately in the middle of the $Cl^- + SO_4^=$ zone. Still farther westward, we find analyses #12, #13, #14, and #15, all with a positive base exchange index. Finally we reach analyses #10, #11 and #118, which again show a negative base exchange index. Now the question is: where amongst the analyses with a positive base exchange index is the line dividing the westward and eastward flow located? Of necessity, some of these analyses with a positive b.e.i. belong to the flow coming from the east and some belong to the flow coming from the west. In other words, where should analyses #12 and #13 belong? Should they belong with the analyses belonging to the westward flow or with those of the eastward flow and similarly for analysis #74? After further study of the semi-logarithmic diagrams (Figs. 31 and 32) and the cross-section (Fig. 5), it was decided to place the line where it is shown on Figure 3. It is only a coincidence that this dividing line approximates the 800 foot topographical contour line. The other dividing line separating the southward flow from the westward flow was determined in a similar way.

The next question is: where does all the groundwater go after the three flows converge? The groundwater flow from the west is strictly a flow within the till aquifer, with the exception of the upward-moving groundwater from the Swan River Formation. The southward and westward flows are considered to be through the bedrock aquifers as well as in the till. In the till aquifer, the groundwater from the three flows converges in the $Cl^- + SO_4^=$ zone, and this zone can be called the ultimate or Cl^- zone for the till aquifer. Therefore the groundwater, having reached its ultimate goal or discharge end, should be almost stagnant. If movement of groundwater exists in this till aquifer, it should be at a minimum rate of flow, especially in the centre of the Cl^- zone. If this is the case, the movement of the groundwater in the aquifer, after the three flows have met, should be in a northeasterly direction, parallel to the Red River north of its junction with the Assiniboine River, and so towards Lake Winnipeg.

The strongest of the three flows is without a doubt the flow from the east. It is assumed that it will take along with it, on its western route, part of the southward flow. Therefore, the writer believes that the groundwater flow in the bedrock is in a westward direction as indicated by the largest arrow on Figure 3. This main westward flow in the bedrock continues under what is shown on Figure 3 as the eastward flow (this is also illustrated in Fig. 4) until it reaches the oil fields of southwestern Manitoba, represented by the analyses of Category II, Unit A, Group 11 (Fig. 34). At that stage, which is here considered as the beginning of a deep discharge zone, stagnation of the groundwater seems almost inevitable. One way this groundwater could complete the hydrological cycle, that is, return to the sea naturally, would be by an upheaval of the earth's crust.

Before going on to discuss the next figure, the writer would like to point out how well the analyses of Category III fit together on Figure 3. All the analyses within the area under study are plotted on this map. The analyses for which the groundwater was obtained from unconfined aquifers (U) are purposely put in the background and not actually used in this interpretation of groundwater movement. And yet the analyses of Category III, which previously seemed different from those of Category II, because of their chemical characteristics, fit very well in the overall picture and are useful in the interpretation of groundwater movement.

CHAPTER 10

A Topographical, Geological, and Recharge-Discharge Interpretation of Direction of Groundwater Movement, as shown by Figure 4

Figure 4 is basically the same as Figure 3, and the location points for all analyses are shown on both figures. However, the total dissolved solids (T.D.S.) value and the depth of the well is given for only those analyses that are used in this interpretation. The base exchange symbol (±) has also been omitted from Figure 4. In other words, the chemical properties of the analyses are not used in this interpretation.

The topographical contours have more importance in this interpretation of groundwater movement than was the case for Figure 3. The only geological features presented on this figure are those that can assist in the interpretation of groundwater movement in this area. A general strike and dip symbol is shown, which averages as closely as possible the average strike and dip of the bedrock formations encountered in the area. The limit of the evaporite beds, the contact between the sedimentary and the Precambrian rocks, and the southeastern limits of the red shale of the Amaranth Formation are the only geological details given. Three alternatives for the limit of the Amaranth Formation are shown on Figure 4. The dotted line is the interpretation as given in the stratigraphic map series #12, published by the Mines Branch of the Province of Manitoba (1960). The small dashed line, is the interpretation of B.B. Bannatyne (1959) and the large dashed line, is the interpretation by the writer as derived from the hydrogeological study and well inventory of this part of the Red River Valley.

The construction and interpretation of this map are based on two major ideas: 1) both topography and geology control groundwater movement; 2) for every area of recharge there should exist an area of discharge.

Therefore, the first thing done in the construction of the map, after the topographical contours and the geological features mentioned previously had been plotted, was to determine the areas of recharge. This was done with the help of the infiltration map (Fig. 1). The recharge areas in the eastern part of the map are readily seen, but for the western and northern half of the area they are not so easily located. Then the discharge zones or areas were determined and plotted. It may be helpful to explain here what is meant by discharge zones or areas. A flowing well is considered in this report as a discharge point (man-made); a spring is also a discharge point, but a natural one. The two are different in many respects. Therefore, some may disagree with the writer in regarding a flowing well as a discharge point equivalent to a spring. However, once the hole has been made, the continuous flowing of the water is a permanent phenomenon and, from that time on, discharge occurs as from a spring. Because the well inventory consisted of over 10,000 wells, it was very simple to group the flowing wells and determine the zones or areas of discharge.

The largest discharge zone shown on Figure 4 covers a large area northwest of the highlands of Sandilands Forest Reserve. A smaller zone is found in the southwest corner of the map-area, east of Winkler, Manitoba. Another fairly large area is known to have existed northwest of Winnipeg, but only a very small remnant of that still exists today. Because of a lowering in the piezometric level of the groundwater each year, the three zones previously mentioned are decreasing in size. Many other smaller discharge areas exist and these are also shown on the map. They occur mostly in the northeast and extreme southeast-part of the map-area. They are local in extent and help to prove the hypothesis that recharge is never far away. Most of the time it is close at hand as shown by these smaller discharge areas.

It is obvious that the largest of the flowing zones is the discharge area for the groundwater that has its recharge area in the highlands to the southeast, in Sandilands Forest Reserve. The location of the recharge area for the discharge zone near the town of Winkler, Manitoba, is not as obvious and if it lies to the west it must be outside the map-area. Meyboom, et al., describing hydrogeological studies in southwestern Manitoba, came to the conclusion that this must be the discharge zone for the sandstone aquifer of the Swan River Formation. This interpretation is best seen on Figure 5. In the case of the almost extinct flowing zone in the north of the map-area, it is assumed that recharge takes place north of the map-area, as was suggested by Johnston (1934). He established the existence of a recharge area between Lake Manitoba and Lake Winnipeg.

Because topography was assumed to have some control over groundwater movement, arrows were drawn from the recharge zones to the discharge zones, using the topographical contours as control or equipotential lines. The very large yellow arrows 1, 2, 3, represent "basin" flow and

correspond to the large arrows describing the three main flows interpreted from the geochemistry on Figure 3. The large black and red arrows represent regional flow. The red arrow indicates a relatively fast flow, direct from recharge to discharge, while the black arrows represent long term recharge as a slow flow produced by the seepage of the bog water through the semi-permeable till. The smaller coloured arrows represent local groundwater flow. The flowing wells in the vicinity of Piney, Manitoba are a good example of this. But the best example of local groundwater flow is given by analyses #122, #135, and #136 in Townships 9 and 10, Range 7 east of the Principal Meridian. The recharge area for these flowing wells is immediately to the east in the small gravelly hills, which are represented by the 900-foot contour on Figure 4.

Thus in this study, the distance between recharge and discharge is in the order of 1 to 3 miles for the local flow, 3 to 25 miles for the regional flow and 25 to 50 or more miles for the basin flow.

The only other feature of this map yet to be explained, is called by the writer the "true" direction of the groundwater flow. On Figure 3, the small arrows between the location points of the analyses represent the relative direction of groundwater movement between these two points (analyses). On Figure 4, the writer tries to show with the use of the smaller arrows the true direction of groundwater movement at a number of points on the map. They were arrived at as follows. The two criteria used are the total dissolved solids (T.D.S.) value and the depth of the well. Two or more location points are considered at a time; the greater the number of points that can be joined together the better the result will be. The idea is to find at least two location points or analyses with a similar T.D.S. value, which also have a similar well depth. The two points are then joined by a curved line. As mentioned before, if three or four analyses with similar T.D.S. values and similar well depth values can be joined together, the end result should be better. Next, an arrow is drawn normal to the curve. At the point on the curve touched by the arrow, the direction of the arrow is believed to represent the true direction of the horizontal component of groundwater movement. Consequently at any other point on the same curve the true direction of the horizontal component of groundwater flow will be normal to that curve. Again these many small arrows agree in a general way with what has already been illustrated by the geochemistry. It may be argued that the T.D.S. value of the analyses was used in the interpretation of both Figures 3 and 4, and with this the writer agrees, but the approach used to arrive at the same conclusion is different.

Up to a point, Figure 4 explains groundwater movement in the area, but the question remains: where does the groundwater from the three established flows go? The hydrochemical interpretation (Fig. 3) supplies an answer while the interpretation of Figure 4 does not. Therefore, the geochemical approach would seem to give better overall results. Nevertheless, the second approach should not be put aside and forgotten. It proves that, to some extent, topography does control groundwater movement.

Plotting of the various flowing wells to delineate the boundary of the largest of the discharge areas brought forward an interesting problem. It has been known for a long time that the extent of the area of flowing wells related to the westward flow is gradually diminishing. Figure 39 shows how the northwest boundary of the area is retreating towards the southeast. At first, the writer believed that the boundary was retreating uniformly, as a line from the northwest towards the southeast. But this is not so. The fact is that the entire area is "undermining" itself. In other words, many wells to the southeast, within the flowing zone, have stopped flowing sooner than other wells within the same flowing zone but more to the northwest. This is illustrated by Figure 40. Many factors can contribute to this undermining and no single reason can be given at the present time.

Now let us look at the geological features shown on Figure 3. The large dip-strike symbol was placed there to explain geologically the movement of groundwater. It has been shown thus far that this area of the Red River Valley is characterized by three distinct groundwater flows. In relation to the geology of the area, the westward flow can be said to be down-dip (Fig. 5), the eastward flow is up-dip (in the Swan River Formation) (Fig. 5), and the southward flow is approximately along the strike of the rock. This example proves that groundwater will flow in any direction in relation to the strike and dip of the rock strata, depending on the pressures affecting it.

The protruding lense of red shale of the Amaranth Formation shown in the southern part of Figures 2 and 4 provides an explanation for the groundwater movement in that part of the map-area. From the topography, it could be assumed that the groundwater that infiltrates the sandy highlands in the southeast corner of the map-area, should normally flow in a southwesterly direction, as indicated by the large black arrow. Some groundwater does move in that general direction. But the writer believes that the semi-permeable till and the impermeable red shale of the Amaranth Formation act as an impermeable barrier, preventing the groundwater from continuing its normal southwestward course. Assuming this to be the case, the groundwater will then follow a course offering less resistance and the path is indicated in this region by the large red arrow. This explanation may also account for the exceptionally strong flow encountered in the flowing artesian zone, simply because more groundwater is available than would have been the case had the impermeable barrier not existed.

Summary

For every region that one can study, there exists what may be called a practical depth of groundwater. This depth can be defined as the maximum depth at which good potable groundwater is available. From the economic point of view, it can be defined as the depth which will yield the maximum amount of potable water with the minimum cost of recovery. On the other hand, in the oil industry the practical depth is much greater, because the salt content of the water does not have such a decided influence on the usefulness of the water.

In the Red River Valley, the practical depth appears to be, both regionally and locally, that of the unconfined aquifers, as shown by thousands of water-table wells on thousands of farms; but the maximum practical depth at which potable water is available is in the order of 400 to 450 feet. This depth coincides with the depth, given previously in this report, that limits topographical control over groundwater movement.

Most hydrogeological studies deal with groundwater above the maximum practical depth. This study is no exception to this general rule, because all the analyses used to explain groundwater movement, with the exception of the analyses of Figure 34, were derived from above the practical depth. Nevertheless, this hydrochemical study not only has presented some new ideas pertaining to the zones above the practical depth but it has also permitted us to explore below the practical depth.

The study has emphasized many points which may be classified as characteristic of any groundwater body. They are:

1. Most groundwater is saturated or near-saturated in $CaCO_3$.
2. Most groundwater is not saturated in $CaSO_4$.
3. The absolute chloride value is the most important indicator of the degree of sluggishness of a body of groundwater.
4. From recharge to discharge, the groundwater tends to become more acidic.
5. In a continuous groundwater flow, a change from a positive base exchange index (+b.e.i.) to a negative base exchange index (−b.e.i.) is not possible. Where such a change is found, it indicates that we have left the discharge zone and are approaching a new divide. Therefore we have a reversal of flow.
6. In unconfined aquifers, groundwater movement is mainly controlled by topography.
7. In confined aquifers, groundwater movement may be controlled by the topography to a certain depth. That depth depends on the type of region.
8. In confined aquifers the direction of groundwater movement can be determined from the hydrochemistry of the groundwater, after topographical control has ceased to exist.
9. The recharge area for a body of groundwater is often nearby.
10. A flowing artesian zone undermines itself, until a new equilibrium is established.
11. In areas of heavy man-made fresh-water discharge, a salt-water zone may advance at the expense of a fresh-water zone until a new equilibrium is reached.
12. Time is the most important factor in bringing about the chemical characteristics enumerated above.

CONCLUSION

The hydrochemical approach to a hydrogeological study, like the one presented in this report, opens up new horizons and presents the subject of hydrogeology in a new perspective. This study has demonstrated that a hydrochemical approach can be used successfully to determine the direction of groundwater movement on a local, regional and "basin-wide" basis. It also offers the possibility of application on a continental basis.

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CANADA

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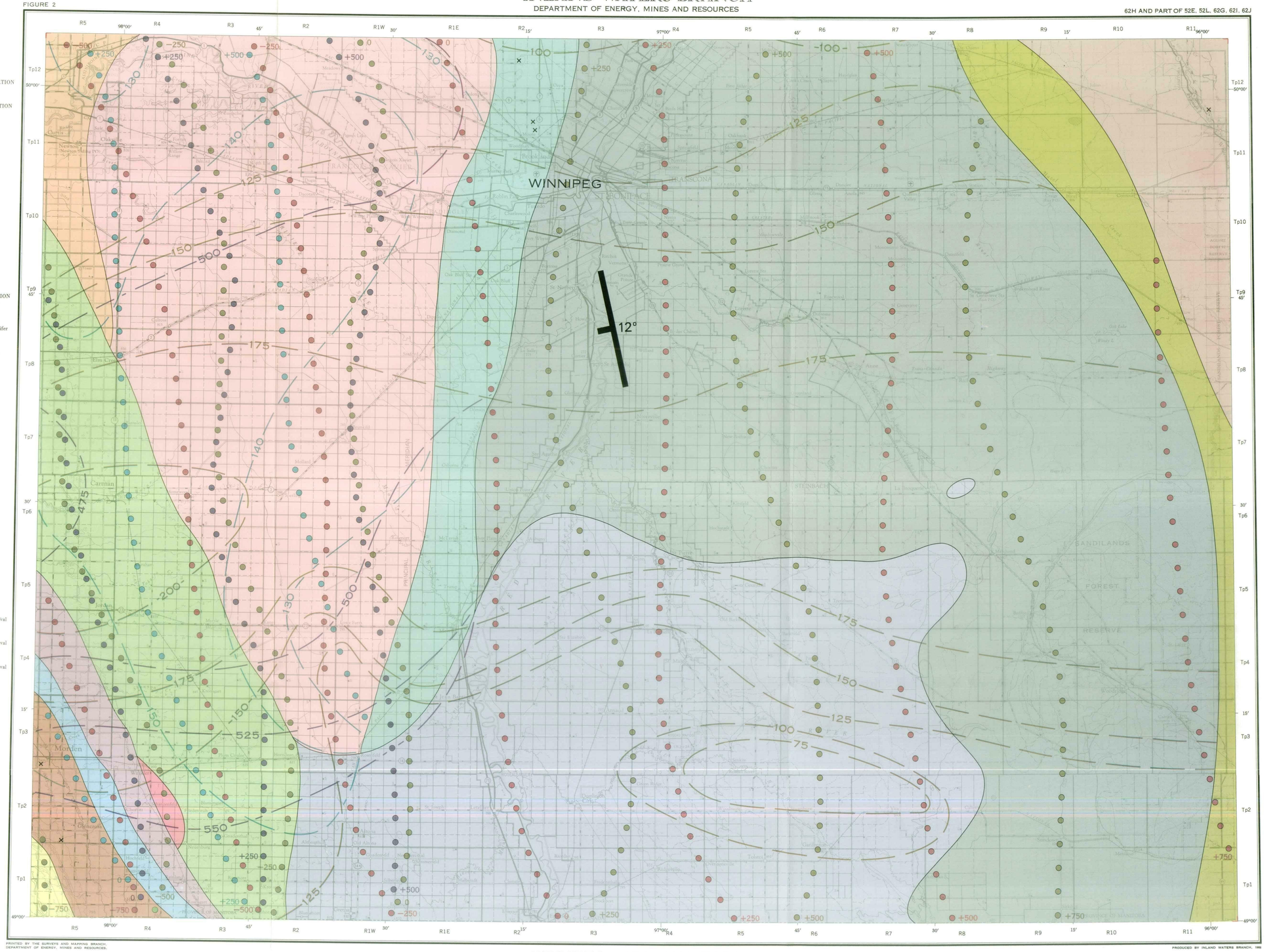
FIGURE 2

62H AND PART OF 52E, 52L, 62G, 62I, 62J



LEGEND

MESOZOIC

CRETACEOUS

- RIDING MOUNTAIN FORMATION — Shale — Aquifer
- VERMILION RIVER FORMATION — Shale — Aquiclude
- FAVEL FORMATION — Shale — Aquiclude
- ASHVILLE FORMATION — Shale — Aquiclude
- SWAN RIVER FORMATION — Sandstone — Aquifer

JURASSIC

- SUNDANCE FORMATION — Shale — Aquiclude
- AMARANTH FORMATION — Shale — Aquiclude

PALAEOZOIC

DEV.

- ELK POINT GROUP — Limestone — Aquifer

SIL.

- INTERLAKE GROUP — Dolomite — Aquifer

ORDOVICIAN

- STONY MOUNTAIN FORMATION — Shale and Dolomite — Aquifer
- RED RIVER FORMATION — Limestone and Dolomite — Aquifer
- WINNIPEG FORMATION — Shale and Sandstone — Aquifer

PRECAMBRIAN

- Granite—Aquiclude

× BEDROCK OUTCROP

STRIKE AND DIP

STRUCTURE CONTOURS

250′ Contour interval

ISOPACHS

500 — 25′ Contour interval

140 — 10′ Contour interval

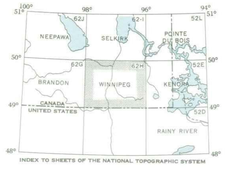
100 — 25′ Contour interval

BEDROCK CONTACT (APPROX.)

Mean magnetic declination 9°E., decreasing 3′ annually. Readings vary from 8°E. to 11°E.

Compiled by J. E. Charron
to accompany Paper by J. E. Charron

Base map prepared by the Surveys and Mapping Branch, 1956
Cartography by the Inland Waters Branch, 1968.
Printed by the Surveys and Mapping Branch, 1968.



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WINNIPEG AREA—MANITOBA
BEDROCK GEOLOGY MAP

SCALE 1:250,000

SCALE OF MILES

SCALE 1:250,000

SCALE OF KILOMETRES

CANADA

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FIGURE 1

62H AND PART OF 52E, 52L, 62G, 62I, 62J

LEGEND

SURFICIAL DEPOSITS PERMEABLE AREAS (Aquifers)
(Covering 1251 square miles or 18% of total area)

FAST RECHARGE

Gravel and sand
Beaches, Kames and Eskers

Gravel and coarse sand
Glacial outwash, sand bar and dune sand

Fine sand
Flood plain deposits

SLOW RECHARGE

Silt
Flood plain and lacustrine deposits

SEMI-PERMEABLE AREAS (Aquifers)
(Covering 2351 square miles or 34% of the total area,
of this 608 square miles or 26% are covered by bogs and marshes)

VERY SLOW RECHARGE

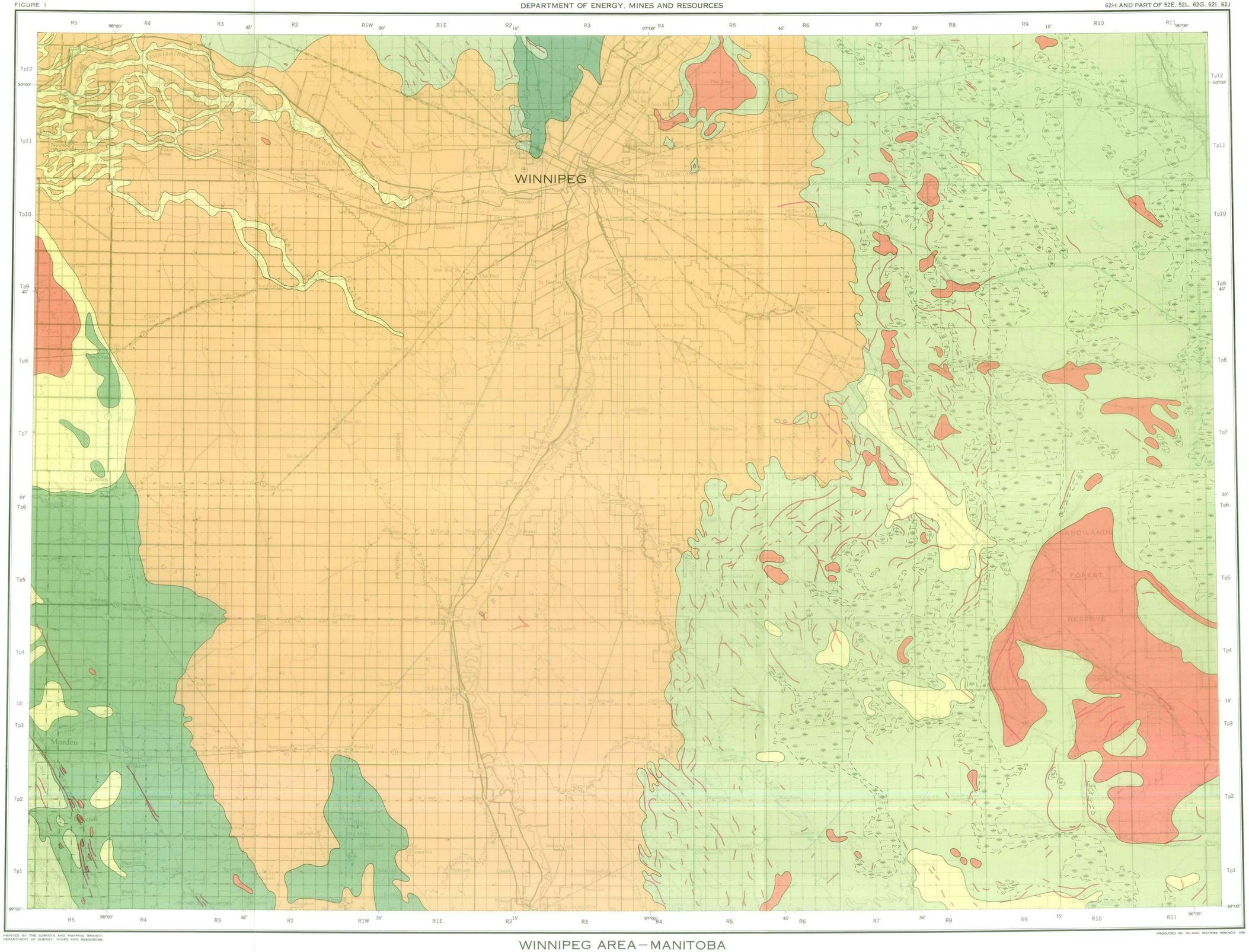
Clayey till
Ground moraine

Bogs and marshes

IMPERMEABLE AREAS (Aquiclude)
(Covering 3400 square miles or 48% of the total area)

NO RECHARGE

Clay
Lacustrine deposits



Mean magnetic declination 9°E., decreasing 3′ annually. Readings vary from 8°E. to 11°E.

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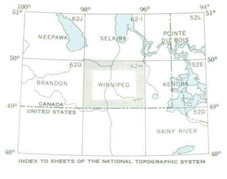

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WINNIPEG AREA – MANITOBA
INFILTRATION MAP

SCALE 1:250,000

5 0 5 10 15
SCALE OF MILES

SCALE 1:250,000

5 0 5 10 15 20 25 30
SCALE OF KILOMETRES

CANADA

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FIGURE 4

62H AND PART OF 52E, 52L, 62G, 62I, 62J

LEGEND

DISCHARGE AREAS

AREAS OF FLOWING WELLS

Recharge area — sandy

Spring

DIRECTION OF GROUNDWATER FLOW

CONFINED AQUIFERS

True direction of the horizontal component of groundwater movement at the point along the curve.

LOCAL FLOW

REGIONAL FLOW

BASIN FLOW

1 — Western flow — down dip

2 — Eastern flow — up dip

3 — Southern flow — along strike

Note: Groundwater flow in unconfined aquifers is not shown as it is believed to be strictly local and controlled by the surface topography.

GEOLOGICAL SYMBOLS

Note: The only bedrock features described are those that affect groundwater movement in the area.

BEDROCK SUBCROP LIMIT

SWAN RIVER FORMATION

AMARANTH FORMATION

Derived from stratigraphic map series #12 (1960), Manitoba, Mines and Natural Resources, Mines Branch.

Author's interpretation (1965)

Derived by Bannantyne (1959)

Limit of evaporite beds

Contact between Western Plains sedimentary bedrock and Precambrian rocks.

STRIKE AND DIP

Bicarbonate zone

Bicarbonate zone

Bicarbonate sulphate

Sulphate chloride

Bicarbonate chloride

Chloride bicarbonate

Chloride sulphate

Location analysis from bedrock (B)

Location analysis from till (T)

Total dissolved solids in p.p.m. — 360 – 117′ — Depth of well in feet

Number of sample (B) — 45 – 61 — Year sample taken

Mean magnetic declination 9°E., decreasing 3′ annually. Readings vary from 8°E. to 11°E.

Compiled by J. E. Charron
to accompany Paper by J. E. Charron

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Cartography by the Inland Waters Branch, 1968.
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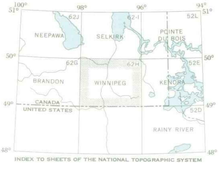

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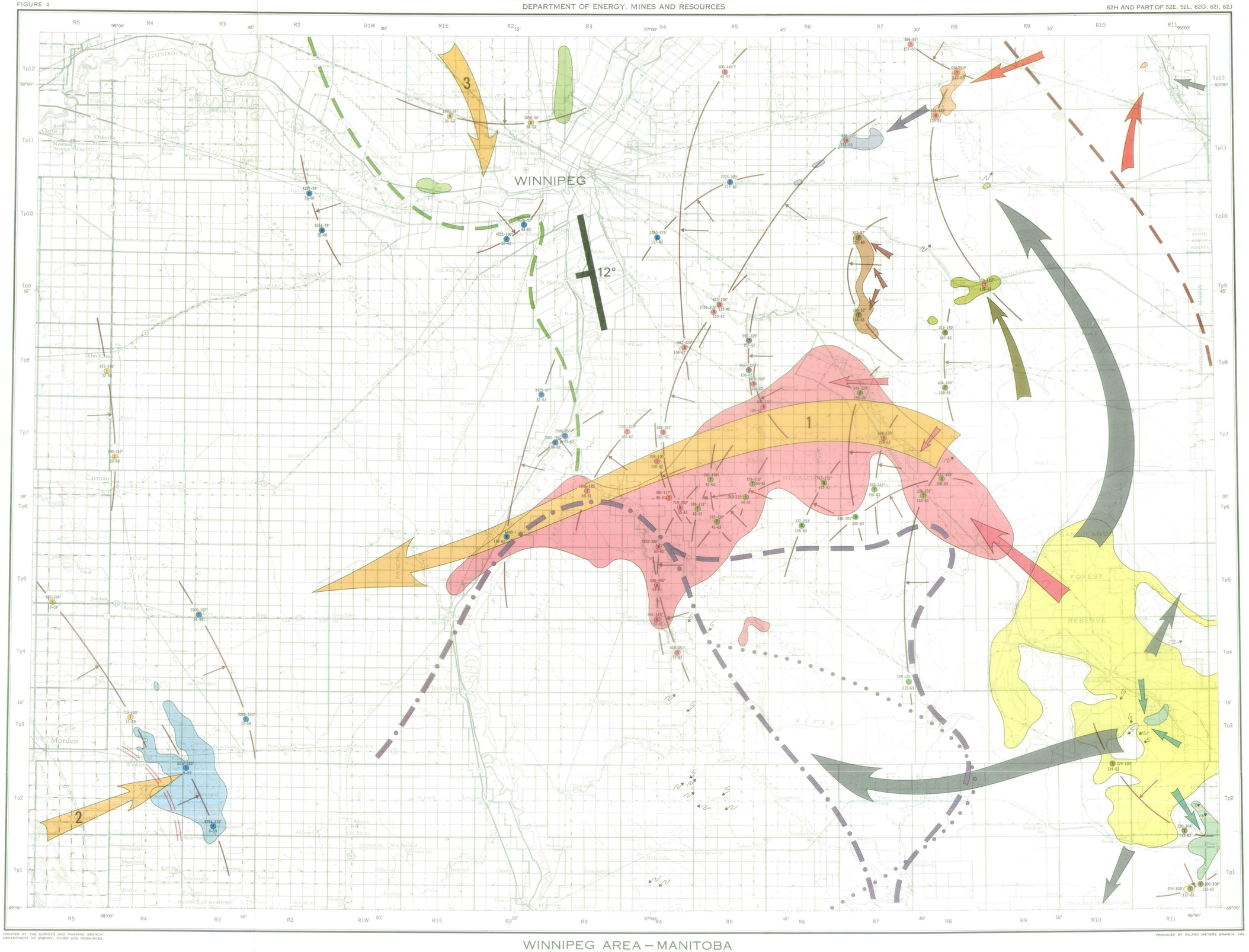

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WINNIPEG AREA – MANITOBA
A TOPOGRAPHICAL, GEOLOGICAL AND RECHARGE–DISCHARGE INTERPRETATION OF DIRECTION OF GROUNDWATER MOVEMENT

SCALE 1:250,000

5 0 5 10 15

SCALE OF MILES

SCALE 1:250,000

5 0 5 10 15 20 25 30

SCALE OF KILOMETRES

CANADA
INLAND WATERS BRANCH
DEPARTMENT OF ENERGY, MINES AND RESOURCES

FIGURE 6

62H AND PART OF 52E, 52L, 62G, 62I, 62J

LEGEND

HYDROCHEMICAL ZONES

- HCO_3^- zone
- HCO_3^- zone
- HCO_3^- zone
- $HCO_3^- + Cl^-$ zone
- $HCO_3^- + SO_4^=$ zone
- $Cl^- + HCO_3^-$ zone
- $SO_4^= + HCO_3^-$ zone
- $SO_4 + Cl^-$ zone
- $Cl^- + SO_4^=$ zone

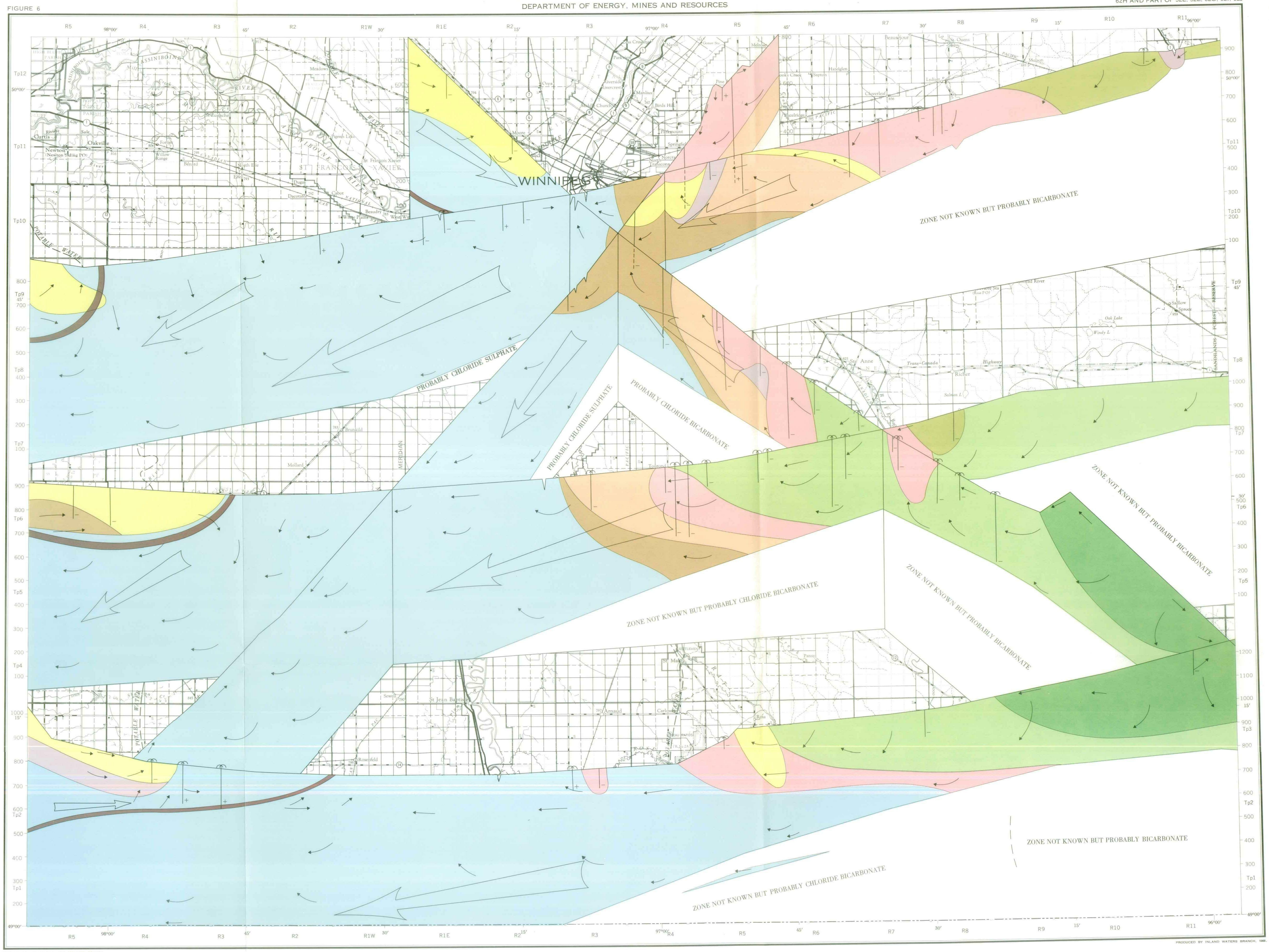
GROUNDWATER FLOW

Primary Flow (Basin Flow)

Secondary Flow (Regional, Local, Artesian Flow)

a) b) Drilled Well: a) Non-flowing b) Flowing Base exchange index ±

Lines dividing major groundwater flows



Mean magnetic declination 9°E., decreasing
3' annually. Readings vary from 8°E. to 11°E.

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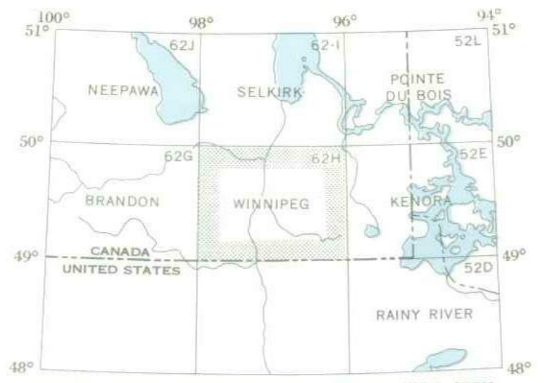

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WINNIPEG AREA – MANITOBA
A HYDROCHEMICAL FENCE DIAGRAM OF THE RED RIVER VALLEY

SCALE 1:250,000

5 0 5 10 15

SCALE OF MILES

SCALE 1:250,000

5 0 5 10 15 20 25 30

SCALE OF KILOMETRES

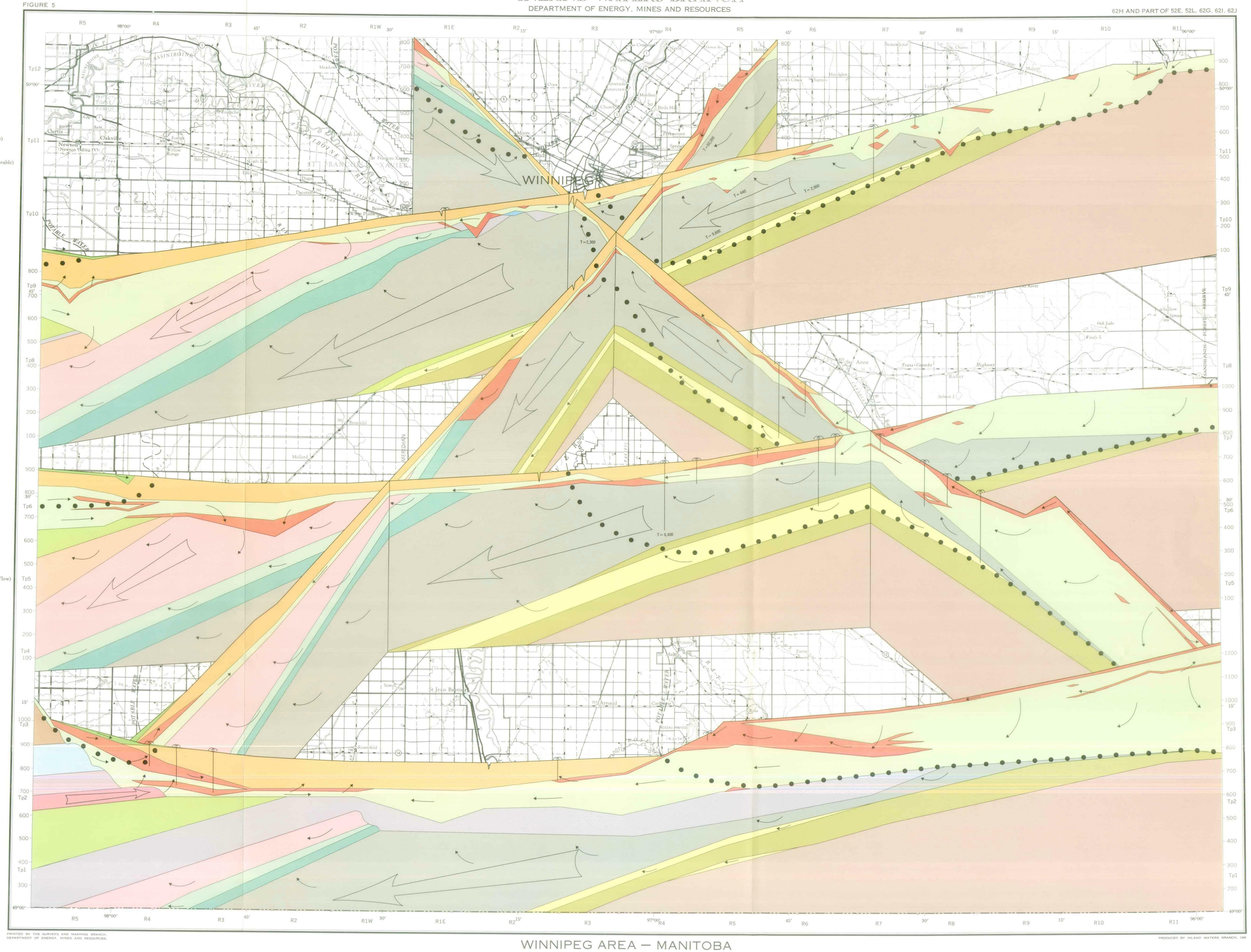
CANADA

INLAND WATERS BRANCH

DEPARTMENT OF ENERGY, MINES AND RESOURCES

FIGURE 5

62H AND PART OF 52E, 52L, 62G, 62I, 62J



LEGEND

CENOZOIC — RECENT AND PLEISTOCENE

- Silt — Aquifer
- Clay — Aquiclude
- Till unconsolidated — Aquifer (permeable)
- Till unconsolidated — Aquifer (semi-permeable)

MESOZOIC — CRETACEOUS — UPPER

- VERMILION RIVER FORMATION — Shale — Aquiclude
- FAVEL FORMATION — Shale — Aquiclude

MESOZOIC — CRETACEOUS — LOWER

- ASHVILLE FORMATION — Shale — Aquiclude
- SWAN RIVER FORMATION — Sandstone — Aquifer

MESOZOIC — JURASSIC

- SUNDANCE FORMATION — Shale — Aquiclude
- AMARANTH FORMATION — Shale — Aquiclude

PALAEOZOIC — DEV.

- ELK POINT GROUP — Limestone — Aquifer

PALAEOZOIC — SIL.

- INTERLAKE GROUP — Dolomite — Aquifer

PALAEOZOIC — ORDOVICIAN

- STONY MOUNTAIN FORMATION — Dolomite — Aquifer
- STONY MOUNTAIN FORMATION — Shale — Aquiclude
- RED RIVER FORMATION — Limestone and Dolomite — Aquifer
- WINNIPEG FORMATION — Shale — Aquiclude
- WINNIPEG FORMATION — Sandstone — Aquifer

PRECAMBRIAN

- Granite — Aquiclude

GROUNDWATER MOVEMENT

- Primary Flow (Basin Flow)
- Secondary Flow (Regional, Local, Artesian Flow)
- Maximum depth of potable water
- Drilled Well: Flowing

T=60,000 Transmissibility in gpd/ft.

Mean magnetic declination 9°E., decreasing 3′ annually. Readings vary from 8°E. to 11°E.

Compiled by J. E. Charron
to accompany Paper by J. E. Charron

Base map prepared by the Surveys and Mapping Branch, 1956
Cartography by the Inland Waters Branch, 1968.
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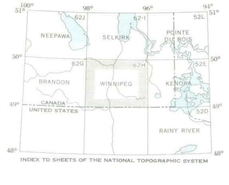

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WINNIPEG AREA — MANITOBA
A HYDROGEOLOGICAL FENCE DIAGRAM OF THE RED RIVER VALLEY

SCALE 1:250,000

5 0 5 10 15

SCALE OF MILES

SCALE 1:250,000

5 0 5 10 15 20 25 30

SCALE OF KILOMETRES

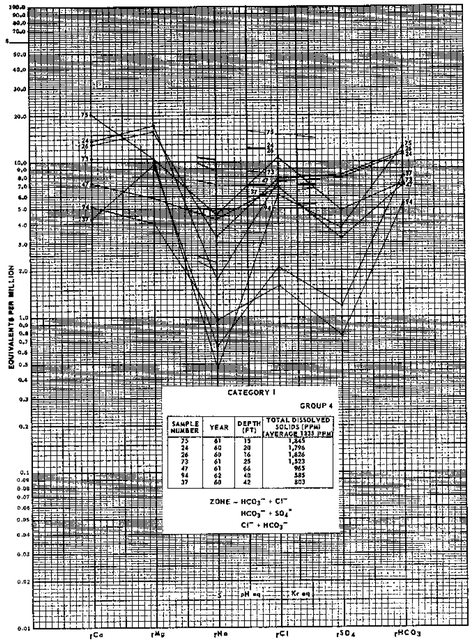

FIGURE 12

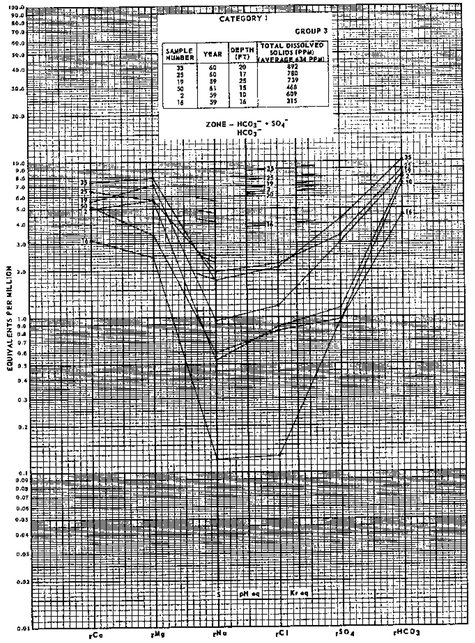

FIGURE 11

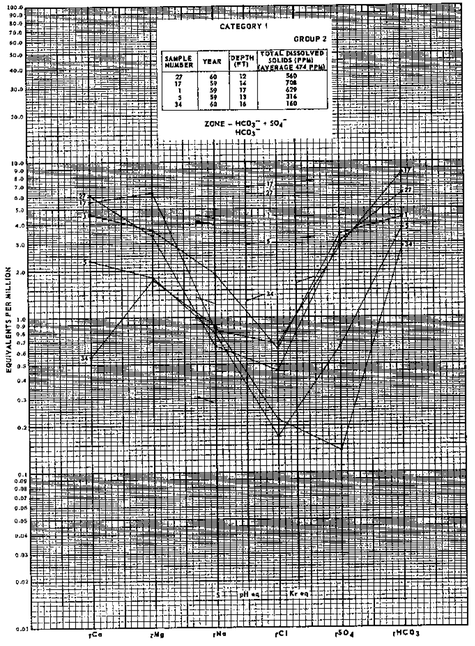

FIGURE 10

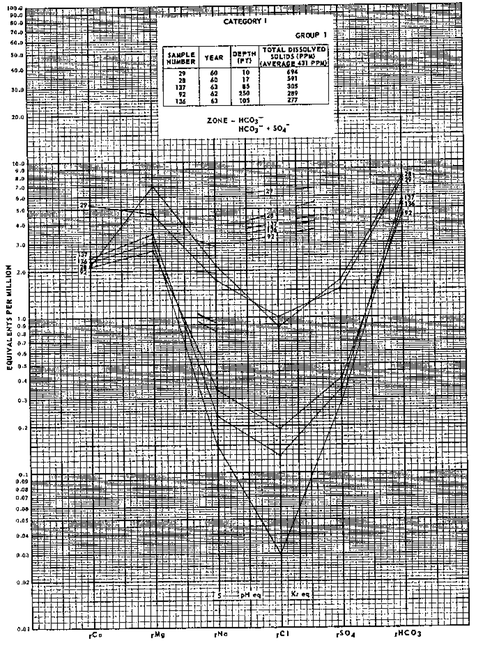

FIGURE 9

SEMI-LOGARITHMIC DIAGRAMS

CATEGORY I

UNCONFINED AQUIFERS
GROUPS 1-4

FIGURES 9-12

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DEPARTMENT OF THE ENVIRONMENT

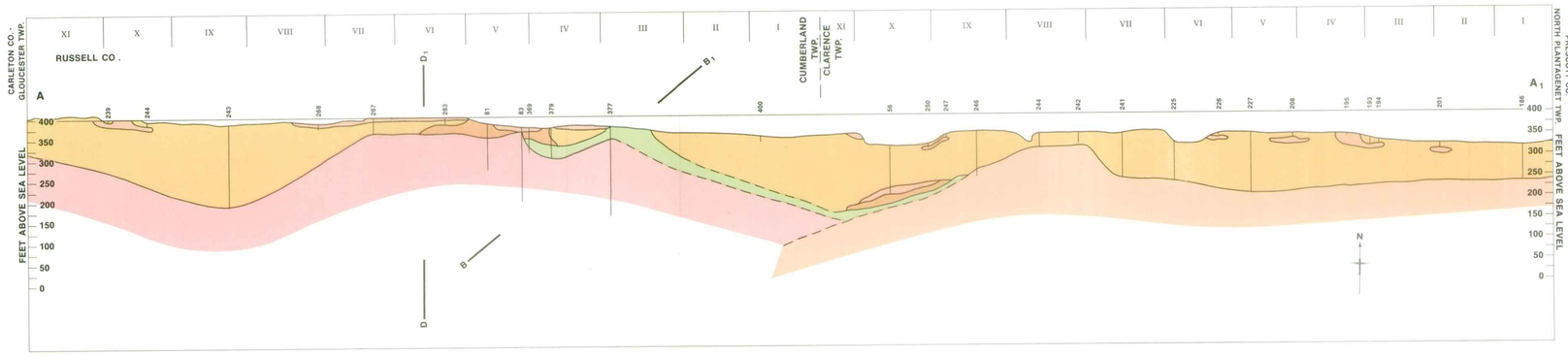


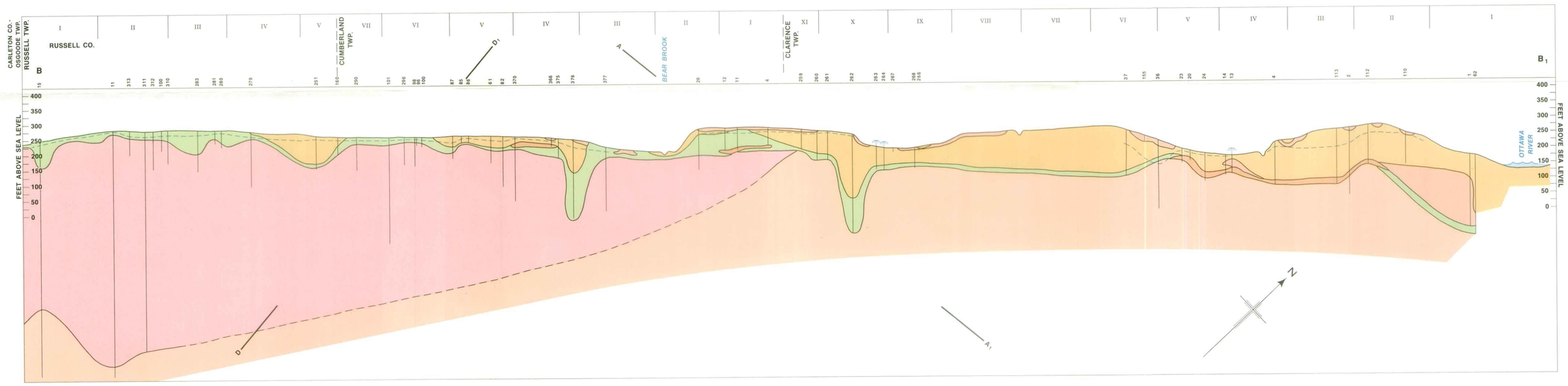
FIGURE 6 - GEOLOGICAL CROSS SECTIONS
A - A1, B - B1, C - C1

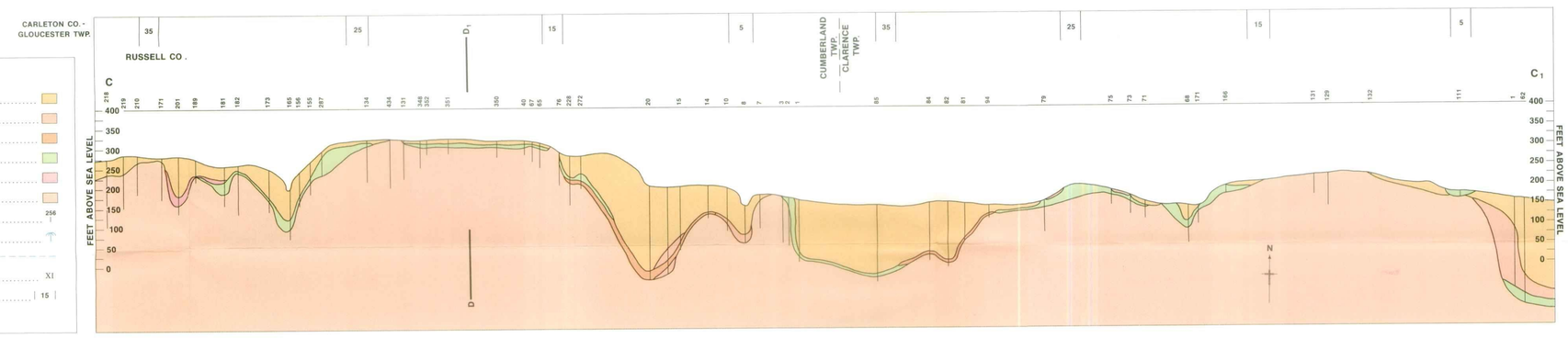
SCALE 1:63,360

SCALE OF MILES

SCALE OF KILOMETRES

Horizontal Scale - 1 INCH TO 1 MILE
Vertical Scale - 1 INCH TO 200 FEET





LEGEND

RECENT AND PLEISTOCENE
- Clay
- Sand
- Gravel
- Till

ORDOVICIAN
- Shale
- Limestone

Well location and identifying number (256)

Flowing well

Piezometric surface

Concession (XI)

Ottawa front lot (15)

Note: Extension of wells no. 11 and 15 were derived from logs of wells obtained from Consumer Gas Co.

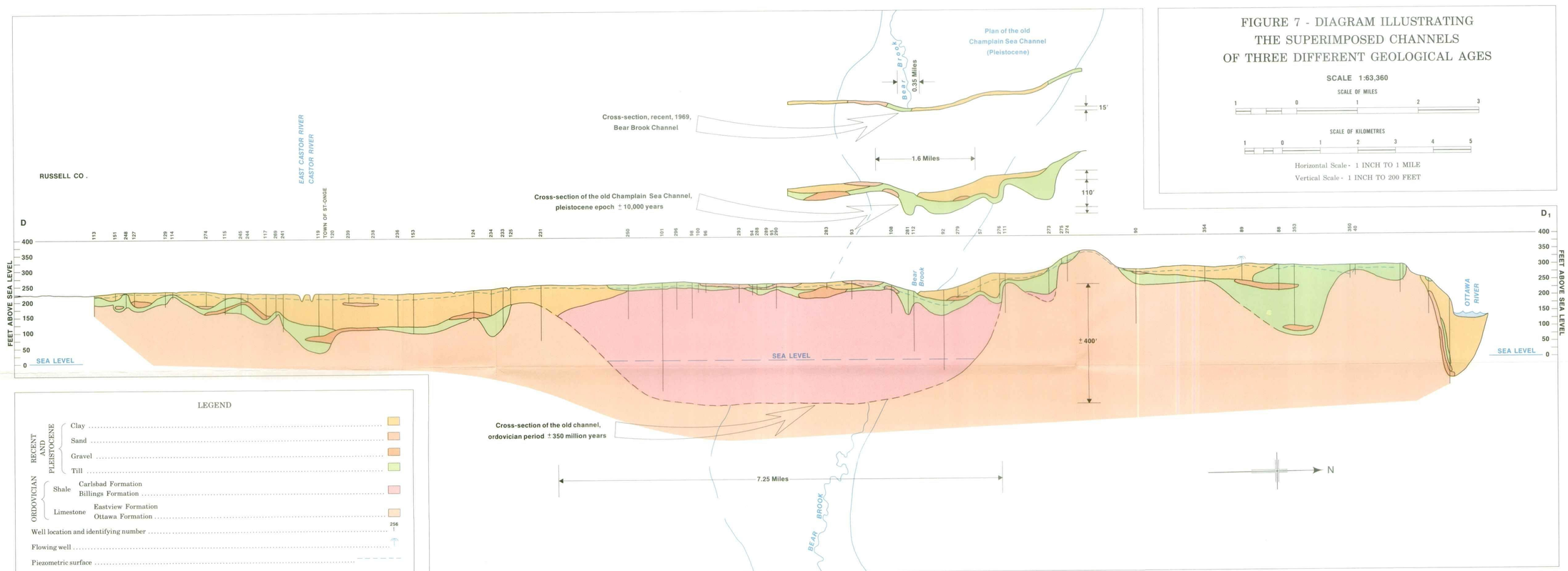


FIGURE 7 - DIAGRAM ILLUSTRATING THE SUPERIMPOSED CHANNELS OF THREE DIFFERENT GEOLOGICAL AGES

SCALE 1:63,360

SCALE OF MILES

SCALE OF KILOMETRES

Horizontal Scale - 1 INCH TO 1 MILE
Vertical Scale - 1 INCH TO 200 FEET

LEGEND

RECENT AND PLEISTOCENE
- Clay
- Sand
- Gravel
- Till

ORDOVICIAN
- Shale: Carlsbad Formation, Billings Formation
- Limestone: Eastview Formation, Ottawa Formation

Well location and identifying number (256)

Flowing well

Piezometric surface

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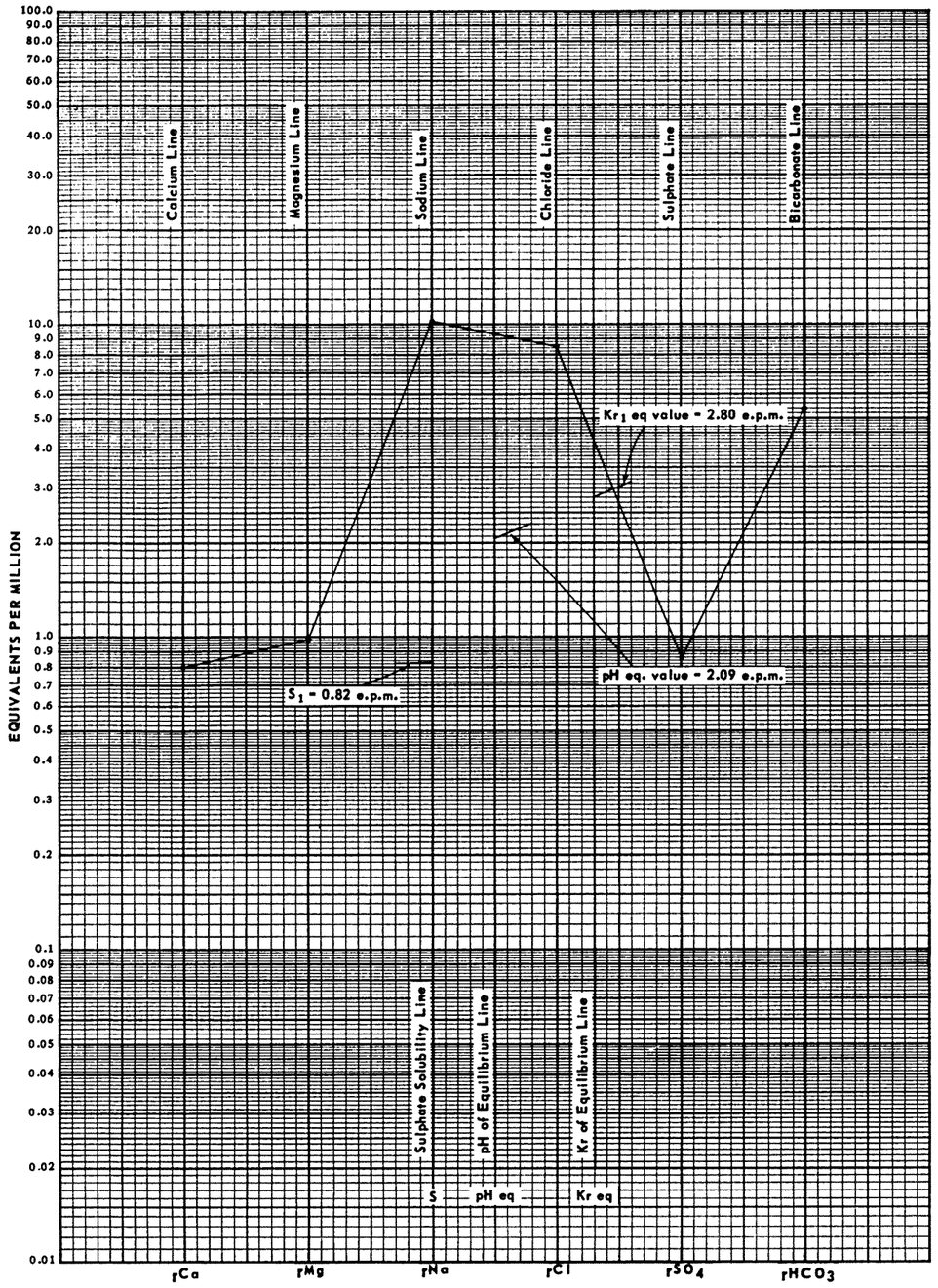


FIGURE 7 – SCHOELLER DIAGRAM ILLUSTRATING SEMI-LOGARITHMIC GRAPH CONSTRUCTION

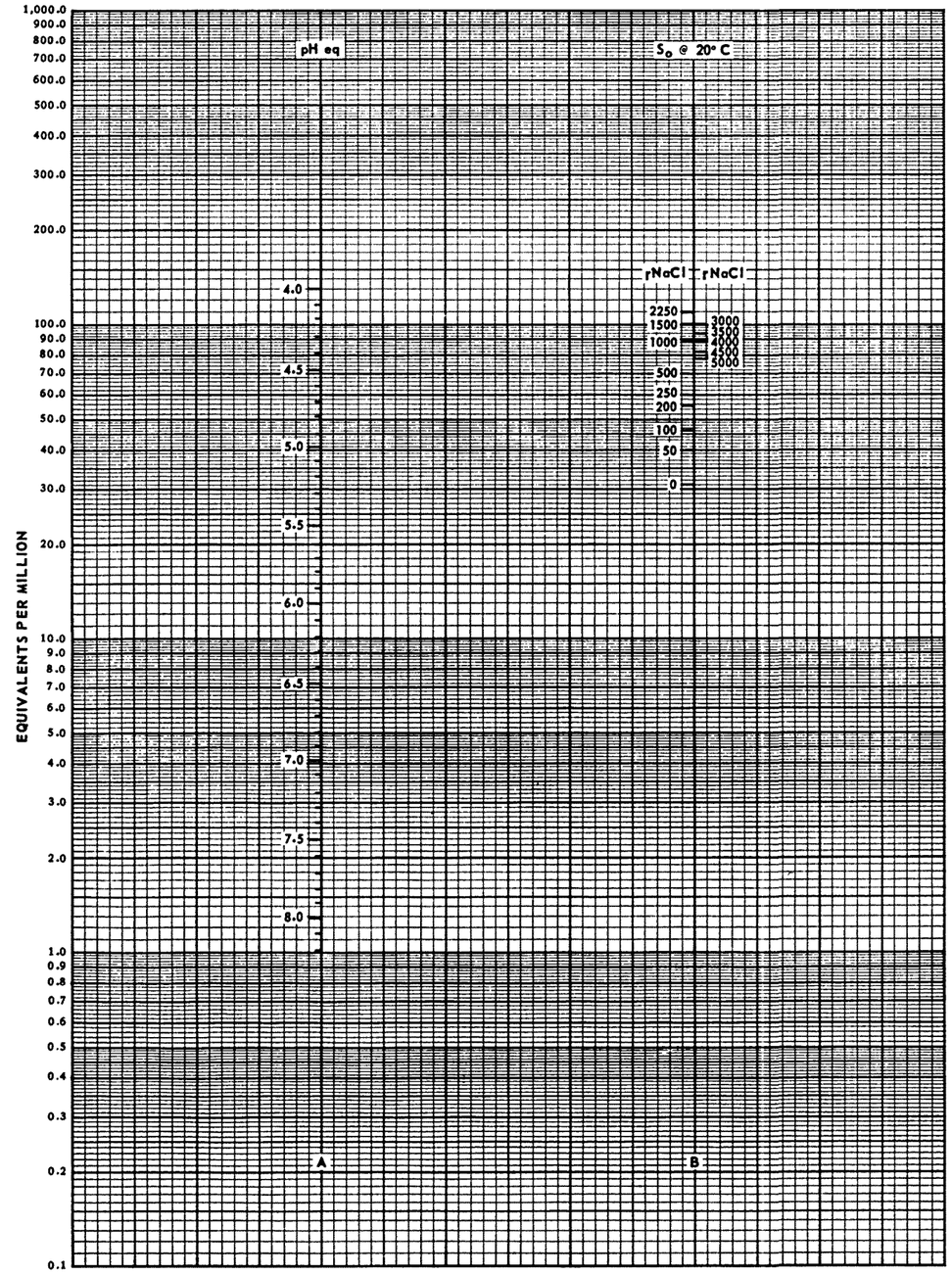


FIGURE 8 – SOLUBILITY SCALES: A, SOLUBILITY SCALE OF THE pH OF EQUILIBRIUM; B, SOLUBILITY SCALE OF $CaSO_4, 2H_2O$

CANADA

INLAND WATERS DIRECTORATE

DEPARTMENT OF THE ENVIRONMENT

31 G/6 WE AND PART OF 31 G/3 WE, 31 G/5E, 31 G/7 W, 31 G/11 WE, 31 G/12 E

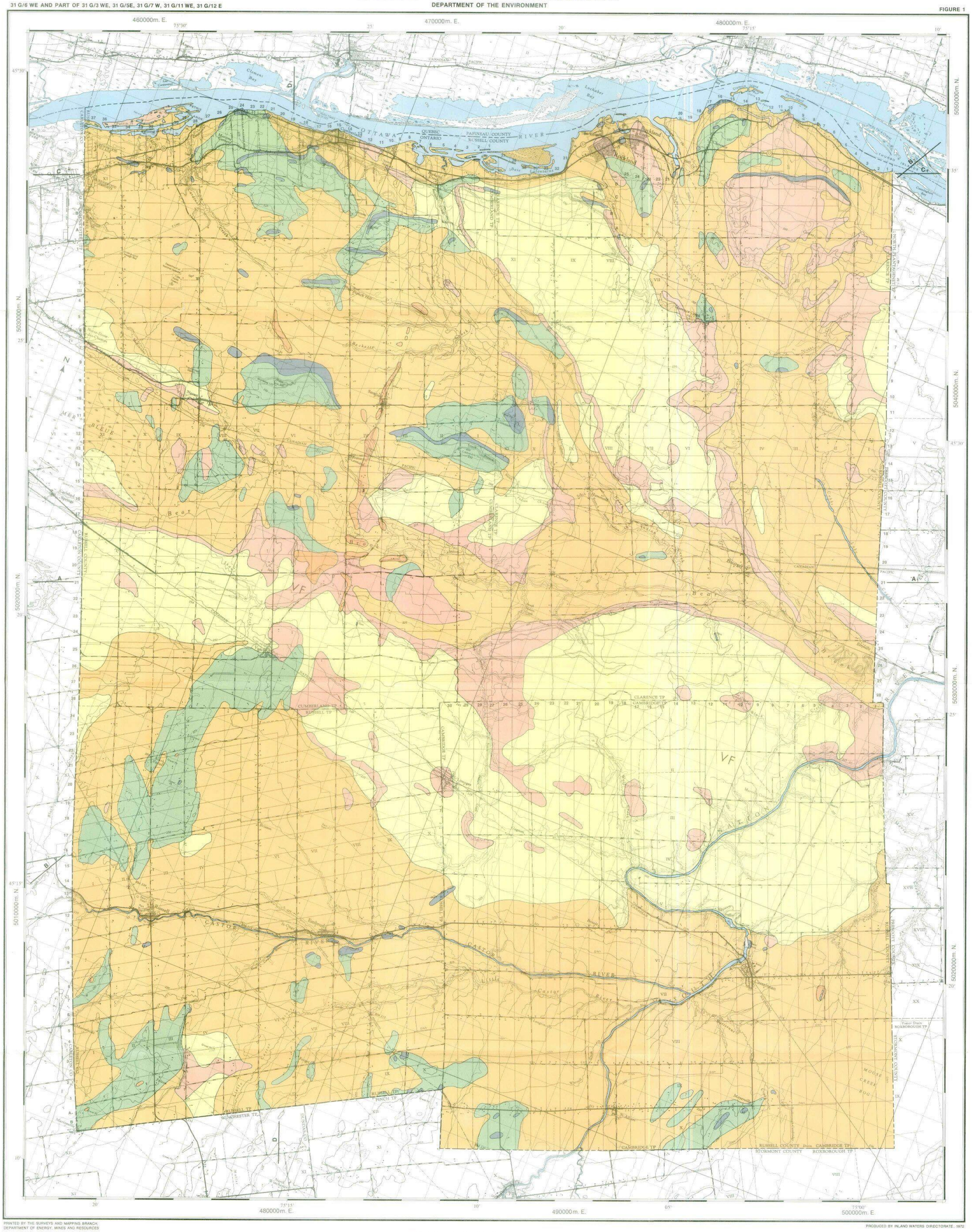
FIGURE 1

LEGEND

- Clay - Impermeable areas Very slow recharge
- Sand (fine)
- Sand (coarse)
- Gravel

} Permeable areas Fast recharge

- Till - Semipermeable areas Slow recharge
- Bedrock - Impermeable areas Very slow recharge



Use diagram only to obtain numerical values.
APPROXIMATE MEAN DECLINATION 1970
FOR CENTRE OF MAP
Annual change increasing 0.3'

GRID ZONE DESIGNATION	100,000 M. SQUARE IDENTIFICATION
18 T	VF

TO GIVE A REFERENCE TO NEAREST 100 METRES

EXAMPLE: FIRE TOWER

EASTING: Read number on grid line immediately to left of point	89
Estimate tenths of a square from this line eastward to point.	2
	892
NORTHING: Read number on grid line immediately below point	26
Estimate tenths of a square from this line northward to point.	7
	267
MILITARY GRID REFERENCE	892267

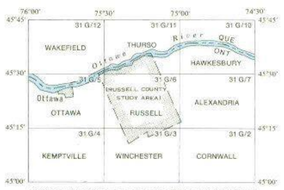
Nearest similar grid reference 100,000 metres (about 63 miles)

ONE THOUSAND METRE
UNIVERSAL TRANSVERSE MERCATOR GRID
ZONE 18

NOTE - Since January 1st 1969, all of the Township of Cumberland has been incorporated into the Regional Municipality of Ottawa-Carleton.

Compiled by J.E. Charron
to accompany Paper by J.E. Charron

Base map prepared by the Surveys and Mapping Branch, 1968.
Cartography by the Inland Waters Directorate, 1972.
Printed by the Surveys and Mapping Branch, 1972.



INDEX TO SHEETS OF THE NATIONAL TOPOGRAPHIC SYSTEM

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DEPARTMENT OF ENERGY, MINES AND RESOURCES

PRODUCED BY INLAND WATERS DIRECTORATE, 1972

RUSSELL COUNTY - ONTARIO

INFILTRATION MAP

SCALE 1:63,360

1 0 1 2 3

SCALE OF MILES

SCALE 1:63,360

1 0 1 2 3 4 5

SCALE OF KILOMETRES

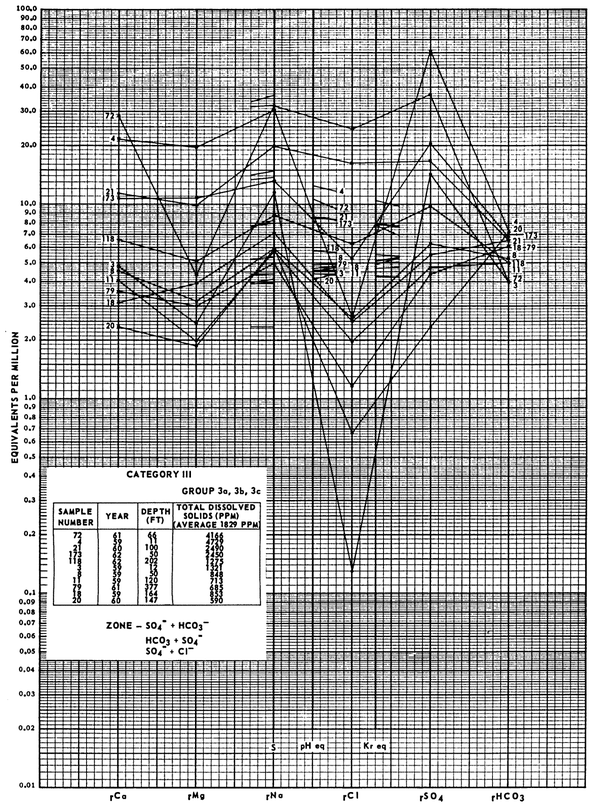


FIGURE 15

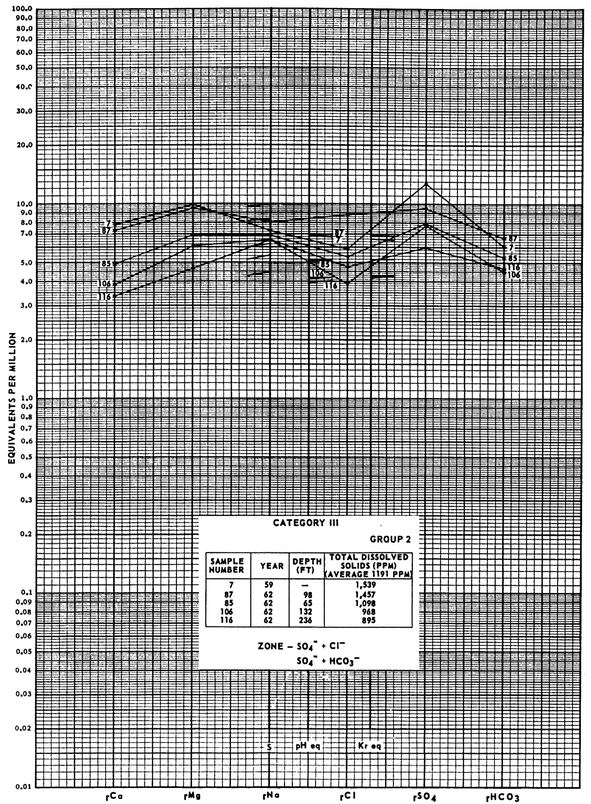


FIGURE 14

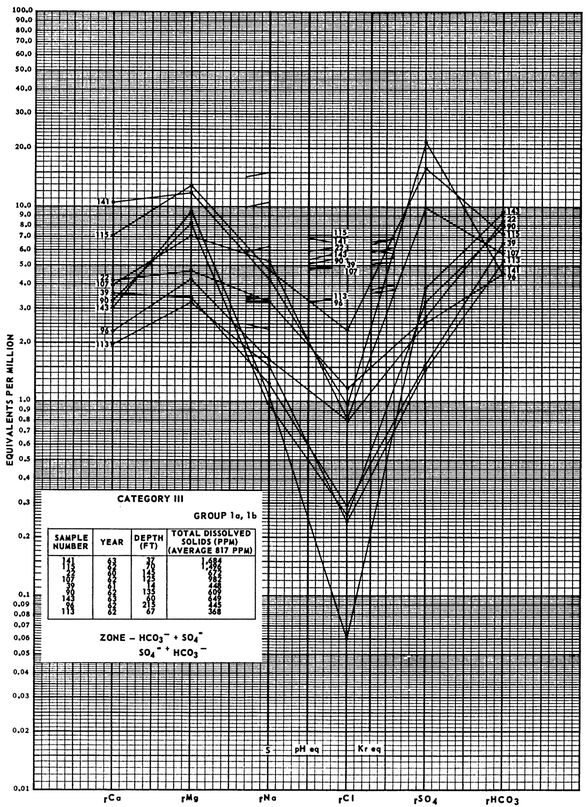


FIGURE 13

SEMI-LOGARITHMIC DIAGRAMS

CATEGORY III

CONFINED AQUIFERS
SULPHATE WATERS

GROUPS 1-3

FIGURES 13-15

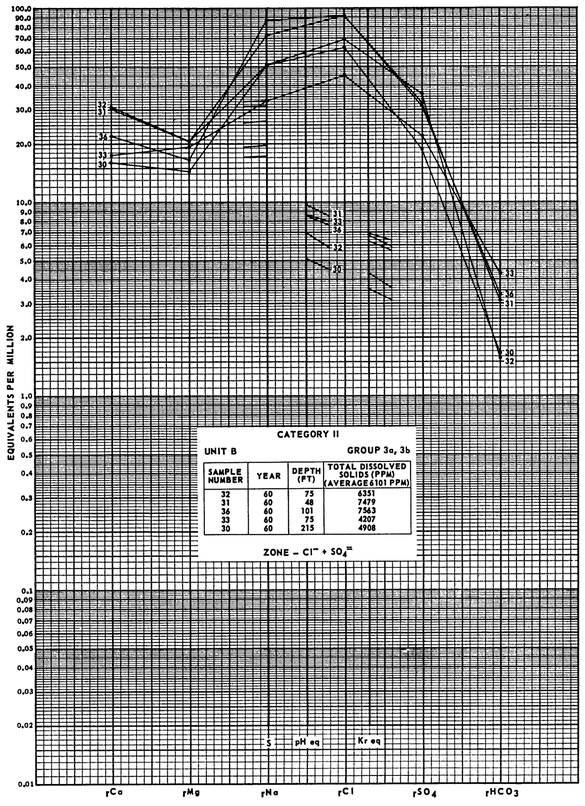


FIGURE 37

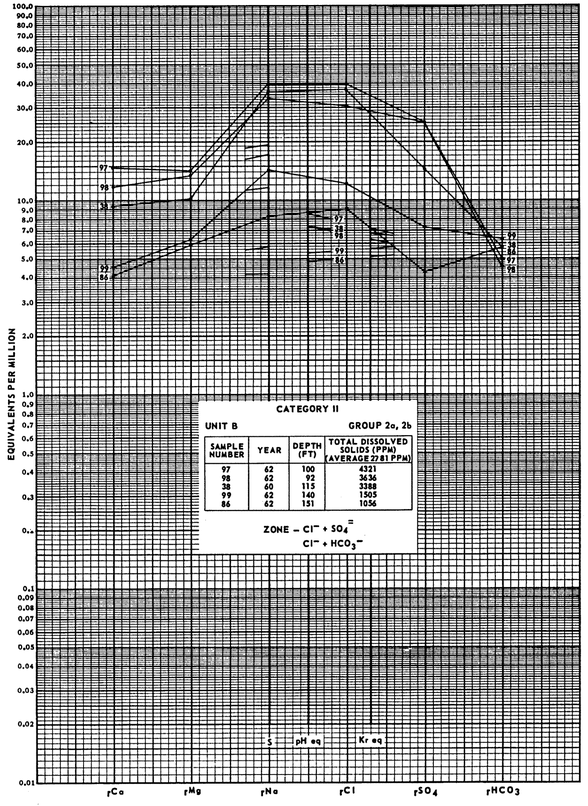


FIGURE 36

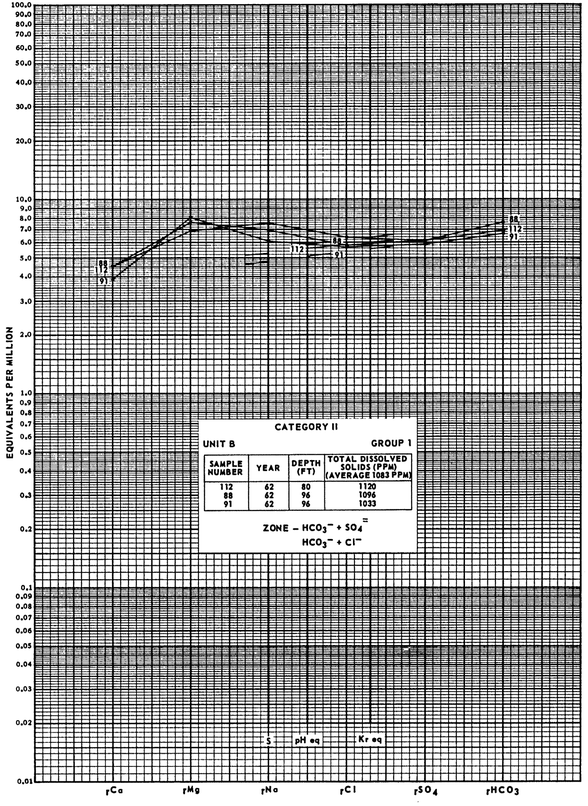


FIGURE 35

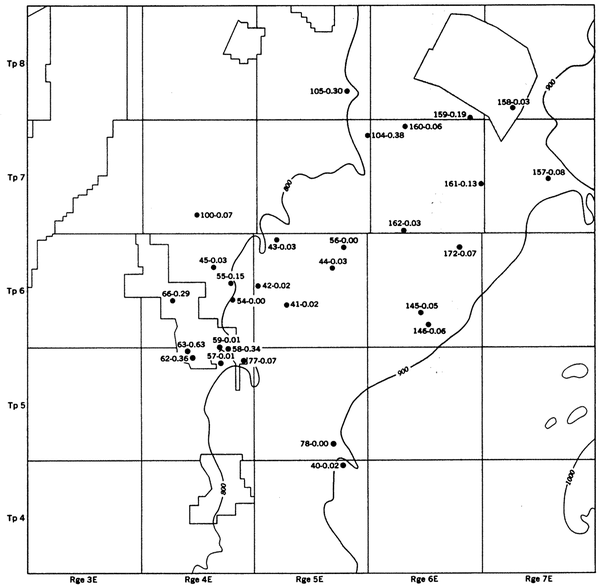
SEMI-LOGARITHMIC DIAGRAMS

CATEGORY II UNIT B

CONFINED AQUIFERS SOUTHERN FLOW

GROUPS 1-3

FIGURES 35-37



LEGEND

Location of Analysis . . . . . ●

Number of Analysis 100

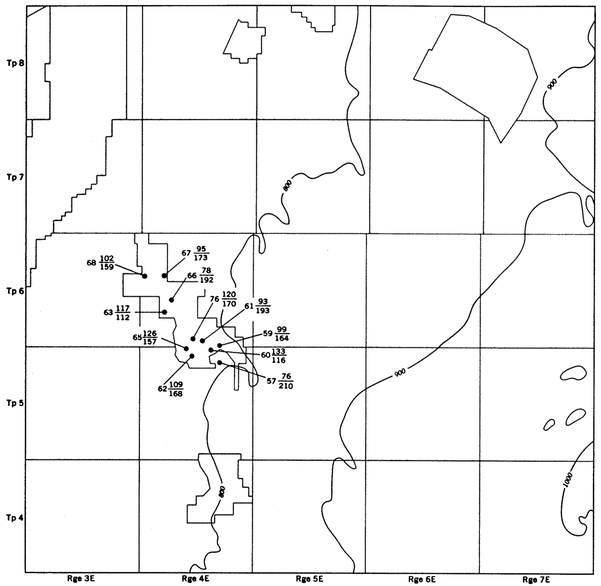
Sulphate Value in e.p.m. 0.07

Elevation Contours (Interval 100 feet) . . . —800—

Scale 1:250,000

Miles 5 0 5

FIGURE 38
LOCATION OF ANALYSES WITH LOW SULPHATE VALUES
DUE TO THE SULPHATE REDUCTION PHENOMENON



LEGEND

Location of Analysis . . . . . ●

Number of Analysis 76

Carbonate Hardness in p.p.m. 93
Sodium Bicarbonate in p.p.m. 193

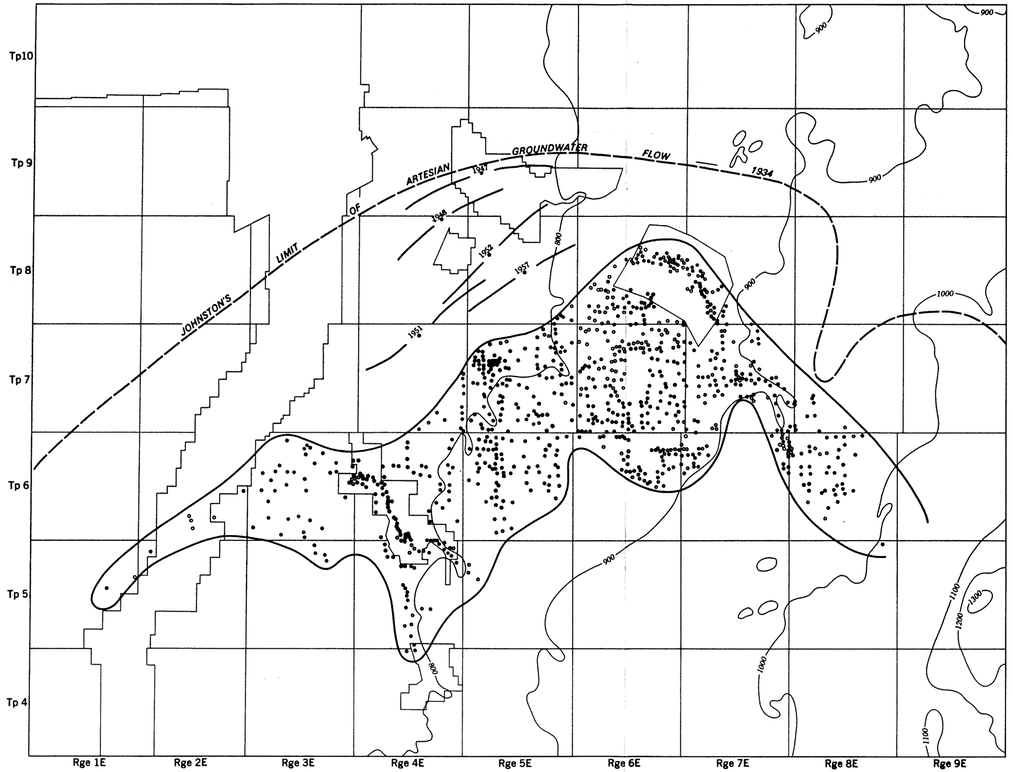
Elevation contours (interval 100 feet). . . . — 900 —

Note: In all the analyses the carbonate hardness is also the total hardness.

Scale 1:250,000

Miles 5 0 5

FIGURE 39
SOFT-WATER ANALYSES FROM THE VICINITY OF
ST-PIERRE, MANITOBA



LEGEND

Flowing well . . . . . ●

Non-flowing well . . . . . ●

Flowing artesian zone . . . . . ~

Elevation Contours (interval 100 feet) . . . . . —800—

The year in which the well stopped flowing . . . 1951

Scale 1:250,000

Miles 5 0 5

FIGURE 40
THE "UNDERMINING" OF A FLOWING
ARTESIAN ZONE. — 1965

FIGURE 34

FIGURE 35

FIGURE 36

FIGURE 37

FIGURE 38

FIGURE 39

FIGURE 40

FIGURE 41

FIGURE 42

FIGURE 43

FIGURE 44

FIGURE 45

FIGURE 46

FIGURE 47

FIGURE 48

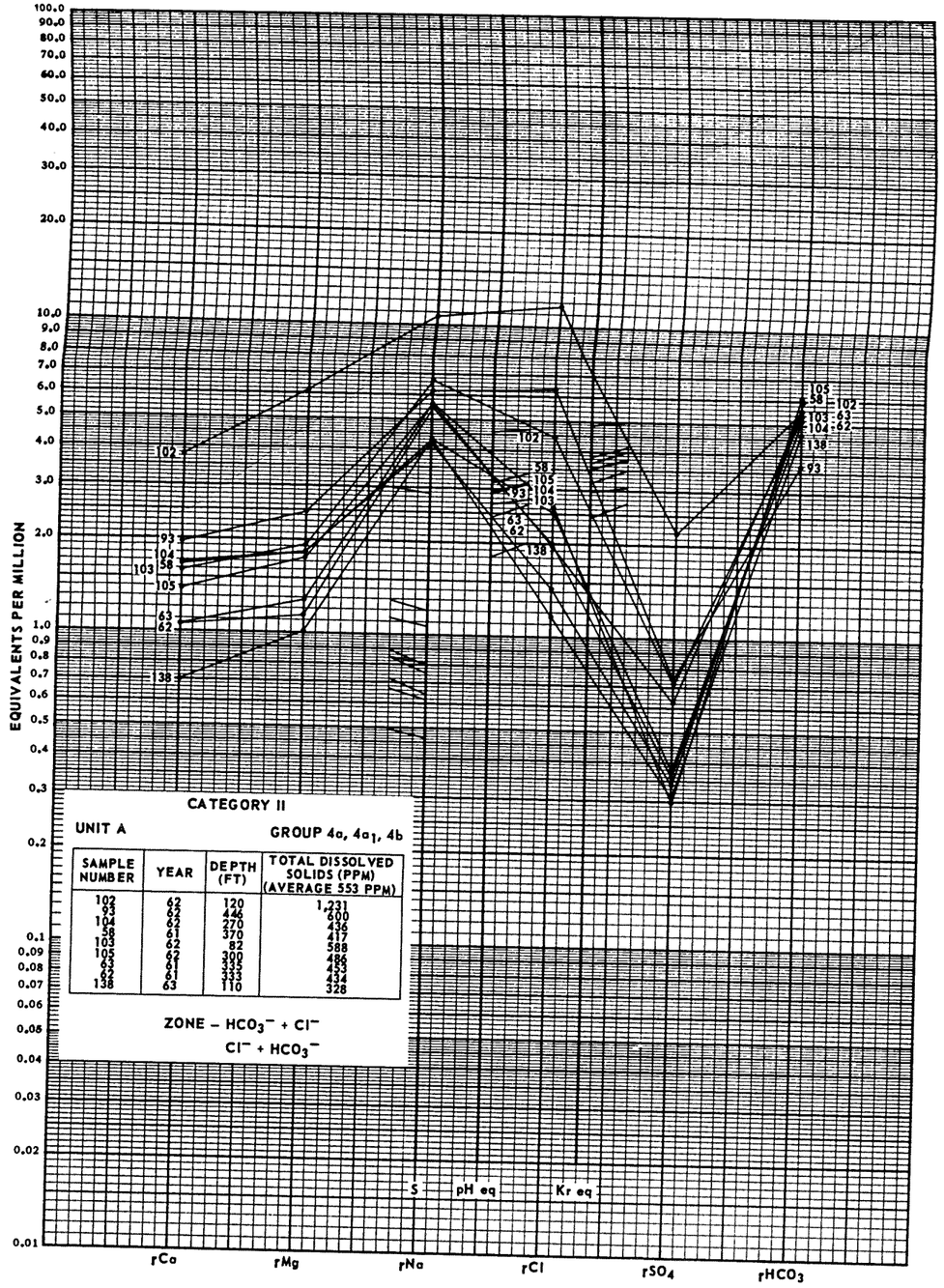
FIGURE 49

FIGURE 50

SEMI-LOGARITHMIC DIAGRAMS

CATEGORY D UNIT A
CONFINED ALLUVIUM
WESTERN AND EASTERN FLOW
GROUPS 1-11

FIGURES 34-50



CATEGORY II

UNIT A

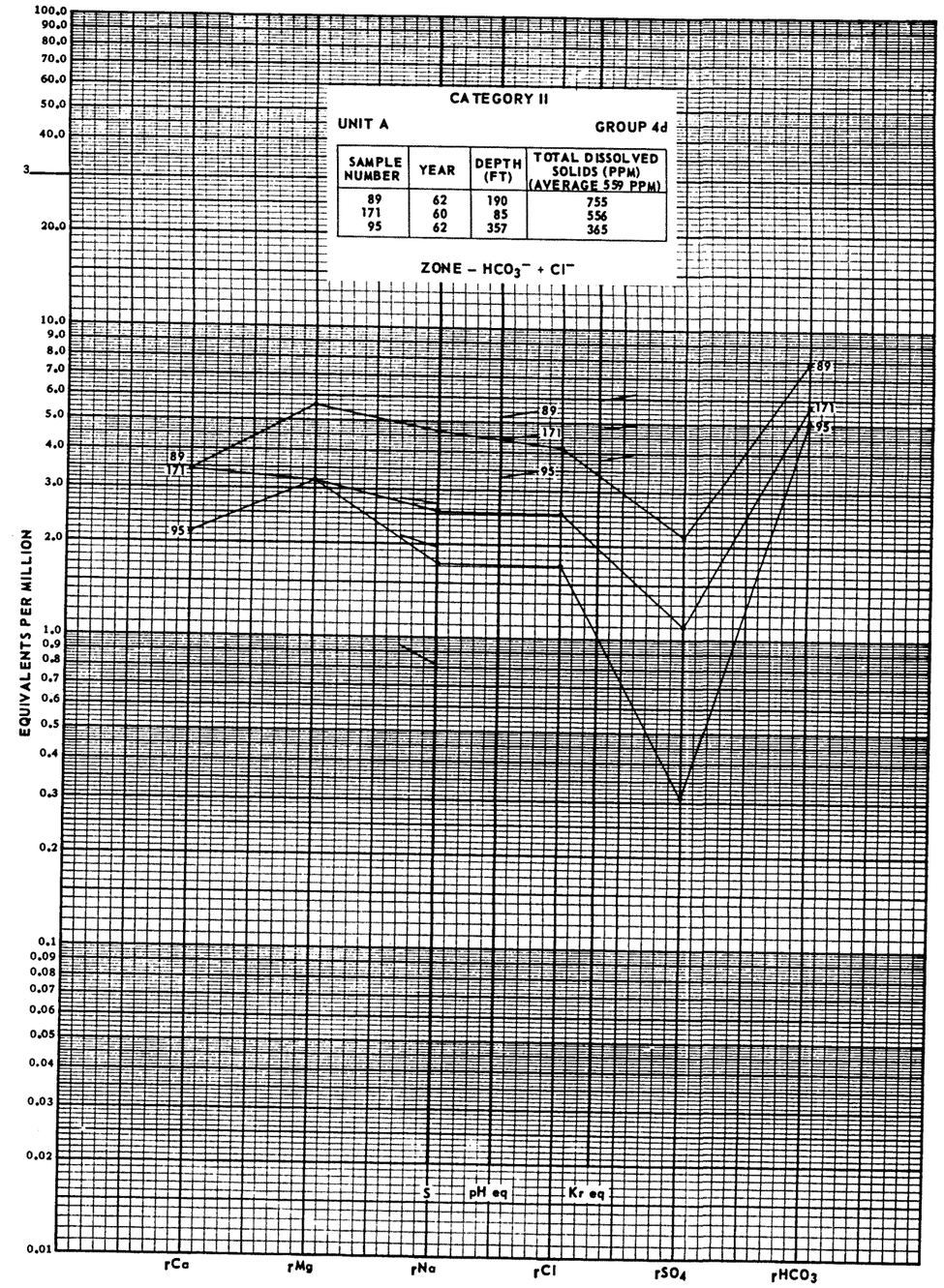
GROUP 4a, 4a1, 4b

SAMPLE NUMBER	YEAR	DEPTH (FT)	TOTAL DISSOLVED SOLIDS (PPM) (AVERAGE 553 PPM)
102	62	120	1,231
93	62	446	600
104	62	270	496
58	61	370	417
103	62	82	588
105	62	300	486
63	61	335	453
62	61	333	434
138	63	110	328

ZONE – HCO_3^- + Cl^-

Cl^- + HCO_3^-

FIGURE 23



CATEGORY II

UNIT A

GROUP 4d

SAMPLE NUMBER	YEAR	DEPTH (FT)	TOTAL DISSOLVED SOLIDS (PPM) (AVERAGE 559 PPM)
89	62	190	755
171	60	85	556
95	62	357	365

ZONE – HCO_3^- + Cl^-

FIGURE 25

Guide to Table I and Figures 9 to 37

Sample No.	Category	Unit	Group	Figure	Sample No.	Category	Unit	Group	Figure	Sample No.	Category	Unit	Group	Figure	Sample No.	Category	Unit	Group	Figure
1	I	A	2	10	46	II	A	9a	31	91	II	A	1	35	136	I	A	11	9
2	I	A	2	11	47	I	A	4	12	92	I		1	9	137	I		1	9
3	III		3c	15	48	II	A	9a	31	93	II	A	4b	23	138	II	A	4a	23
4	III		3b	15	49	II	A	9b	31	94	I		4	12	139	II	A	1b	17
5	I		2	10	50	I		3	11	95	I	A	4d	25	140	II	A	4c	24
6	II	A	10b	33	51	II	A	4c	24	96	III		1a	13	141	III		1b	13
7	III		2	14	52	II	A	7b	29	97	II	B	2b	36	142	II	A	6a	27
8	III		3b	15	53	II	A	7b	29	98	II	B	2a	36	143	III		1a	13
9	II	A	10b	33	54	II	A	3a	22	99	II	B	2a	36	144	II	A	4c	24
10	II	A	10b	33	55	II	A	3b	22	100	II	A	2d	21	145	II	A	2b	19
11	III		3a	15	56	II	A	2c	20	101	II	A	7a	28	146	II	A	2b	19
12	II	A	10a	32	57	II	A	5a	26	102	II	A	4b	23	147	II	A	1b	17
13	II	A	10a	32	58	II	A	4a$_1$	23	103	II	A	4a	23	148	II	A	1b	17
14	II	A	10a	32	59	II	A	3b	22	104	II	A	4a$_1$	23	149	II	A	2d	21
15	II	A	10a	32	60	II	A	7a	28	105	II	A	4a	23	150	II	A	2d$_1$	21
16	I		3a	11	61	II	A	5b	26	106	II	A	2	14	151	II	A	2b	19
17	I		2	10	62	II	A	4a	23	107	III	A	1b	13	152	II	A	2b	19
18	III		3a	15	63	II	A	4a	23	108	II	A	6b	27	153	II	A	2b	19
19	II		3	11	64	II	A	7b	29	109	II	A	6b	27	154	II	A	2b	19
20	III		3b	15	65	II	A	5b	26	110	II	A	6b	27	155	II	A	2b	19
21	III		3	15	66	II	A	3b	22	111	II	A	4c	24	156	II	A	2b	19
22	III		1a	13	67	II	A	5a	26	112	II	B	1	35	157	II	A	3a	22
23	II	A	10b	33	68	II	A	5a	26	113	III		1a	13	158	II	A	2d	21
24	I		4	12	69	II	A	7b	29	114	II	A	7a	28	159	II	A	2d	21
25	I		3	11	70	II	A	7b	29	115	II		1a	13	160	II	A	2c	20
26	I		4	12	71	II	A	7b	29	116	III		2	14	161	II	A	2b	19
27	I		2	10	72	III		3b	15	117	II	A	6a	27	162	II	A	2c	20
28	I		1	9	73	I		4	12	118	III		3b	15	163	II	A	11a	34
29	I		1	9	74	II	A	9a	31	119	II	A	2a	18	164	II	A	11b	34
30	II	B	3b	37	75	I		4	12	120	II	A	4c	24	165	II	A	11b	34
31	II	B	3b	37	76	II	A	5b	26	121	II	A	6b	27	166	II	A	11a	34
32	II	B	3b	37	77	II	A	3a	22	122	II	A	2a	18	167	II	A	11a	34
33	II	B	3a	37	78	II	A	2d	21	123	II	A	2c	20	168	II	A	11b	34
34	I		2	10	79	III		3d	15	124	II	A	1a	16	169	II	A	11c	34
35	I		3	11	80	II	A	2d	21	125	II	A	1a	16	170	II	A	8b	30
36	II	B	3a	37	81	II	A	9b	31	126	II	A	1a	16	171	II	A	4d	25
37	I		4	12	82	II	A	8a	30	127	II	A	1a	16	172	II	A	2c	20
38	II	B	2b	36	83	II	A	8a	30	128	II	A	1a	16	173	III		3b	15
39	III		1a	13	84	II	A	8b	30	129	II	A	1a	16					
40	II	A	2d	21	85	III	A	2	14	130	II	A	1a	16					
41	II	A	2c	20	86	II	A	2b	36	131	II	A	1b	17					
42	II	A	2c	20	87	III	A	2	14	132	II	A	1b	17					
43	II	A	2d$_1$	21	88	II	B	1	35	133	II	A	2a	18					
44	II	A	2b	19	89	II	A	4d	25	134	II	A	2c	20					
45	II	A	2d	21	90	III		1a	13	135	II	A	2a	18					

Table I – Chemical Analyses[1] of Groundwater

(1)

					Chemical Constituents in epm (equivalents per million) and Ratios																					
Sample No.	Year Taken	Category	Unit	Group	Calcium (rCa)	Magnesium (rMg)	Sodium (rNa)	Chloride (rCl)	Sulphate (rSO_4)	Bicarbonate ($rHCO_3$)	rMg/rCa	rNa/rMg	rSO_4/rCl	$\frac{rCl - rNa}{rCl}$ (b.e.i.)	$\sqrt{(rCa)(rSO_4)}$ S_1	$\sqrt[3]{(rHCO_3)^2 (rCa)}$ Kr_1 eq.	$\sqrt{(rCa)(rHCO_3)}$ pH eq.	*Total Dissolved Solids (T.D.S.)	Ionic Strength μ	$3.618\sqrt{\mu}$ ΔpH (epm)	Temp. @ Testing (°C)	Correction for Temperature θ (epm)	pH	$\theta + \Delta pH + pH$ eq. (pH eq. Corrected) (epm)	pH eq. Corrected from scale	REMARKS
92	62	I		1	2.13	2.72	0.34	0.19	0.42	4.56	1.28	0.13	2.21	-0.79	0.95	3.54	3.12	10.36	0.008	0.33	24	+0.02	8.0	3.47	7.2	
136	63	I		1	2.28	3.04	0.15	0.03	0.29	5.26	1.33	0.05	9.66	-4.00	0.81	3.98	3.46	11.05	0.008	0.33	25	0.00	7.8	3.79	7.1	
137	63	I		1	2.42	3.43	0.23	0.13	0.35	5.67	1.42	0.07	2.69	-0.77	0.92	4.27	3.70	12.23	0.009	0.35	24	+0.02	8.0	4.07	7.0	
28	60	I		1	2.15	7.01	2.17	0.86	1.72	7.97	3.26	0.31	2.00	-1.52	1.92	5.15	4.14	21.88	0.016	0.47	26	-0.02	8.2	4.59	6.9	irregular T.D.S. 591 p.p.m.
29	60	I		1	5.29	4.68	1.74	1.00	1.55	7.46	0.88	0.37	1.55	-0.74	2.86	6.65	6.28	21.72	0.017	0.48	26	-0.02	7.9	6.74	6.6	694 p.p.m.
34	60	I		2	0.56	1.76	0.87	0.22	0.14	2.88	3.14	0.49	0.64	-2.95	0.28	1.67	1.27	6.43	0.004	0.23	26	-0.02	7.9	1.48	7.9	
5	59	I		2	2.31	1.80	0.78	0.17	0.65	3.77	0.78	0.43	3.82	-3.59	1.22	3.20	2.95	9.48	0.007	0.31	26	-0.02	7.9	3.24	7.2	
1	59	I		2	4.60	3.62	1.90	0.63	3.46	4.39	0.79	0.52	5.49	-2.11	3.99	4.46	4.49	18.60	0.012	0.40	26	-0.02	7.7	4.87	6.8	
27	60	I		2	6.09	3.33	0.65	0.46	3.12	6.41	0.55	0.20	6.78	-0.41	4.36	6.30	6.25	20.06	0.016	0.47	24	+0.02	8.3	6.74	6.6	
17	59	I		2	5.64	6.41	0.83	0.68	2.87	8.46	1.14	0.13	4.22	-0.22	4.02	7.39	6.91	24.89	0.020	0.52	24	+0.02	8.0	7.45	6.5	
16	59	I		3	3.15	2.42	0.12	0.13	0.97	4.56	0.77	0.05	7.46	+0.08	1.75	4.03	3.79	11.35	0.009	0.35	24	+0.02	7.9	4.16	7.0	
50	61	I		3	5.09	3.36	0.59	0.81	0.96	7.24	0.66	0.18	1.19	+0.27	2.21	6.44	6.07	18.05	0.014	0.44	24	+0.02	7.8	6.53	6.6	
2	59	I		3	4.99	5.69	0.54	0.87	1.13	7.95	1.14	0.09	1.30	+0.38	2.37	6.80	6.30	21.17	0.016	0.47	26	-0.02	8.1	6.75	6.6	
19	59	I		3	5.64	7.15	0.95	1.18	3.04	8.20	1.27	0.13	2.58	+0.19	4.14	7.24	6.80	26.16	0.021	0.53	24	+0.02	8.1	7.35	6.5	
25	60	I		3	6.49	5.67	1.98	2.20	3.35	8.90	0.87	0.35	1.52	+0.10	4.66	8.01	7.60	28.59	0.022	0.55	24	+0.02	8.3	8.17	6.4	
35	60	I		3	7.44	7.88	1.72	2.10	4.25	10.16	1.06	0.22	2.02	+0.18	5.62	9.16	8.69	33.55	0.027	0.59	25	0.00	8.0	9.28	6.3	
94	62	I		4	5.19	4.01	0.96	1.59	0.76	5.43	0.77	0.24	0.48	+0.40	1.98	5.35	5.31	17.94	0.014	0.44	24	+0.02	8.0	5.77	6.7	
37	60	I		4	4.29	9.54	0.65	2.09	1.17	8.01	2.22	0.07	0.56	+0.69	2.24	6.50	5.86	25.75	0.020	0.52	26	-0.02	8.3	6.36	6.6	
47	61	I		4	7.24	5.79	4.32	6.94	3.21	7.08	0.80	0.75	0.46	+0.38	4.82	7.13	7.16	34.58	0.028	0.60	23	+0.04	7.5	7.80	6.4	
73	61	I		4	10.68	10.61	4.61	10.66	4.93	7.31	0.99	0.43	0.46	+0.57	7.26	8.29	8.84	48.80	0.038	0.69	23	+0.04	7.5	9.57	6.3	
26	60	I		4	12.77	15.71	3.30	7.84	8.33	11.47	1.23	0.21	1.06	+0.58	10.31	11.89	12.10	59.42	0.048	0.79	24	+0.02	8.2	12.91	6.1	
24	60	I		4	13.77	17.27	1.76	7.47	7.95	11.36	1.25	0.10	1.06	+0.76	10.46	12.11	12.51	59.58	0.054	0.84	24	+0.02	8.0	13.37	6.0	1,796 p.p.m.
75	61	I		4	20.31	10.12	0.47	6.18	3.81	12.51	0.50	0.05	0.62	+0.92	8.80	14.70	15.94	53.40	0.043	0.76	23	+0.04	7.8	16.74	5.8	irregular T.D.S. 1,845 p.p.m.

Table I – Chemical Analyses[1] of Groundwater (cont'd)

(2)

					Chemical Constituents in epm (equivalents per million) and Ratios																					
Sample No.	Year Taken	Category	Unit	Group	Calcium (rCa)	Magnesium (rMg)	Sodium (rNa)	Chloride (rCl)	Sulphate (rSO_4)	Bicarbonate ($rHCO_3$)	rMg/rCa	rNa/rMg	rSO_4/rCl	$\frac{rCl - rNa}{rCl}$ (b.e.i.)	$\sqrt{(rCa)(rSO_4)}$ S_1	$\sqrt[3]{(rHCO_3)^2 (rCa)}$ Kr_1 eq.	$\sqrt{(rCa)(rHCO_3)}$ pH eq.	*Total Dissolved Solids (T.D.S.)	Ionic Strength μ	$3.618\sqrt{\mu}$ ΔpH (epm)	Temp. @ Testing (°C)	Correction for Temperature θ (epm)	pH	$\theta + \Delta pH + pH$ eq. (pH eq. Corrected) (epm)	pH eq. Corrected from Scale	REMARKS
129	63	II	A	1a	2.23	1.34	0.15	0.01	0.19	3.54	0.60	0.11	19.00	-14.00	0.65	3.03	2.81	7.46	0.006	0.28	24	+0.02	8.0	3.11	7.2	
125	63	II	A	1a	2.23	1.50	0.36	0.02	0.07	4.03	0.67	0.24	3.50	-17.00	0.40	3.31	3.00	8.21	0.006	0.28	25	0.00	7.9	3.28	7.2	
130	63	II	A	1a	2.26	1.53	0.28	0.01	0.16	3.97	0.68	0.18	16.00	-27.00	0.60	3.29	2.99	8.21	0.006	0.28	24	+0.02	8.0	3.29	7.2	
126	63	II	A	1a	2.50	1.54	0.23	0.01	0.12	4.16	0.62	0.15	12.00	-22.00	0.55	3.44	3.22	8.56	0.006	0.28	24	+0.02	7.9	3.52	7.1	
127	63	II	A	1a	2.52	2.01	0.18	0.01	0.05	4.62	0.80	0.09	5.00	-17.00	0.35	3.77	3.41	9.39	0.007	0.31	24	+0.02	7.8	3.74	7.1	
124	63	II	A	1a	3.45	1.85	0.20	0.01	0.09	5.43	0.54	0.11	9.00	-19.00	0.56	4.67	4.33	11.03	0.008	0.33	25	0.00	8.1	4.66	6.9	
128	63	II	A	1a	3.17	2.52	0.46	0.02	0.06	6.15	0.79	0.18	3.00	-22.00	0.44	4.93	4.35	12.38	0.009	0.35	24	+0.02	8.0	4.72	6.9	
131	63	II	A	1b	0.60	2.48	0.65	0.03	0.11	3.67	4.13	0.26	3.66	-20.67	0.25	2.01	1.48	7.54	0.005	0.26	24	+0.02	7.8	1.76	7.7	200 p.p.m.
132	63	II	A	1b	1.36	1.29	1.04	0.04	0.07	3.70	0.95	0.81	1.75	-25.00	0.31	2.65	2.24	7.50	0.005	0.26	24	+0.02	7.8	2.52	7.4	irregular T.D.S. 209 p.p.m.
139	63	II	A	1b	2.09	2.79	0.43	0.05	0.17	5.05	1.33	0.15	3.40	- 7.60	0.60	3.76	3.25	10.58	0.008	0.33	24	+0.02	7.9	3.60	7.1	
147	63	II	A	1b	2.32	3.12	0.70	0.05	0.07	6.21	1.34	0.22	1.40	-13.00	0.40	4.47	3.80	12.47	0.009	0.35	23	+0.04	8.1	4.19	7.0	
148	63	II	A	1b	2.82	4.38	0.95	0.03	0.04	8.08	1.55	0.22	1.33	-30.67	0.34	5.69	4.77	16.30	0.012	0.40	23	+0.04	8.1	5.21	6.8	
133	63	II	A	2a	2.34	2.36	0.50	0.03	0.41	4.80	1.01	0.21	13.66	-15.67	0.98	3.78	3.35	10.44	0.008	0.33	25	0.00	8.0	3.68	7.1	
135	63	II	A	2a	2.20	2.71	0.72	0.03	0.73	5.03	1.23	0.27	24.33	-23.00	1.27	3.82	3.33	11.42	0.008	0.33	24	+0.02	8.0	3.68	7.1	
122	63	II	A	2a	2.79	2.90	0.37	0.01	0.22	5.83	1.04	0.13	22.00	-36.00	0.78	4.56	4.03	12.12	0.009	0.35	25	0.00	7.9	4.38	7.0	
119	63	II	A	2a	2.86	3.18	0.41	0.05	0.22	6.24	1.11	0.13	4.40	- 7.20	0.79	4.81	4.22	12.96	0.010	0.37	25	0.00	7.8	4.59	6.9	Winnipeg River Basin
151	63	II	A	2b	1.90	1.32	0.62	0.16	0.04	3.71	0.69	0.47	0.25	- 2.88	0.28	2.97	2.66	7.75	0.006	0.28	23	+0.04	7.7	2.98	7.3	
153	63	II	A	2b	1.97	1.96	0.62	0.11	0.04	4.52	0.99	0.32	0.36	- 4.64	0.28	3.43	2.98	9.22	0.007	0.31	25	0.00	8.0	3.29	7.2	
161	63	II	A	2b	1.90	2.42	0.85	0.22	0.13	4.96	1.27	0.35	0.59	- 2.86	0.50	3.60	3.07	10.48	0.007	0.31	24	+0.02	8.0	3.40	7.2	
152	63	II	A	2b	3.26	2.32	0.69	0.08	0.04	6.25	0.71	0.30	0.50	- 7.63	0.36	5.03	4.51	12.64	0.009	0.35	23	+0.04	8.0	4.90	6.8	
155	63	II	A	2b	3.06	2.94	0.67	0.07	0.02	6.53	0.96	0.23	0.29	- 8.57	0.25	5.07	4.47	13.29	0.010	0.37	24	+0.02	8.2	4.86	6.8	irregular pH eq. Corrected
44	61	II	A	2b	3.26	3.00	0.74	0.04	0.03	6.93	0.92	0.25	0.75	-17.50	0.32	5.39	4.75	14.00	0.010	0.37	23	+0.04	7.8	5.16	6.8	
145	63	II	A	2b	3.50	3.16	0.71	0.06	0.05	7.23	0.90	0.22	0.83	-10.17	0.42	5.68	5.03	14.71	0.011	0.39	24	+0.02	7.9	5.44	6.7	
156	63	II	A	2b	3.80	3.35	0.62	0.06	0.05	7.80	0.88	0.19	0.83	- 9.33	0.44	6.14	5.44	15.68	0.011	0.39	24	+0.02	8.1	5.85	6.7	irregular T.D.S. 393 p.p.m.
146	63	II	A	2b	4.00	3.07	0.63	0.06	0.06	7.62	0.77	0.21	1.00	- 9.50	0.49	6.15	5.62	15.44	0.011	0.39	23	+0.04	8.0	5.95	6.7	399 p.p.m.
154	63	II	A	2b	4.53	3.92	0.53	0.04	0.04	8.72	0.87	0.14	1.00	-12.25	0.43	7.01	6.28	17.78	0.013	0.42	24	+0.02	8.0	6.72	6.6	

Table I – Chemical Analyses[1] of Groundwater (cont'd)

(3)

					Chemical Constituents in epm (equivalents per million) and Ratios																					
Sample No.	Year Taken	Category	Unit	Group	Calcium (rCa)	Magnesium (rMg)	Sodium (rNa)	Chloride (rCl)	Sulphate (rSO_4)	Bicarbonate ($rHCO_3$)	rMg/rCa	rNa/rMg	rSO_4/rCl	$\frac{rCl - rNa}{rCl}$ (b.e.i.)	$\sqrt{(rCa)(rSO_4)}$ S_1	$\sqrt[3]{(rHCO_3)^2 (rCa)}$ Kr_1 eq.	$\sqrt{(rCa)(rHCO_3)}$ pH eq.	*Total Dissolved Solids (T.D.S.)	Ionic Strength μ	$3.618\ \mu$ ΔpH (epm)	Temp. @ Testing (°C)	Correction for Temperature θ (epm)	pH	$\theta + \Delta pH + pH$ eq. (pH eq. Corrected) (epm)	pH eq. Corrected from Scale	REMARKS
160	63	II	A	2c	1.88	1.66	1.71	0.21	0.06	5.38	0.88	1.03	0.29	- 7.14	0.34	3.79	3.18	10.90	0.007	0.31	25	0.00	8.1	3.49	7.2	
123	63	II	A	2c	1.96	2.00	1.57	0.12	0.04	5.43	1.02	0.79	0.33	-12.08	0.28	3.87	3.26	11.12	0.007	0.31	24	+0.02	7.5	3.59	7.1	
162	63	II	A	2c	2.47	2.53	1.04	0.28	0.03	5.83	1.02	0.41	0.11	- 2.71	0.27	4.38	3.79	12.18	0.009	0.35	24	+0.02	8.0	4.16	7.0	
x172	57	II	A	2c	2.54	2.41	1.61	0.36	0.07	5.77	0.95	0.46	0.19	- 2.08	0.42	4.39	3.83	12.26	0.009	0.35	–	–	7.8	4.18	7.0	Town of Steinbach
56	61	II	A	2c	2.61	2.85	1.24	0.21	0.00	6.56	1.09	0.44	0.00	- 4.90	0.00	4.82	4.14	13.47	0.009	0.35	23	+0.04	7.9	4.53	6.9	
42	61	II	A	2c	2.82	2.09	1.13	0.14	0.02	7.00	1.10	0.37	0.14	- 7.07	0.24	5.17	4.44	14.20	0.010	0.37	23	+0.04	7.9	4.85	6.8	
41	61	II	A	2c	3.04	3.08	1.22	0.09	0.02	7.36	1.01	0.40	0.22	-12.56	0.24	5.48	4.73	14.81	0.010	0.37	23	+0.04	7.8	5.14	6.8	
134	63	II	A	2c	4.60	5.16	2.00	0.32	0.09	11.51	1.12	0.39	0.28	- 5.25	0.64	8.48	7.28	23.68	0.017	0.48	25	0.00	7.6	7.76	6.4	
80	61	II	A	2d	1.19	1.41	1.46	0.19	0.01	4.06	1.18	1.04	0.01	- 6.68	0.03	2.70	2.20	8.32	0.005	0.26	22	+0.06	7.4	2.52	7.4	
100	62	II	A	2d	1.59	2.34	2.28	0.64	0.07	5.74	1.47	0.97	0.11	- 2.56	0.33	3.74	3.02	12.66	0.008	0.33	23	+0.04	8.1	3.39	7.2	
159	63	II	A	2d	2.13	2.03	2.24	0.87	0.19	5.54	0.95	1.10	0.22	- 1.57	0.64	4.03	3.44	13.00	0.009	0.35	25	0.00	7.9	3.79	7.1	
149	63	II	A	2d	2.32	2.08	2.35	1.18	0.03	5.12	0.90	1.13	0.03	- 0.99	0.26	3.93	3.45	13.08	0.009	0.35	23	+0.04	8.1	3.84	7.1	
158	63	II	A	2d	1.97	2.27	2.37	0.58	0.03	6.25	1.15	1.04	0.05	- 3.09	0.24	4.25	3.51	13.47	0.009	0.35	24	+0.02	7.8	3.88	7.1	
45	61	II	A	2d	2.04	2.47	2.35	0.52	0.03	6.56	1.21	0.95	0.06	- 3.52	0.24	4.44	3.66	13.97	0.009	0.35	23	+0.04	7.8	4.05	7.0	
78	61	II	A	2d	2.49	2.85	2.17	0.26	0.00	7.36	1.14	0.76	0.00	- 7.35	0.00	5.13	4.28	15.13	0.010	0.37	23	+0.04	7.8	4.69	6.9	
40	61	II	A	2d	2.47	2.83	2.24	0.24	0.02	7.42	1.15	0.79	0.08	- 8.33	0.22	5.14	4.28	15.22	0.010	0.37	23	+0.04	7.8	4.69	6.9	
150	63	II	A	2d$_1$	2.47	2.19	1.74	0.39	0.04	6.10	0.89	0.79	0.10	- 3.46	0.31	4.51	3.88	12.93	0.009	0.35	23	+0.04	8.2	4.27	7.0	
43	61	II	A	2d$_1$	2.50	2.70	1.52	0.38	0.03	6.39	1.08	0.56	0.08	- 3.00	0.28	4.67	4.00	13.52	0.009	0.35	23	+0.04	7.8	4.39	6.9	
77	61	II	A	3a	1.39	1.70	3.13	0.77	0.07	5.70	1.22	1.84	0.09	- 3.06	0.31	3.56	2.81	12.76	0.007	0.31	23	+0.04	8.2	3.16	7.2	
54	61	II	A	3a	1.58	1.43	3.74	0.62	0.00	6.42	0.91	2.62	0.00	- 5.03	0.00	4.02	3.18	13.79	0.008	0.33	23	+0.04	7.7	3.55	7.1	
157	63	II	A	3a	2.22	2.45	2.84	1.12	0.08	6.58	1.10	1.16	0.07	- 1.54	0.42	4.58	3.82	15.29	0.010	0.37	24	+0.02	8.1	4.21	7.0	
59	61	II	A	3b	0.76	1.22	5.13	1.99	0.01	5.24	1.61	4.20	0.01	- 1.58	0.09	2.75	1.99	14.35	0.008	0.33	24	+0.02	8.2	2.34	7.5	
66	61	II	A	3b	0.74	0.82	8.91	4.79	0.29	5.39	1.11	10.87	0.06	- 0.86	0.46	2.78	2.00	20.94	0.011	0.39	23	+0.04	7.9	2.43	7.5	
55	61	II	A	3b	1.37	1.69	9.78	6.57	0.15	6.23	1.23	5.79	0.02	- 0.49	0.14	3.76	2.92	25.79	0.015	0.45	23	+0.04	7.8	3.41	7.2	

Table I – Chemical Analyses[1] of Groundwater (cont'd)

(4)

					Chemical Constituents in epm (equivalents per million) and Ratios																					
Sample No.	Year Taken	Category	Unit	Group	Calcium (rCa)	Magnesium (rMg)	Sodium (rNa)	Chloride (rCl)	Sulphate (rSO_4)	Bicarbonate ($rHCO_3$)	rMg/rCa	rNa/rMg	rSO_4/rCl	$\frac{rCl - rNa}{rCl}$ (b.e.i.)	$\sqrt{(rCa)(rSO_4)}$ S_1	$\sqrt[3]{(rHCO_3)^2 (rCa)}$ Kr_1 eq.	$\sqrt{(rCa)(rHCO_3)}$ pH eq.	*Total Dissolved Solids (T.D.S.)	Ionic Strength μ	$3.618\sqrt{\mu}$ ΔpH (epm)	Temp. @ Testing (°C)	Correction for Temperature θ (epm)	pH	$\theta + \Delta pH + pH$ eq. (pH eq. Corrected) (epm)	pH eq. Corrected from Scale	REMARKS
138	63	II	A	4a	0.70	1.00	4.33	1.17	0.31	4.71	1.43	4.33	0.26	-2.70	0.47	2.49	1.82	12.22	0.07	0.31	24	+0.02	7.9	2.15	7.6	
62	61	II	A	4a	1.04	1.13	5.52	2.00	0.36	5.52	1.09	4.88	0.18	-1.76	0.61	3.16	2.40	15.57	0.009	0.35	24	+0.02	8.0	2.77	7.4	
63	61	II	A	4a	1.06	1.28	5.65	1.98	0.63	5.57	1.21	4.41	0.32	-1.85	0.82	3.20	2.43	16.17	0.010	0.37	23	+0.04	8.1	2.84	7.3	
105	62	II	A	4a	1.37	1.76	5.57	2.62	0.30	6.11	1.28	3.16	0.11	-1.13	0.64	3.71	2.89	17.73	0.011	0.39	23	+0.04	8.3	3.32	7.2	
103	62	II	A	4a	1.57	1.92	6.70	4.46	0.71	5.36	1.22	3.49	0.16	-0.50	1.06	3.56	2.90	20.72	0.013	0.42	23	+0.04	8.1	3.36	7.2	
58	61	II	A	4a$_1$	1.64	1.82	4.13	1.42	0.34	6.00	1.11	2.27	0.24	-1.91	0.75	3.89	3.14	15.35	0.009	0.35	24	+0.02	8.1	3.51	7.1	
104	62	II	A	4a$_1$	1.68	1.83	4.35	2.52	0.38	5.21	1.09	2.38	0.15	-0.73	0.80	3.57	2.96	15.97	0.010	0.37	23	+0.04	8.2	3.37	7.2	irregular pH eq. Corrected
93	62	II	A	4b	1.93	2.49	6.22	6.32	0.74	3.69	1.29	2.50	0.12	+0.02	1.20	2.97	2.67	21.39	0.013	0.42	24	+0.02	8.2	3.11	7.3	
102	62	II	A	4b	3.80	6.23	10.87	11.90	2.21	5.61	1.64	1.74	0.19	+0.09	2.90	4.93	4.62	40.62	0.026	0.58	23	+0.04	8.0	5.24	6.8	
140	63	II	A	4c	0.95	1.28	2.49	0.32	0.35	4.18	1.35	1.95	1.09	-6.78	0.58	2.55	1.99	9.57	0.006	0.28	24	+0.02	8.0	2.29	7.5	
120	63	II	A	4c	0.89	1.23	4.35	1.15	0.94	4.62	1.38	3.54	0.82	-2.78	0.91	2.67	2.03	13.18	0.008	0.33	25	0.00	8.2	2.36	7.5	
144	63	II	A	4c	0.78	0.97	6.26	1.85	1.04	5.35	1.24	6.45	0.56	-2.38	0.90	2.82	2.04	16.25	0.010	0.37	24	+0.02	8.1	2.43	7.5	
111	62	II	A	4c	1.50	2.36	10.09	5.36	3.35	5.47	1.57	4.28	0.63	-0.88	2.24	3.55	2.87	28.13	0.018	0.49	24	+0.02	8.1	3.38	7.2	
51	61	II	A	4c	2.97	2.15	9.35	4.09	3.98	6.34	0.72	4.35	0.97	-1.29	3.44	4.92	4.34	28.88	0.019	0.51	23	+0.04	8.1	4.89	6.8	
95	62	II	A	4d	2.18	3.21	1.76	1.71	0.31	5.08	1.47	0.55	0.18	-0.03	0.82	3.83	3.33	14.25	0.010	0.37	24	+0.02	8.2	3.72	7.1	
‡171	60	II	A	4d	3.44	3.21	2.57	2.54	1.10	5.69	0.93	0.80	0.43	-0.01	1.95	4.81	4.42	18.55	0.013	0.42	23	+0.04	7.5	4.88	6.8	Town of Beausejour
89	62	II	A	4d	3.50	5.65	4.70	4.15	2.17	7.87	1.61	0.83	0.52	-0.13	2.76	6.01	5.25	28.04	0.020	0.52	24	+0.02	8.2	5.79	6.7	
57	61	II	A	5a	0.64	0.87	11.74	7.42	0.01	5.64	1.36	13.49	0.00	-0.58	0.10	2.73	1.90	26.32	0.014	0.44	24	+0.02	8.4	2.36	7.5	
67	61	II	A	5a	0.86	1.04	12.83	8.54	0.96	5.34	1.21	12.34	0.11	-0.50	0.91	2.90	2.14	29.57	0.016	0.47	23	+0.04	7.9	2.65	7.4	
68	61	II	A	5a	1.00	1.04	13.26	8.91	1.17	5.21	1.04	12.75	0.13	-0.49	1.08	3.01	2.28	30.59	0.017	0.48	23	+0.04	8.3	2.80	7.3	
61	61	II	A	5b	0.83	0.96	16.09	11.48	0.75	5.64	1.16	16.76	0.07	-0.40	0.79	2.98	2.16	35.75	0.019	0.51	24	+0.02	8.0	2.69	7.4	
65	61	II	A	5b	1.24	1.27	16.09	11.76	1.18	5.64	1.02	12.67	0.10	-0.37	1.21	3.40	2.64	37.18	0.020	0.52	23	+0.04	8.2	3.20	7.2	
76	61	II	A	5b	1.24	1.15	17.09	12.63	0.85	5.79	0.93	14.86	0.07	-0.35	1.02	3.46	2.68	38.75	0.021	0.53	23	+0.04	8.1	3.25	7.2	

Table I – Chemical Analyses[1] of Groundwater (cont'd) (5)

Sample No.	Year Taken	Category	Unit	Group	Chemical Constituents in e.p.m. (equivalents per million) and Ratios: Calcium (rCa)	Magnesium (rMg)	Sodium (rNa)	Chloride (rCl)	Sulphate (rSO_4)	Bicarbonate ($rHCO_3$)	rMg/rCa	rNa/rMg	rSO_4/rCl	$\frac{rCl-rNa}{rCl}$ (b.e.i.)	$\sqrt{(rCa)(rSO_4)}$	$\sqrt[3]{(rHCO_3)^2(rCa)}$ K_2 eq.	$\sqrt{(rCa)(rHCO_3)}$ pH eq.	*Total Dissolved Solids (T.D.S.)	Ionic Strength μ	$\frac{3.618\sqrt{\mu}}{\Delta pH}$ (epm)	Temp. @ Testing (°C)	Correction for Temperature θ (epm)	pH	$\theta + \Delta pH + pH$ eq. (pH eq. Corrected) (epm)	pH eq. Corrected from Scale	REMARKS
142	63	II	A	6a	0.23	0.56	9.57	2.62	2.24	5.39	2.43	17.09	0.85	-2.65	0.72	1.88	1.11	20.61	0.012	0.40	24	+0.02	8.1	1.53	7.9	
117	62	II	A	6a	0.30	0.78	39.13	28.71	5.73	5.43	2.60	50.16	0.20	-0.36	1.31	2.07	1.28	80.08	0.043	0.76	23	+0.04	8.0	2.08	7.6	
121	63	II	A	6b	0.08	0.57	13.75	6.62	3.41	5.15	7.13	24.12	0.52	-1.08	0.52	1.28	0.64	29.58	0.017	0.48	25	0.00	7.8	1.12	8.1	Not saturated in $CaCO_3$
108	62	II	A	6b	0.30	0.69	15.74	8.80	2.06	5.62	2.30	22.81	0.23	-0.79	0.79	2.12	1.30	33.21	0.018	0.49	25	0.00	7.9	1.79	7.7	
110	62	II	A	6b	0.22	0.72	16.74	10.69	2.27	5.28	2.25	23.25	0.21	-0.57	0.65	2.07	1.42	36.02	0.020	0.52	24	+0.02	7.9	1.96	7.6	
109	62	II	A	6b	0.48	0.83	28.91	21.01	3.91	5.20	1.73	34.83	0.19	-0.38	1.37	2.35	1.58	60.34	0.033	0.65	24	+0.02	7.9	2.25	7.5	
101	62	II	A	7a	1.21	2.07	11.87	8.69	2.00	4.74	1.71	5.73	0.23	-0.37	1.56	3.01	2.39	30.58	0.018	0.49	24	+0.02	8.1	2.90	7.3	
60	61	II	A	7a	1.16	1.49	15.83	10.46	3.44	4.97	1.28	10.62	0.33	-0.51	2.00	3.06	2.40	37.35	0.022	0.55	24	+0.02	8.1	2.97	7.3	
114	62	II	A	7a	1.54	2.82	23.48	15.43	7.27	5.46	1.83	8.33	0.47	-0.52	3.35	3.58	2.90	56.00	0.034	0.65	24	+0.02	7.9	3.57	7.1	
53	61	II	A	7b	1.54	1.38	7.83	3.16	1.96	5.87	0.90	5.67	0.62	-1.48	1.74	3.76	3.01	26.74	0.013	0.42	23	+0.04	8.0	3.47	7.2	
64	61	II	A	7b	1.80	1.52	13.04	7.95	2.64	5.75	0.84	8.58	0.33	-0.64	2.18	3.90	3.22	32.70	0.019	0.51	23	+0.04	7.8	3.77	7.1	irregular T.D.S. 957 p.p.m.
52	61	II	A	7b	1.93	1.53	12.61	6.85	3.58	6.02	0.79	8.24	0.52	-0.84	2.63	4.12	3.41	32.52	0.020	0.52	24	+0.02	7.9	3.95	7.0	964 p.p.m.
70	61	II	A	7b	1.98	1.47	20.65	14.97	3.60	5.85	0.74	14.05	0.24	-0.38	2.67	4.08	3.40	48.52	0.027	0.58	23	+0.04	7.9	4.02	7.0	
69	61	II	A	7b	2.23	1.69	28.26	22.81	3.93	5.36	0.76	16.72	0.17	-0.24	2.96	4.00	3.46	64.28	0.036	0.69	23	+0.04	7.9	4.19	7.0	
71	61	II	A	7b	6.64	5.12	60.52	38.24	29.65	4.90	0.77	11.82	0.78	-0.58	14.03	5.42	5.70	145.07	0.093	1.09	23	+0.04	7.9	6.83	6.6	
83	62	II	A	8a	3.02	2.98	37.61	33.05	6.02	4.29	0.99	12.62	0.18	-0.14	4.26	3.82	3.60	86.97	0.058	0.87	25	0.00	8.0	4.47	6.9	
82	62	II	A	8a	17.37	12.58	118.48	128.31	21.19	2.43	0.72	9.41	0.17	+0.08	19.19	4.77	6.50	300.36	0.176	1.52	25	0.00	7.7	8.02	6.4	
84	62	II	A	8b	2.50	3.04	41.96	38.15	5.81	4.20	1.22	13.80	0.15	-0.10	3.81	3.53	3.24	95.66	0.054	0.83	25	0.00	7.9	4.07	7.0	
±170	62	II	A	8b	16.87	18.26	80.44	75.29	20.24	4.20	1.08	4.41	0.27	-0.07	18.48	6.68	8.42	215.30	0.135	1.34	–	–	7.0	9.76	6.2	Silver Plains Gypsum
48	61	II	A	9a	11.08	13.08	10.44	21.69	8.39	5.21	1.18	0.80	0.39	+0.52	9.64	6.70	7.60	69.89	0.051	0.82	23	+0.04	7.5	8.46	6.4	
74	61	II	A	9a	16.92	13.24	15.96	36.72	6.29	4.44	0.78	1.21	0.17	+0.57	10.32	6.93	8.67	93.57	0.065	0.90	23	+0.04	7.4	9.61	6.3	
46	61	II	A	9a	28.59	28.46	48.70	96.16	7.39	3.59	0.99	1.71	0.08	+0.49	14.54	7.17	10.13	212.89	0.138	1.34	23	+0.04	7.5	11.51	6.1	

Table I – Chemical Analyses[1] of Groundwater (cont'd) (6)

Sample No.	Year Taken	Category	Unit	Group	Chemical Constituents in epm (equivalents per million) and Ratios: Calcium (rCa)	Magnesium (rMg)	Sodium (rNa)	Chloride (rCl)	Sulphate (rSO_4)	Bicarbonate ($rHCO_3$)	rMg/rCa	rNa/rMg	rSO_4/rCl	$\frac{rCl-rNa}{rCl}$ (b.e.i.)	$\sqrt{(rCa)(rSO_4)}$ S_1	$\sqrt[3]{(rHCO_3)^2(rCa)}$ K_2 eq.	$\sqrt{(rCa)(rHCO_3)}$ pH eq.	*Total Dissolved Solids (T.D.S.)	Ionic Strength	$\frac{3.618\sqrt{\mu}}{\Delta pH}$ (epm)	Temp. @ Testing (°C)	Correction for Temperature θ (epm)	pH	$\theta + \Delta pH + pH$ eq. (pH eq. Corrected) (epm)	pH eq. Corrected from Scale	REMARKS
81	62	II	A	9b	13.97	12.50	26.61	26.09	14.70	9.13	0.89	2.13	0.56	-0.02	14.33	10.77	11.29	103.00	0.072	0.98	25	0.00	7.6	12.27	6.1	
49	61	II	A	9b	28.79	20.15	37.39	57.25	27.40	4.72	0.70	1.36	0.48	+0.35	28.09	8.62	11.66	175.70	0.126	1.28	24	+0.02	7.5	12.96	6.0	
15	59	II	A	10a	12.43	10.69	15.74	25.07	9.54	5.28	0.86	1.47	0.38	+0.37	10.89	7.02	8.40	78.75	0.056	0.86	25	0.00	8.1	8.96	6.3	
12	59	II	A	10a	20.61	12.34	36.10	13.76	3.67	6.60	1.50	0.38	+0.49	16.84	6.52	8.70	105.00	0.076	1.00	25	0.00	7.8	9.70	6.2	
14	59	II	A	10a	16.47	13.41	22.04	38.89	12.08	3.46	0.81	1.64	0.31	+0.43	14.11	5.82	7.55	106.35	0.074	0.98	25	0.00	8.0	8.53	6.4	irregular
13	59	II	A	10a	35.33	30.26	37.48	81.78	19.49	4.25	0.86	1.24	0.24	+0.54	26.24	8.61	12.25	208.39	0.147	1.39	25	0.00	7.8	13.64	6.0	pH eq. Corrected
23	60	II	A	10b	5.99	4.32	19.00	18.78	6.58	4.70	0.72	4.40	0.35	-0.01	6.28	5.10	5.31	59.37	0.038	0.71	24	+0.02	8.0	6.04	6.7	
10	59	II	A	10b	10.13	6.47	48.26	46.53	14.66	5.64	0.64	7.46	0.32	-0.04	12.19	6.86	7.56	131.69	0.081	1.03	25	0.00	8.0	8.59	6.4	
9	59	II	A	10b	14.27	9.13	61.31	64.01	18.34	4.34	0.64	6.72	0.29	+0.04	16.17	6.45	7.87	171.40	0.107	1.18	25	0.00	7.9	9.05	6.3	irregular
6	59	II	A	10b	19.46	11.68	82.35	92.21	19.36	2.77	0.60	7.05	0.21	+0.11	19.41	4.57	7.34	227.83	0.139	1.35	26	-0.02	7.5	8.67	6.4	pH eq. Corrected
x163	–	II	A	11a	26.90	16.50	142.90	133.40	39.40	12.80	0.61	8.66	0.30	-0.07	32.56	16.40	18.56	371.90	0.227	1.74	–	–	–	20.30	5.6	Loc. 11-14-5w (LS) Red River Form.
x166	–	II	A	11a	105.10	41.50	1,011.30	1,064.50	87.60	5.80	0.39	24.37	0.08	+0.05	95.95	15.23	24.69	2,315.80	1.275	4.09	–	–	–	28.78	5.3	Loc. 17-12-24w (LS) Red River Form.
x167	–	II	A	11a	136.10	51.10	1,487.40	1,586.90	83.50	4.70	0.37	29.11	0.05	+0.06	106.76	14.45	25.33	3,350.10	1.811	4.88	–	–	–	30.21	5.3	Loc. 17-12-24w (LS) Red River Form.
x165	–	II	A	11b	89.90	33.50	1,251.00	1,190.00	761.00	1.80	0.37	37.34	0.64	-0.05	261.56	6.65	12.72	3,327.20	2.106	5.25	–	–	–	17.97	5.7	Loc. 16-10-19w (LS) Red River Form.
x164	–	II	A	11b	234.70	100.60	2,812.50	3,089.90	56.20	1.60	0.43	27.96	0.02	+0.09	114.85	8.44	19.38	6,295.50	3.344	6.62	–	–	6.0	26.00	5.4	Loc. 1-8-18w (LS) Red River Form.
x168	–	II	A	11b	142.00	68.60	4,247.00	4,372.00	76.40	2.70	0.48	61.91	0.02	+0.03	104.16	10.12	19.58	8,908.70	4.598	7.74	–	–	–	27.32	5.4	Loc. 27-17-26w (LS) Red River Form.
x169	–	II	A	11c	14.30	69.70	4,991.00	4,945.00	58.40	1.70	4.87	71.61	0.01	-0.01	28.90	3.46	4.93	10,080.10	5.111	8.18	–	–	–	13.11	6.0	Loc. 27-17-26w (SS) Winnipeg Form.
91	62	II	B	1	3.88	8.11	6.09	5.70	5.93	6.72	2.09	0.75	1.04	-0.07	4.80	5.60	5.11	36.43	0.027	0.58	24	+0.02	8.1	5.71	6.7	
112	62	II	B	1	4.49	6.88	7.61	6.40	6.08	6.96	1.53	1.11	0.95	-0.19	5.22	6.01	5.59	38.42	0.027	0.58	24	+0.02	8.1	5.71	6.7	
88	62	II	B	1	4.55	7.74	6.87	5.78	6.06	7.67	1.70	0.89	1.05	-0.19	5.25	6.44	5.91	38.67	0.029	0.62	24	+0.02	8.1	6.55	6.6	

Table I – Chemical Analyses[1] of Groundwater (cont'd) (7)

Sample No.	Year Taken	Category	Unit	Group	Chemical Constituents in epm (equivalents per million) and Ratios: Calcium (rCa)	Magnesium (rMg)	Sodium (rNa)	Chloride (rCl)	Sulphate (rSO_4)	Bicarbonate ($rHCO_3$)	rMg/rCa	rNa/rMg	rSO_4/rCl	$\frac{rCl-rNa}{rCl}$ (b.e.i.)	$\sqrt{(rCa)(rSO_4)}$ S_1	$\sqrt[3]{(rHCO_3)^2(rCa)}$ K_2 eq.	$\sqrt{(rCa)(rHCO_3)}$ pH eq.	*Total Dissolved Solids (T.D.S.)	Ionic Strength μ	$\frac{3.618\sqrt{\mu}}{\Delta pH}$ (epm)	Temp. @ Testing (°C)	Correction for Temperature θ (epm)	pH	$\theta + \Delta pH + pH$ eq. (pH eq. Corrected) (epm)	pH eq. Corrected from Scale	REMARKS
99	62	II	B	2a	4.53	6.34	14.35	12.21	7.27	6.36	1.40	2.26	0.60	- 0.18	5.74	5.68	5.37	51.06	0.035	0.69	24	+0.02	7.9	6.08	6.7	
98	62	II	B	2a	11.88	13.49	33.48	30.26	25.30	4.59	1.14	2.48	0.84	- 0.11	17.39	6.30	7.38	119.00	0.085	1.05	24	+0.02	8.1	8.45	6.4	
86	62	II	B	2b	4.12	6.03	8.44	9.02	4.29	5.72	1.46	1.40	0.48	+ 0.06	4.20	5.13	4.85	37.62	0.026	0.58	25	0.00	8.1	5.43	6.7	
38	60	II	B	2b	9.43	10.28	36.09	37.51	14.41	5.77	1.09	3.51	0.38	+ 0.04	11.66	6.80	7.38	113.49	0.074	0.98	26	-0.02	8.0	8.34	6.4	
97	62	II	B	2b	14.92	14.23	39.57	39.87	25.67	4.95	0.95	2.78	0.64	+ 0.01	19.37	7.15	8.59	139.21	0.097	1.12	24	+0.02	7.9	9.73	6.2	
33	60	II	B	3a	17.42	19.41	33.91	45.54	22.07	4.31	1.11	1.75	0.48	+ 0.26	19.61	6.87	8.66	142.66	0.100	1.14	26	-0.02	8.1	9.78	6.2	
36	60	II	B	3a	32.01	16.69	86.96	91.28	31.65	3.31	0.76	5.21	0.35	+ 0.05	26.39	6.23	8.54	251.90	0.161	1.45	26	-0.02	7.7	9.97	6.2	
30	60	II	B	3b	16.02	14.56	51.31	63.17	18.74	1.66	0.91	3.52	0.30	+ 0.19	17.33	3.54	5.16	165.46	0.107	1.18	26	-0.02	7.3	6.32	6.6	
32	60	II	B	3b	32.09	20.81	51.31	69.09	36.12	1.56	0.65	2.47	0.52	+ 0.26	34.04	4.27	7.08	210.98	0.150	1.40	26	-0.02	7.7	8.46	6.4	
31	60	II	B	3b	30.59	20.81	73.05	90.55	32.90	3.13	0.68	3.51	0.36	+ 0.19	31.74	6.69	9.79	251.03	0.168	1.48	26	-0.02	8.0	11.25	6.1	
113	62	III		1a	1.95	3.26	1.52	0.24	1.45	5.28	1.67	0.47	6.04	- 5.33	1.68	3.79	3.21	13.70	0.010	0.37	24	+0.02	8.2	3.60	7.1	
96	62	III		1a	2.29	4.24	1.65	0.82	2.58	4.89	1.85	0.39	3.15	- 1.01	2.43	3.64	3.24	16.17	0.013	0.42	24	+0.02	8.4	3.68	7.1	
39	61	III		1a	3.59	3.41	1.22	0.29	1.52	6.48	0.95	0.36	5.24	- 3.21	2.34	5.33	4.83	16.52	0.013	0.42	23	+0.04	7.7	5.29	6.8	
90	62	III		1a	3.29	7.32	0.98	0.26	3.25	8.00	2.22	0.13	12.50	- 2.77	3.27	5.95	5.13	23.10	0.018	0.49	25	0.00	7.9	5.62	6.7	
143	63	III		1a	3.03	8.44	1.07	0.06	3.15	9.53	2.79	0.13	52.50	-16.83	3.09	6.50	5.37	25.28	0.020	0.52	23	+0.04	7.9	5.93	6.7	649 p.p.m.
22	60	III		1a	4.15	4.73	3.26	1.17	2.71	8.49	1.14	0.69	2.32	- 1.79	3.35	6.71	5.94	24.51	0.018	0.49	24	+0.02	8.2	6.45	6.6	irregular T.D.S. 672 p.p.m.
115	62	III		1a	7.14	12.91	4.74	2.34	15.89	7.24	1.81	0.37	6.79	- 1.03	10.65	7.21	7.19	50.26	0.043	0.76	23	+0.04	8.2	7.99	6.4	
107	62	III		1b	3.94	7.07	5.26	0.80	9.93	5.80	1.79	0.74	12.41	- 5.58	6.25	5.10	4.78	32.80	0.037	0.69	25	0.00	7.8	5.47	6.8	
141	63	III		1b	10.68	11.80	4.26	0.96	21.38	4.62	1.10	0.36	22.27	- 3.44	15.11	6.11	7.02	53.70	0.049	0.80	24	+0.02	8.0	7.84	6.5	Winnipeg River Basin
116	62	III		2	3.35	4.67	6.74	4.77	5.98	4.67	1.39	1.44	1.25	- 0.41	4.48	4.18	3.95	30.18	0.022	0.55	23	+0.04	8.0	4.54	6.9	
106	62	III		2	3.84	6.01	6.52	3.92	7.81	4.51	1.57	1.08	1.99	- 0.66	5.48	4.27	4.16	32.61	0.025	0.58	25	0.00	7.9	4.74	6.9	
85	62	III		2	4.89	6.92	6.96	5.39	7.95	5.31	1.42	1.01	1.47	- 0.29	6.23	5.17	5.10	37.42	0.029	0.62	24	+0.02	8.1	5.74	6.7	

Table I – Chemical Analyses[1] of Groundwater (cont'd) (8)

Sample No.	Year Taken	Category	Unit	Group	Chemical Constituents in epm (equivalents per million) and Ratios: Calcium (rCa)	Magnesium (rMg)	Sodium (rNa)	Chloride (rCl)	Sulphate (rSO_4)	Bicarbonate ($rHCO_3$)	rMg/rCa	rNa/rMg	rSO_4/rCl	$\frac{rCl-rNa}{rCl}$ (b.e.i.)	$\sqrt{(rCa)(rSO_4)}$ S_1	$\sqrt[3]{(rHCO_3)^2(rCa)}$ K_2 eq.	$\sqrt{(rCa)(rHCO_3)}$ pH eq.	*Total Dissolved Solids (T.D.S.)	Ionic Strength μ	$\frac{3.618\sqrt{\mu}}{\Delta pH}$ (epm)	Temp. @ Testing (°C)	Correction for Temperature θ (epm)	pH	$\theta + \Delta pH + pH$ eq. (pH eq. Corrected) (epm)	pH eq. Corrected from Scale	REMARKS
7	59	III		2	7.78	9.95	7.26	5.87	12.91	6.06	1.28	0.73	2.20	- 0.24	10.02	6.59	6.87	49.83	0.040	0.72	26	-0.02	7.9	7.57	6.5	
87	62	III		2	7.29	9.54	8.04	8.83	9.54	6.75	1.31	0.84	1.08	+ 0.09	8.34	6.93	7.02	49.99	0.038	0.69	24	+0.02	8.1	7.73	6.5	
11	59	III		3a	4.07	1.99	5.74	1.99	4.73	5.00	0.49	2.83	2.38	- 1.88	4.39	4.67	4.51	23.52	0.017	0.48	25	0.00	8.1	4.99	6.8	
18	59	III		3a	3.11	3.94	7.09	2.50	5.54	6.64	1.27	1.80	2.22	- 1.84	4.15	5.16	4.54	28.82	0.021	0.53	24	+0.02	8.0	5.09	6.8	
20	60	III		3b	2.34	1.88	5.87	0.67	2.35	7.20	0.80	3.12	3.51	- 7.76	2.35	4.95	4.10	20.31	0.013	0.42	24	+0.02	8.1	4.54	6.9	
79	61	III		3b	3.57	3.01	5.00	1.17	4.43	6.16	0.84	1.66	3.79	- 3.27	3.98	5.13	4.69	23.34	0.017	0.48	23	+0.04	7.8	5.21	6.8	
8	59	III		3b	4.52	3.18	5.87	2.58	6.25	5.29	0.90	1.85	2.42	- 1.28	5.32	5.01	4.89	27.69	0.021	0.53	24	+0.02	8.1	5.44	6.7	
118	62	III		3b	6.64	5.13	8.70	6.35	9.72	4.98	0.77	1.70	1.53	- 0.37	8.03	5.74	5.75	41.52	0.032	0.65	24	+0.02	7.7	6.42	6.6	Winkler Aquifer Pump-Test
±173	62	III		3b	10.88	10.94	13.04	5.22	20.72	6.80	1.01	1.19	3.97	- 1.50	15.01	7.95	8.60	67.60	0.055	0.23	–	–	7.8	8.83	6.3	Manitoba drill-hole
21	60	III		3b	11.38	9.95	20.00	16.44	16.86	6.64	0.87	2.01	1.03	- 0.22	13.85	7.95	8.69	81.27	0.060	0.89	24	+0.02	8.0	9.60	6.3	
72	61	III		3b	28.49	4.35	32.22	24.56	36.89	4.06	0.15	7.41	1.50	- 0.31	32.41	7.77	10.75	130.57	0.100	1.16	23	+0.04	7.5	11.95	6.1	
4	59	III		3b	21.71	19.90	30.70	2.65	62.04	7.23	0.92	1.54	23.41	-10.58	36.70	10.43	12.53	144.23	0.124	1.27	26	-0.02	7.8	13.78	5.9	
3	59	III		3c	4.80	2.43	11.52	0.13	14.37	4.00	0.51	4.74	110.54	-87.62	8.31	4.25	4.38	37.25	0.029	0.62	26	-0.02	7.7	4.98	6.8	

[1] Analyzed by Industrial Minerals Division, Department of Energy, Mines and Resources
* Sum of six ions: rCa, rMg, rNa, rCl, rSO_4, $rHCO_3$
‡ Analyzed by Manitoba Health Laboratory
x Analyzed by "Unknown" – samples from outside area

Samples collected late August or early September of year mentioned

CANADA

INLAND WATERS BRANCH

DEPARTMENT OF ENERGY, MINES AND RESOURCES

FIGURE 3

62H AND PART OF 52E, 52L, 62G, 62I, 62J

LEGEND

HYDROCHEMICAL ZONES

- HCO_3^- zone
- $HCO_3^- + Cl^-$ zone
- $HCO_3^- + SO_4^=$ zone
- $Cl^- + HCO_3^-$ zone
- $SO_4^= + HCO_3^-$ zone
- $SO_4^= + Cl^-$ zone
- $Cl^- + SO_4^=$ zone

HYDROCHEMICAL SEQUENCES

WESTERN FLOW

1) $HCO_3^- \rightarrow HCO_3^- + SO_4^= \rightarrow HCO_3^- + Cl^- \rightarrow Cl^- + SO_4^=$
2) $HCO_3^- \rightarrow HCO_3^- + SO_4^= \rightarrow HCO_3^- + Cl^- \rightarrow Cl^- + HCO_3^- \rightarrow Cl^- + SO_4^=$
3) $HCO_3^- \rightarrow HCO_3^- + Cl^- \rightarrow Cl^- + HCO_3^- \rightarrow SO_4^= + Cl^- \rightarrow Cl^- + SO_4^=$

EASTERN FLOW

1) $HCO_3^- + SO_4^= \rightarrow Cl^- + SO_4^=$
2) $HCO_3^- + SO_4^= \rightarrow SO_4^= + HCO_3^- \rightarrow Cl^- + SO_4^=$
3) $HCO_3^- + SO_4^= \rightarrow SO_4^= + Cl^- \rightarrow Cl^- + SO_4^=$

SOUTHERN FLOW

1) $HCO_3^- + Cl^- \rightarrow HCO_3^- + SO_4^= \rightarrow Cl^- + HCO_3^- \rightarrow SO_4^= + Cl^-$
2) $HCO_3^- + Cl^- \rightarrow HCO_3^- + SO_4^= \rightarrow Cl^- + SO_4^=$

THEORETICAL SEQUENCES

CHEBOTAREV

$HCO_3^- \rightarrow HCO_3^- + Cl^- \rightarrow Cl^- + HCO_3^- \rightarrow Cl^- + SO_4^=$ or $SO_4^= + Cl^- \rightarrow Cl^-$

IGNATOVITCH — SOULINE

$HCO_3^- \rightarrow HCO_3^- + SO_4^= \rightarrow SO_4^= \rightarrow SO_4^= + Cl^- \rightarrow Cl^- + SO_4^= \rightarrow Cl^-$

AUTHOR'S

$HCO_3^- \rightarrow HCO_3^- + Cl^-$ or $HCO_3^- + SO_4^=$

$HCO_3^- + SO_4^=$ or $HCO_3^- + Cl^- \rightarrow Cl^- + HCO_3^-$ or $SO_4^= + HCO_3^-$

$SO_4^= + HCO_3^-$ or $Cl^- + HCO_3^- \rightarrow SO_4^= + Cl^-$ or $Cl^- + SO_4^= \rightarrow Cl^-$

EXPLANATION

Confined aquifers in till ..... (T)
Confined aquifers in bedrock ..... (B)
Unconfined aquifers. (Note: not considered here.) ..... (U)

Location of water analysis

Total dissolved solids in ppm ..... 2410-329 ..... Depth of well in feet
Analysis number ..... 117-62 ..... Year sample taken.

Negative base exchange index ..... −
Positive base exchange index ..... +

GROUNDWATER FLOW

RELATIVE GROUNDWATER MOVEMENT

Local and Regional Flow in till .....
Local and Regional Flow in bedrock .....

Note: Groundwater movement is from one analysis to another — relative to total dissolved solids, depth, aquifer and hydrochemical zone.

Basin Flow

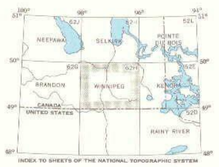
Groundwater dividing line indicating the three groundwater basins .....

Continental Flow (partly)

Mean magnetic declination 9°E., decreasing 3′ annually. Readings vary from 8°E. to 11°E.

Compiled by J. E. Charron
to accompany Paper by J. E. Charron

Base map prepared by the Surveys and Mapping Branch, 1956
Cartography by the Inland Waters Branch, 1968.
Printed by the Surveys and Mapping Branch, 1968.



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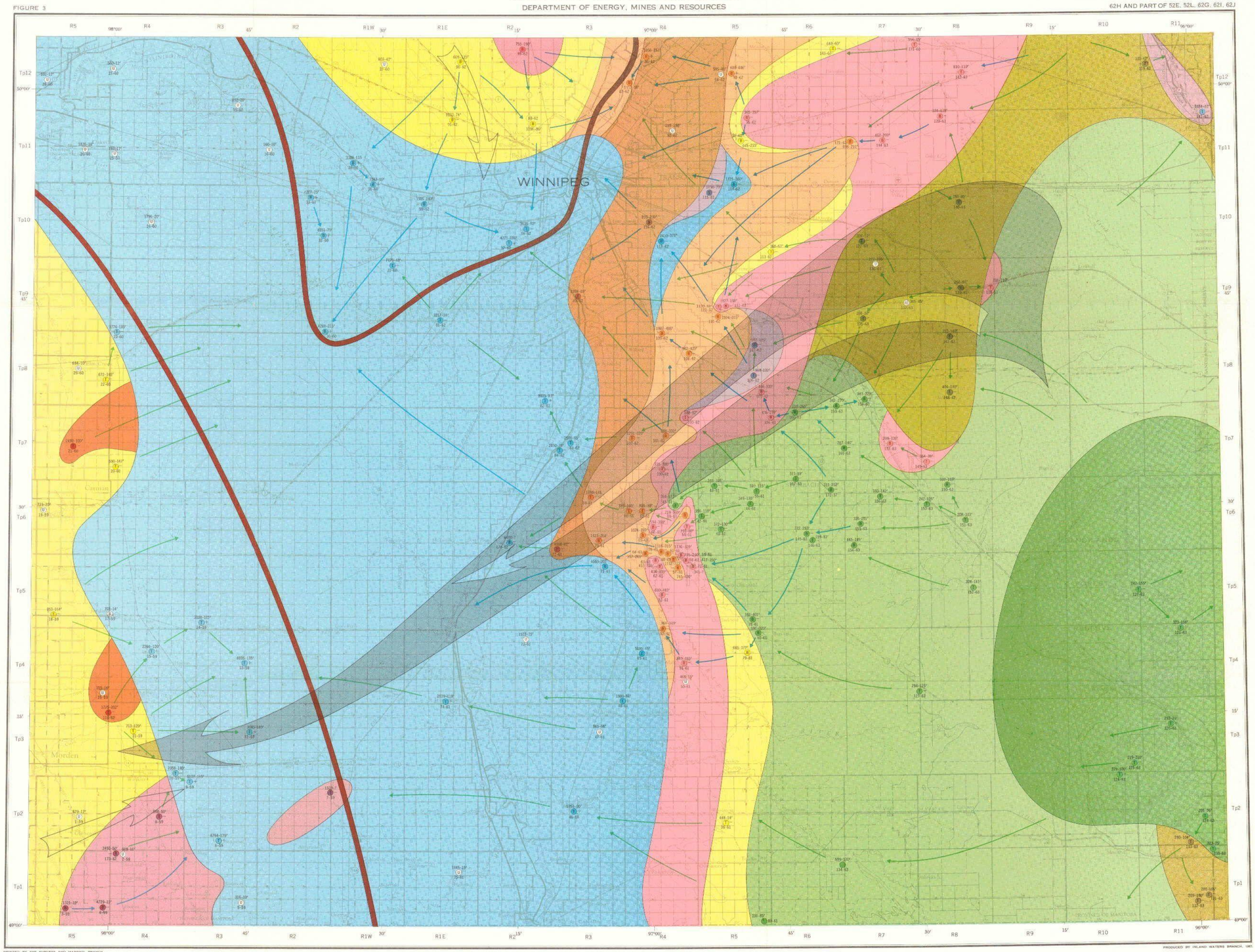

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WINNIPEG AREA – MANITOBA
A HYDROCHEMICAL INTERPRETATION OF DIRECTION OF GROUNDWATER MOVEMENT

SCALE 1:250,000

5 0 5 10 15
SCALE OF MILES

SCALE 1:250,000

5 0 5 10 15 20 25 30
SCALE OF KILOMETRES