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MAPPING OF GROUNDWATER FLOW SYSTEMS IN THE LINDBERGH AREA, ALBERTA

by

Marie Lucie Diane Emond

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ABSTRACT

A technique termed groundwater flow-systems mapping was used to evaluate groundwater flow in the Lindbergh area, Alberta. This method is based on the premise that the hydrological cycle comprises a series of causally-connected subsystems, from which information may be extracted and recombined to produce a three-dimensional representation of the groundwater flow systems. The study area is described in terms of its physiographic and geologic characteristics. Individual studies are then carried out to evaluate groundwater flow conditions. Such studies include field mapping of groundwater flow manifestations, interpretation of the hydraulic head distribution, and the study of hydrogeochemistry. Finally, the results are synthesized and boundaries of groundwater flow systems are delineated. Up to three orders of magnitude of groundwater flow systems may be identified, namely regional, intermediate, and local flow systems.

Ten groundwater flow systems of regional and intermediate order were identified in the Lindbergh area. They are located within five hydrogeological regions, which are geographic areas bounded by regional discharge zones. Approximate recharge, midline and discharge zones are outlined for each groundwater flow system. These areas represent the interpreted hydraulic conditions based on the evidence set forth in this study. Recharge zones are found in areas of higher topography and are typically characterized by hydraulic head maxima and groundwaters low in total dissolved solids. Discharge zones are located in topographic lows. They are associated with potentiometric minima, highly mineralized groundwater (>1000 mg/l) and a series of groundwater discharge manifestations such as springs, seepages, salt precipitates, phreatophytic and halophytic vegetation, and soap holes. Midline regions are broad areas wherein groundwater flow is presumed to be lateral. No particular type of groundwater flow manifestation distinguishes this hydraulic region.

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1. INTRODUCTION

1.1. Background of the study

The stresses imposed on the environment by our industrial society dictate a need for improved management of groundwater resources in order to prevent further depletion and pollution of aquifers. Proper groundwater management cannot be achieved without a full understanding of the interactive relationships which exist between all parts of the hydrogeological environment. This involves the study of the relationships between groundwater flow and its surrounding environment, which can be accomplished by the mapping of groundwater flow systems.

A recent case study of Hydrological Systems Analysis in the Netherlands (Engelen, 1984) has focused attention on regional groundwater flow mapping. The conceptual basis for such mapping is not new to Alberta. In the decade following the development of the theory of regional groundwater flow (Tóth, 1962, 1963; Freeze and Witherspoon, 1967) and the recognition of natural manifestations of groundwater flow (Meyboom, 1962, 1966a; Tóth, 1966b), several workers attempted to apply these concepts to groundwater-related studies (Clissold, 1967; Lissey, 1968; Mifflin, 1968; Freeze, 1969; Leskiw, 1971; Maclean, 1974). Various factors have contributed to the virtual disappearance of groundwater flow mapping in recent years in Western Canada. It would appear that these methods did not have a broad enough spectrum of applications to maintain enthusiasm amongst other workers although the results have generally been acccepted by the hydrogeological community.

Groundwater flow-systems mapping is a viable mapping technique but an updated, integrated approach is necessary. Previous writers tended to concentrate on one aspect of groundwater flow-systems mapping and, consequently, limited its usefulness. Data synthesis is crucial to the ability of groundwater flow-systems mapping to be utilized for groundwater management tasks, both in areas of prediction and remediation.

This study was undertaken in cooperation with the Earth Sciences Division of Alberta Environment. The Lindbergh area was selected for detailed study because of increased oil industry activity in the past five years in this area and the concerns expressed by the local population regarding potentially detrimental effects such activity could have on the groundwater supply. The results of a groundwater flow-systems study are beneficial to all parties involved in this debate.

1.2. Objectives

The study was undertaken with the primary objective of evaluating groundwater flow in terms of its relationships with the surrounding environment. A secondary objective was to demonstrate that groundwater flow-systems mapping may be utilized as a predictive tool in groundwater management and land use evaluations.

1.3. Methodology

In this study, an attempt was made to develop a suitable methodology for flow systems mapping, based on Engelen's (1984) Hydrological Systems Analysis. Hydrological Systems Analysis is a systematic methodology which relies on available data and is applicable at any scale. Engelen (1984) was able to take the concepts of groundwater flow one step further than previous writers, by synthesizing the various data to produce a hierarchy of hydrological systems. This holistic approach to groundwater mapping allows for a better understanding of the groundwater conditions because it leads to the delineation and characterization of groundwater flow systems.

The Alberta data base differs from that of the Netherlands and, hence, a revised method, referred to as groundwater flow-systems mapping, was developed accordingly. Briefly, this method consists of compiling and synthesizing data obtained from a series of interrelated subsystems of a hydrogeological system. These subsystems comprise the following: 1) climatology/meteorology; 2) topography/geomorphology; 3) geology; 4) vegetation; 5) soils; 6) vadose and phreatic zones; 7) surface water; and 8) man-made systems. A summary of the types and sources of data available for each hydrogeological subsystem is presented in Table 1.1. Relevant information required for this study was drawn from these sources. A flow chart outlining the general procedure followed in this study is displayed in Figure 1.1. As shown in this flow chart, three main steps are involved in groundwater flow-systems mapping. First, the study area must be characterized in terms of its hydrogeological environment, or hydrogeological subsystems. This information forms the basis for the work carried out in the next stage. The second step of groundwater flow-systems mapping involves field mapping of groundwater flow manifestations, the study of regional groundwater flow through the interpretation of the hydraulic head distribution and groundwater flow modelling, and the interpretation of groundwater chemistry. As indicated in the flow chart, these studies are treated as separate components. The results of steps 1 and 2 are combined and synthesized in step 3. This process is crucial to the delineation and characterization of groundwater flow systems.

Table 1.1. Data availability for flow systems analysis

Subsystem	Datum type	Source
1) climatology/ meteorology	precipitation temperature	Environment Canada (monthly records)
2) topography	elevations relief geomorphological features	topographic maps aerial photographs
3) geology	lithologies stratigraphy bedrock surface surficial deposits	water well drillers' reports oil well E-logs structure test holes Alberta Environment test holes
4) vegetation	natural vegetation crops	aerial photographs maps
5) soils	soil types	soil surveys
6) vadose and phreatic zones	water levels water table elevation rate of yields transmissivities groundwater quality	water well drillers' reports chemical analyses test holes
7) surface water	drainage patterns	topographic maps aerial photographs Water survey of Canada
8) man-made	dugouts, canals	topographic maps aerial photographs

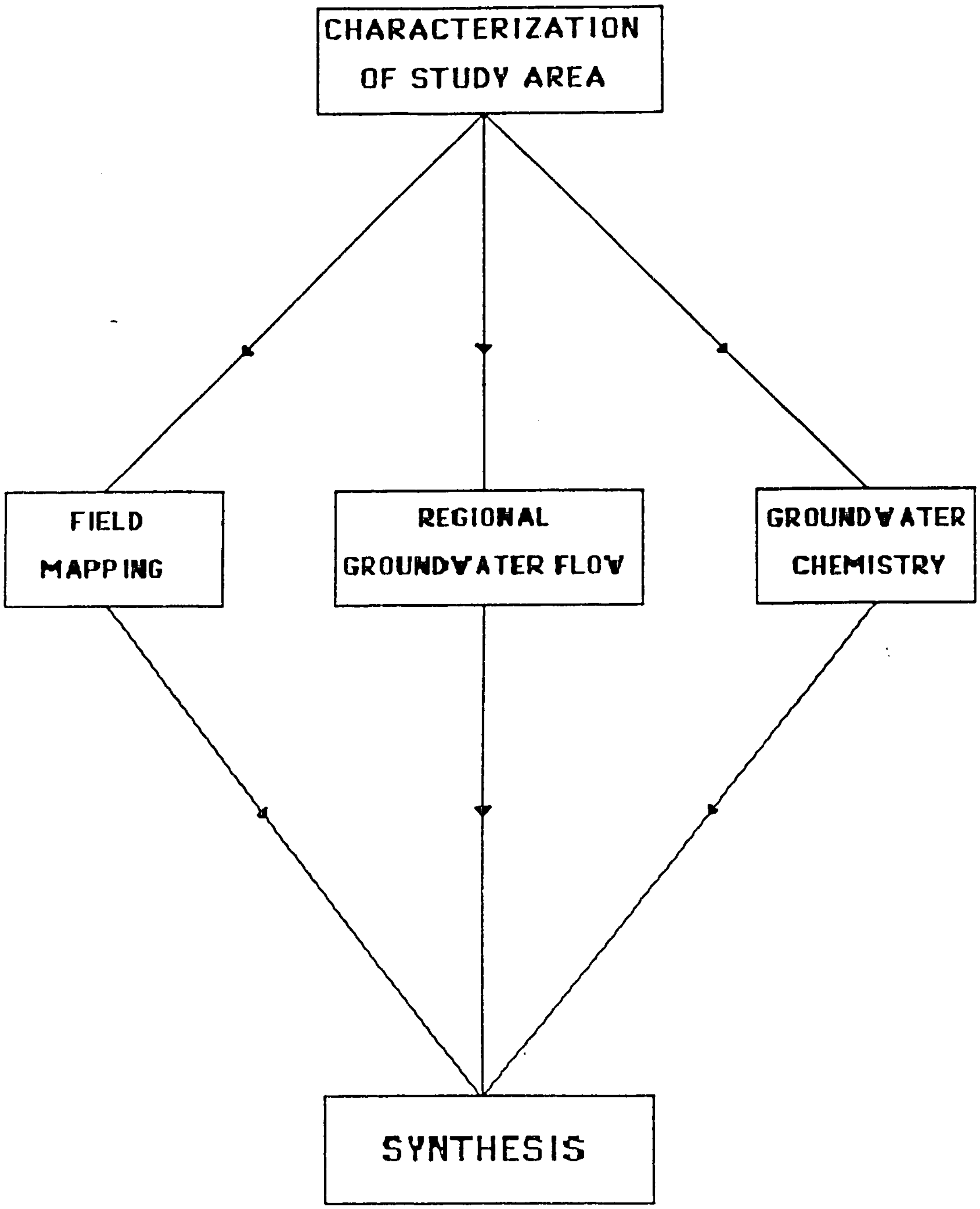


Figure 1.1. Flow chart summarizing the main steps of flow systems analysis

2. HYDROGEOLOGICAL CHARACTERIZATION OF THE LINDBERGH AREA

The characterization of a study area with reference to its hydrogeological setting is essential to groundwater flow-systems mapping because understanding the framework through which groundwater flows is a major criterion in understanding the interactions between groundwater flow and the hydrogeological environment.

2.1. Location of the study area

The Lindbergh area is located in east-central Alberta, approximately 300 kilometres east of Edmonton (Figure 2.1). It covers an area approximately 2880 square kilometres and is located between latitudes 53°27' and 54°00' North and longitudes 110°17' and 111°02' West. In the Dominion Land Survey system, this corresponds to the area within Township 52 to the south of Township 58, Ranges 3 to 7, west of the Fourth Meridian. The study area is located within the Vermilion map sheet (73-E) of the National Topographic System (NTS).

The land is primarily used for agricultural purposes and the main crops grown are wheat, oats and barley. The majority of the wooded areas have been eliminated due to agriculture and many farmers are attempting to reclaim moist depressions for cultivation. Oil wells are located in the southeast part of the study area and in the central region.

In the Lindbergh area, most of the water taken from groundwater supplies is used for domestic purposes and is extracted from shallow wells. Major groundwater users, defined here as those who obtain a groundwater license and must submit an annual water use return, include domestic, industrial and agricultural users (Figure 2.2). The major domestic users include the villages, hamlets and the Whitney Lakes provincial park. The estimated groundwater extraction for domestic purposes varies between 3.2 and 44.6

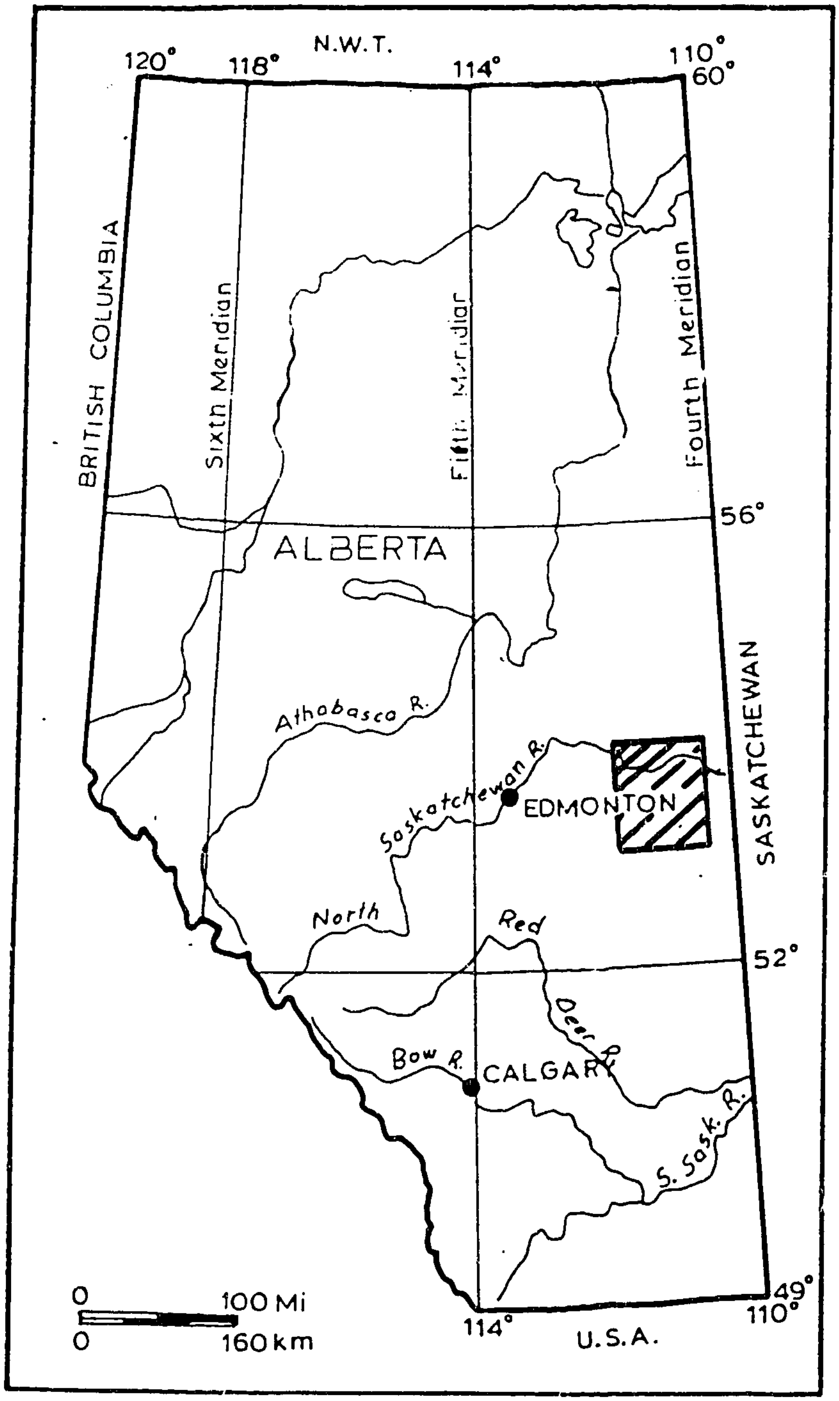


Figure 2.1. Location of the study area

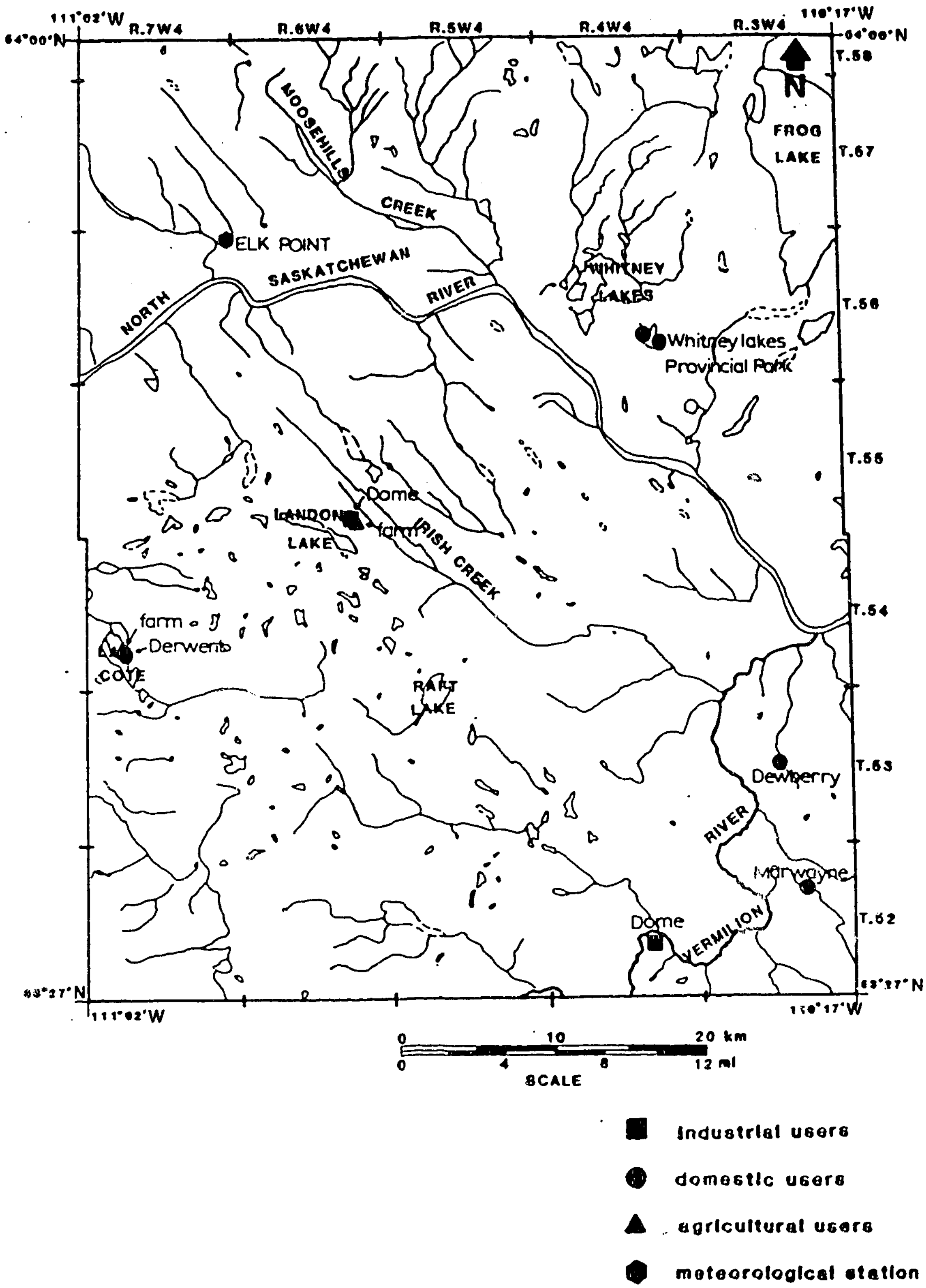


Figure 2.2. Major groundwater users in the Lindbergh area

million litres per annum.

Two heavy oil pilot projects were established in the area in 1984. Both utilized groundwater as part of their water supply. The largest of the two projects consummed 145.5 million litres of groundwater for steam injection. The Lindbergh project required 47.7 million litres of groundwater during the same year.

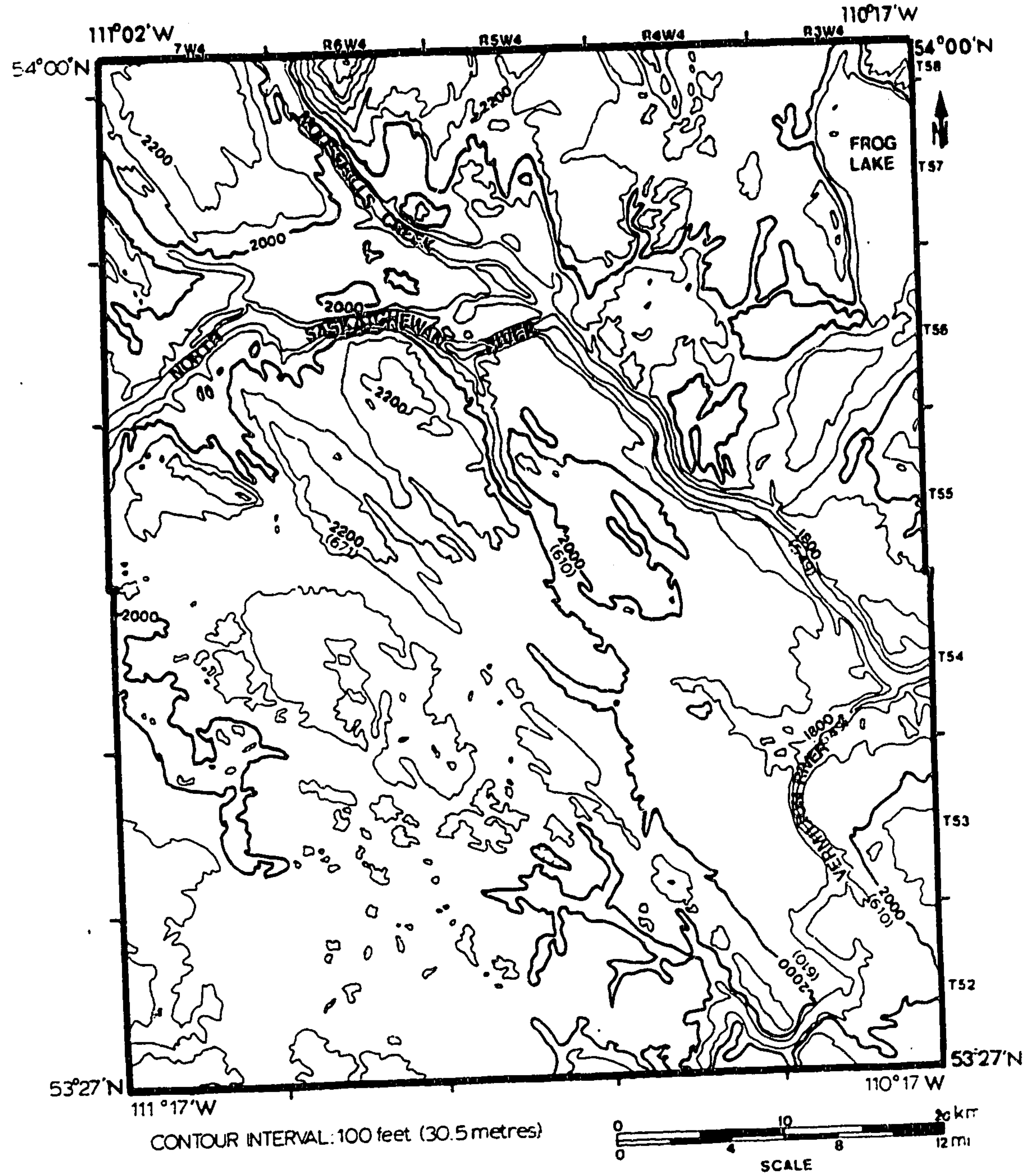
Groundwater is also used in large quantities for agricultural purposes such as irrigation and stockwatering. In the Lindbergh area there are three major agricultural users, each extracting between 4.5 and 18.2 million litres of groundwater per annum.

2.2. Physiographic setting

The area can be described as a gently rolling plain, with elevations varying between 550 metres and 810 metres, and a regional slope toward the east. The local relief varies from 3 to 26 metres (Figure 2.3). An area of greater local relief is found within a southeast trending zone situated in the central part of the study area. Major topographic lows are located along the North Saskatchewan River, Moosehills Creek and the Vermilion River.

The surficial drainage of the Lindbergh area is shown in Figure 2.4. The study area is part of the North Saskatchewan drainage basin. The largest tributary to the North Saskatchewan River in the study area is the Vermilion River. Other tributaries are small and often intermittent. The drainage systems are poorly integrated due to low precipitation and a youthful glaciated surface. There are many undrained sloughs, particularly south of the North Saskatchewan River. Frog Lake, located in the northeast corner of the study area, is the largest permanent body of water. A sub-parallel alignment of drainage courses trends northwest- southeast across the central portion of the study area. In this zone, the drainage pattern has been strongly influenced by the orientation of glacial flutings (discussed in section 2.3).

The North Saskatchewan River valley exceeds 65 metres in depth and 1600 metres



(source: NTS map sheet 73-E)

Figure 2.3. Topography of the Lindbergh area

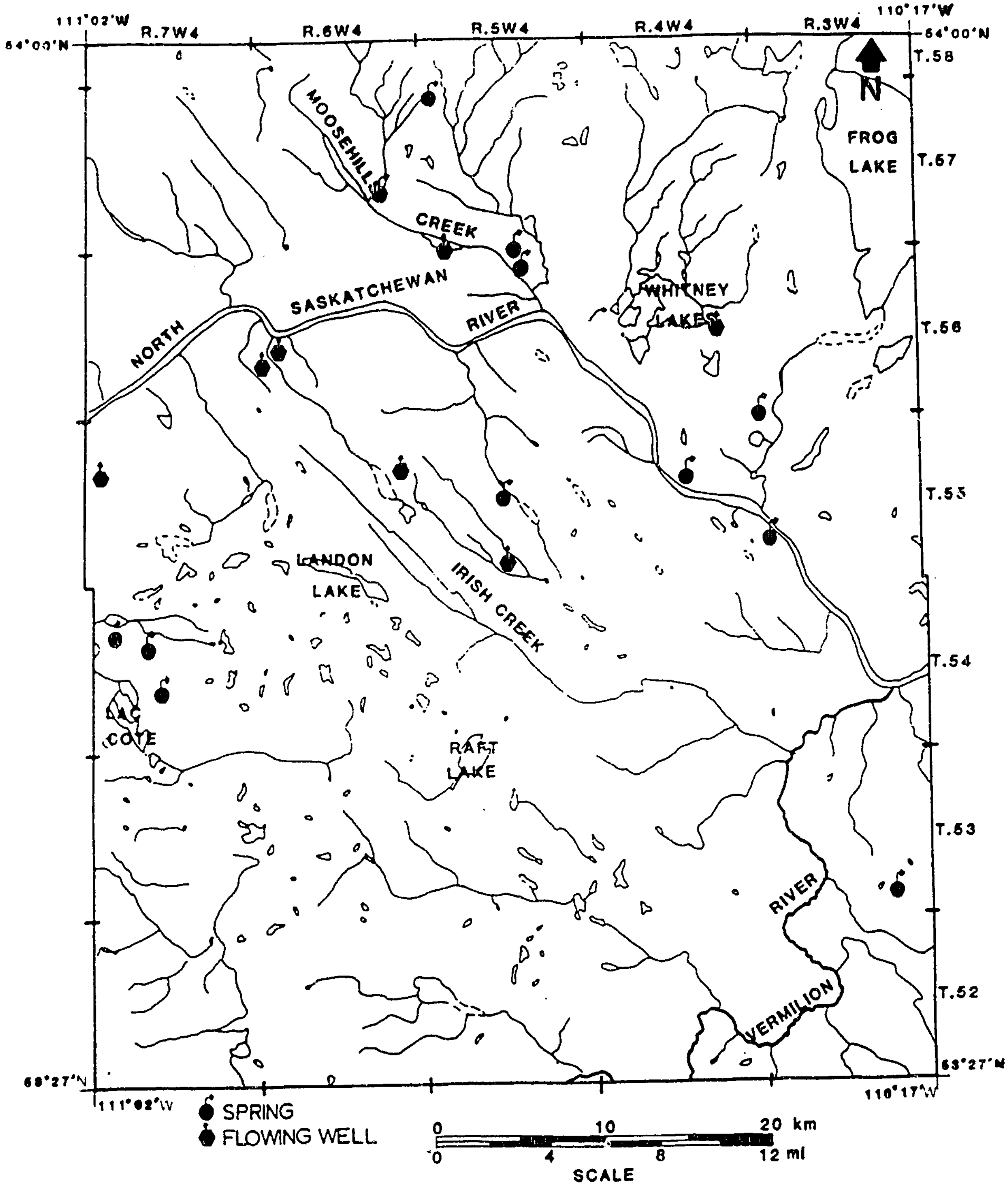


Figure 2.4. Surficial drainage of the Lidbergh area

in width at its widest point. The river follows the course of a pre-existing meltwater channel. The Vermilion River valley is deep and entrenched, and also follows an old meltwater channel. The Moosehills Creek meltwater channel has the same characteristics as the two rivers mentioned previously.

The climate is described as humid continental (Currie and Zacharko, 1976). The meteorological records for the Elk Point station (located on Figure 2.2), between 1981 and 1985, are included in Table 2.1a. There are extreme variations in temperature from winter to summer (Table 2.1b). The mean temperature in January is approximately -15°C and the mean temperature in July is +16°C (Environment Canada, 1981-1985). The average annual precipitation is 415 mm, and occurs mostly during the summer months (Table 2.1b).

According to Ellwood (1961), two main soil types are found in the Lindbergh area. Most of the area is in the Black soil zone. Gray or Podzolic soils are found in wooded areas, and there is a wide band of transitional soils between the two. These soils were classified on the basis of the color of the soil profile, which depends on the amount of precipitation, soil moisture content and vegetation conditions. Consequently, the boundaries between the soil zones are not definite. A soil survey (Wyatt *et al.*, 1944) recorded that 66 per cent of the soils were loam textured, i.e., they contained equal amounts of sand, silt and clay.

The natural vegetation of the Lindbergh area is part of the parkland prairie phytogeographic region (Moss, 1955). Most of the area is cultivated, hence, natural vegetation is found only in patches. Prior to cultivation, poplars (*Populus* sp.) dominated the region. Presently,they are mostly found along roads, near farm buildings, and surrounding water-filled depressions, along with willows (*Salix* sp.). Foxtail barley (*Hordeum Jubatum*), red samphire (*Salicornia rubra*) and gumweed (*Grindelia squarrosa*) are common in saline areas. Common wild rose (*Rosa woodsii*), Saskatoon (*Amelanchier*

Table 2.1. Meteorological records for the Elk Point station, 1981-1985.

(source: Environment Canada) (see Figure 2.2 for location)

(a) Meteorological records: 1981-1985

1981	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	-	DEC
TOT.PREC.(mm)	20.6	5.0	12.2	-	-	47.6	113.5	-	10.6	-	-	19.7
MAX. TEMP. (C)	-3.9	-4.7	3.3	-	-	20.9	23.1	-	19.2	-	-	-9.4
MIN. TEMP. (C)	-14.6	-16.1	-9.5	-	-	5	9.9	-	3.8	-	-	-10.9
MEAN TEMP (C)	-9.3	-10.4	-3.1	-	-	13	16.5	-	11.5	-		-14.7
1982												
TOT.PREC.(mm)	27.3	9.4	31.2	-	-	26.4	98.0	89.0	34.6	-	14.0	9.6
MAX. TEMP. (C)	-21.1	-11.2	-3.9	-	-	22.6	22.0	19.0	17.1	-	-5.7	-7.8
MIN. TEMP. (C)	-32.9	-25.1	-16.4	-	-	6.6	10.0	6.7	3.2	-	-15.1	-17.0
MEAN TEMP (C)	-27.0	-18.2	-10.2	-	-	14.6	16.0	12.9	10.2	-	-10.4	-12.4
1983												
TOT.PREC.(mm)	16.1	12.0	28.8	12.0	23.4	107	118.2	4.8	88.0	7.8	25.9	11.4
MAX. TEMP. (C)	-8.4	-6.4	-1.6	10.8	16.4	20.3	21.9	25.1	14.1	11.1	-1.9	-17.0
MIN. TEMP. (C)	-20.0	-15.2	-10.2	-1.6	0.8	7.4	11.2	8.5	2.0	-3.0	-6.5	-28.6
MEAN TEMP (C)	-14.2	-10.8	-5.9	4.6	8.6	13.9	16.6	16.8	8.1	4.1	-4.2	-22.8
1984												
TOT.PREC.(mm)	17.9	14.6	3.5	16.8	83.8	63.2	43.8	41.2	80.5	35.4	26.0	15.2
MAX. TEMP. (C)	-4.9	0.6	0.0	13.5	14.1	20.9	24.2	24.9	12.3	6.2	-6.7	-14.8
MIN. TEMP. (C)	-17.2	-13.3	-3.5	-1.2	1.4	6.7	8.0	9.0	1.5	-3.0	-15.6	-25.7
MEAN TEMP (C)	-11.1	-6.4	-3.5	6.2	7.8	13.8	16.1	17.0	6.9	1.6	-11.2	-20.3
1985												
TOT.PREC.(mm)	15.6	-	0.4	38.8	49.4	82.6	21.2	37.8	46.9	19.9	5.6	28.4
MAX. TEMP. (C)	-7.2	-	2.6	10.0	18.4	18.6	24.5	22.0	12.1	7.9	-11.4	-4.6
MIN. TEMP. (C)	-19.1	-	-8.6	-1.6	4.3	5.5	8.3	6.0	1.6	-2.9	-21.4	-16.2
MEAN TEMP (C)	-13.2	-	-3.0	4.2	11.4	12.1	16.4	14.0	6.9	2.5	-16.4	-10.4

(b) Mean monthly precipitation and temperature: 1981-1985

Month	Mean Precip. (mm)	Mean Temp. (C)
January	19.54	-14.96
February	10.25	-11.45
March	15.22	-5.14
April	22.53	5.00
May	52.20	9.27
June	65.28	13.48
July	78.94	16.32
August	43.20	15.17
September	52.12	9.18
October	21.03	2.73
November	17.85	-10.55
December	16.86	-16.20

mean total precipitation: 414.99 mm

alnifolia) and silverberry (*Eleagnus commutata*) are commonplace on gentle slopes in pasture fields and near poplar stands.

The locations of springs and flowing wells on record at Alberta Environment are shown in Figure 2.4. Several springs are located along the North Saskatchewan River (SE-7-55-3W4; NW-22-55-4W4), Moosehills Creek (SW-34-56-5W4; SW-3-57-5W4; SW-14-57-6W4), and the Vermilion River (SW-31-52-3W4). Other springs are associated with topographic lows, and with tributaries of the rivers and creek mentioned above. Flowing wells are located at seven locations. All of these wells are located in the vicinity of surface drainage courses, in local topographic lows. The locations of springs and flowing wells are indicative of potential areas of groundwater discharge. This topic will be discussed in section 2.4.

2.3. Geologic setting

The geologic framework of the Lindbergh area consists of subcropping Upper Cretaceous terrestrial sandstones (Belly River Formation) and marine shales (Lea Park Formation), with a regional dip of approximately 0.2 to 1.1 metre per kilometre (ERCB, 1969) overlain by Pleistocene glacial deposits. The aquifers are confined to the Belly River Formation and higher permeability zones, such as sand lenses and buried channels, within the glacial deposits.

A generalized correlation chart of Upper Cretaceous strata in east-central Alberta, shown in Table 2.2, points to the inconsistencies which have developed with reference to nomenclature of the Belly River and Lea Park Formations. The nomenclature adopted in this study is similar to Mclean's (1971) terminology, with the following exception. The term Belly River Formation was chosen rather than the Judith River Formation, to be consistent with the terminology used in the hydrogeological literature of east-central

Table 2.2. Correlation chart of Upper Cretaceous strata in east-central Alberta (after Currie and Zacharko, 1976)

Hume & Hage (1941)	Shaw & Harding (1949)	McLean (1971)	this study
	Belly River Formation	Judith River Formation; Lea Park Formation	Belly River Formation; Lea Park Formation
Pale & Variegated beds	Oldman member	unnamed member	unnamed member
Birch Lake Formation	Upper Birch Lake member	Birch Lake member	Birch Lake member
	Mulga member	Mulga tongue	
	Lower Birch Lake member	unnamed tongue	unnamed tongue
Grizzly Bear Formation	Grizzly Bear member	Grizzly Bear tongue	
Ribstone Creek Formation	Ribstone Creek member	Ribstone Creek tongue	Ribstone Creek tongue
	Vanesti member	Vanesti tongue	
	Victoria member	unnamed tongue	Victoria tongue
	Shandro member	unnamed tongue	
Lea Park Formation	Brosseau member	unnamed tongue	Brosseau tongue
	Lea Park Formation	Lea Park Formation	Lea Park Formation
Alberta Formation	Colorado Group	Upper Colorado Group	Upper Colorado Group

Alberta.

The various shale tongues were grouped as the Lea Park Formation. The use of this terminology is consistent with the interpretation that, in east-central Alberta, the Belly River and Lea Park Formations represent a transgressive-regressive system, with the interdigitation of sandstone and shale units describing the change of depositional environment eastward from terrestrial to marine deposits (Mclean, 1971). The internal geometry of the Belly River Formation suggests that the sands were deposited in a deltaic environment (Mclean, 1971). The sandstone tongues consist of deltaic lobes which prograded into the Lea Park sea. This interpretation concurs with the observation that the Belly River Formation is marked by lateral and vertical variations in lithology. Individual units typically cannot be correlated for more than a few kilometres.

The areal distribution of the bedrock geology in the Lindbergh area is displayed in Figure 2.5. The study area lies along the contact between the Belly River and the Lea Park Formations. Correlation of the Belly River sandstone tongues is difficult because only outlyers remain, and lateral continuity is not always present between sandstone tongues at adjacent localities.

Prior to Pleistocene glaciation, there was a well developed drainage system flowing toward the east-northeast (Currie and Zacharko, 1976). These river systems were entrenched in the Upper Cretaceous strata. Glaciation resulted in the burial of some of these valleys. Using up-to-date subsurface information, a portion of the bedrock topography map (Carlson and Currie, 1971) which covers the study area was revised (Figure 2.6). The thalwegs of known and presumed buried channels are traced on the map.

The largest buried channel in the study area is the Vermilion Channel. Currie and Zacharko (1976) suggest that it extends southwest of the study area. However, a test hole drilled at NW-28-52-4W4 could not locate the channel in question.The Vegreville channel,

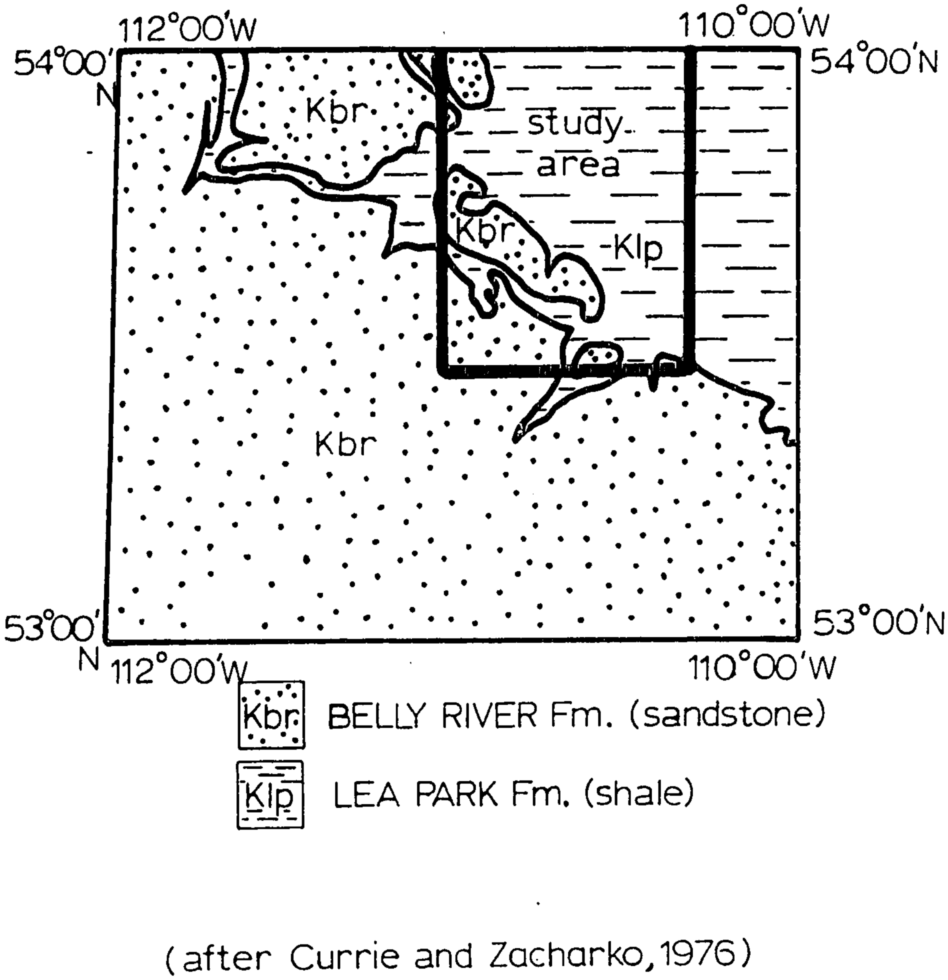


Figure 2.5. Bedrock geology of the Lindbergh area

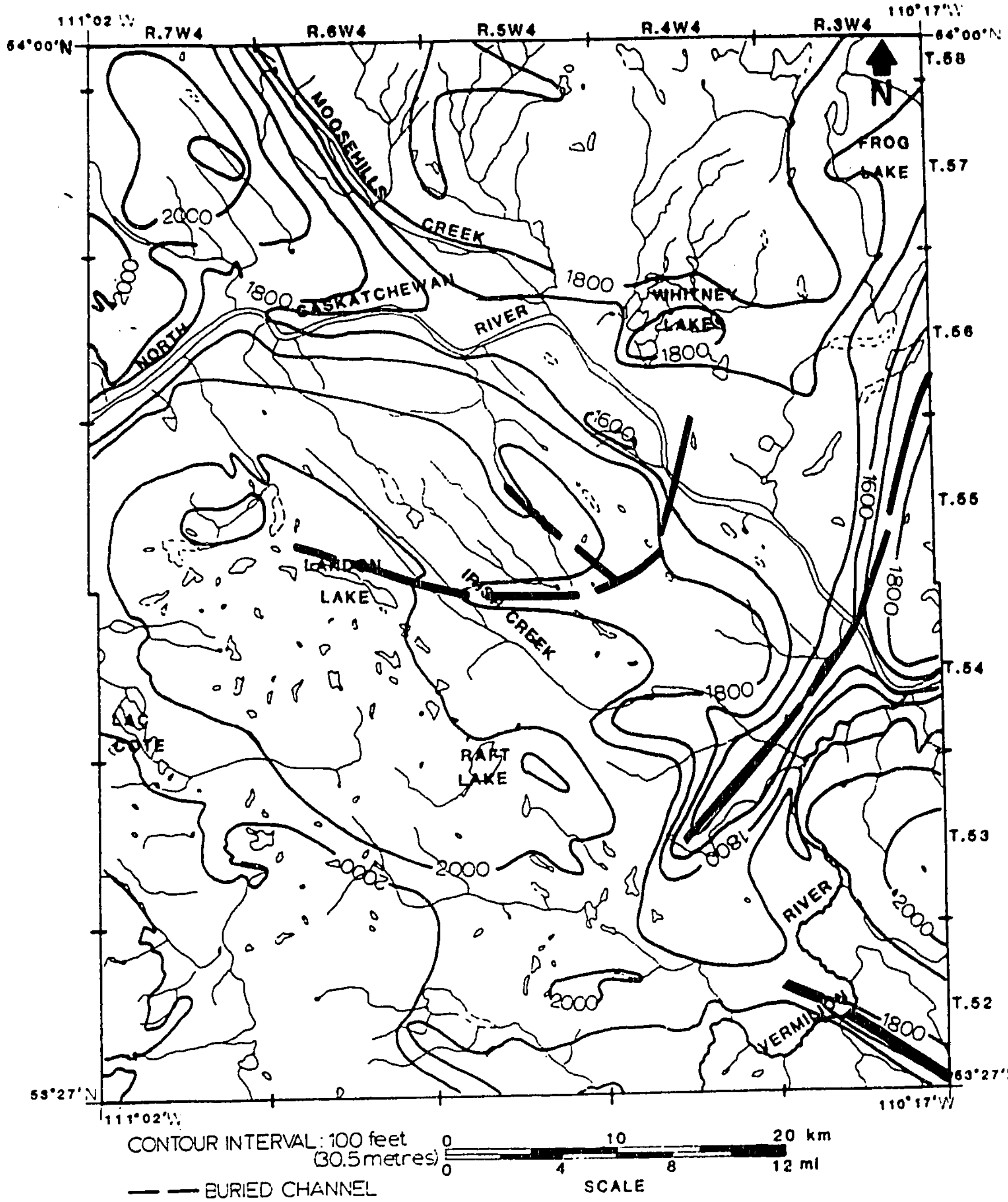


Figure 2.6. Bedrock topography of the Lindbergh area

which trends in a southeast-northwest direction, is present in the southeast corner of the study area.

Several tributary channels to the Vermilion channel have been mapped by Currie and Zacharko (1976). One of these channels, northeast of Landon Lake (Twp 55, R6W4; Figure 2.6), has been investigated in detail as a source of water supply for steam injection (Stanley and Assoc. 1981,1985). A buried tributary channel has also been mapped by the author (Twp. 55, Rge. 4W4) during reconnaissance field mapping along the North Saskatchewan River. This channel is characterized by a thick, fining upward sequence of fine to medium grained unconsolidated sand, overlain by clayey till.

Most of the area is covered by ground moraine, which is characterized by knob and kettle topography (Ellwood, 1961). It consists primarily of till, varying in thickness from a thin veneer (<1 metre) to greater than 25 metres. Lenses of sand and gravel are occasionally found within the till. These lenses of more permeable material often serve as sources of domestic water supply. In this study, the till is undifferentiated because of inconsistencies in water well reports. Sand lenses are noted but no attempt has been made to correlate them from well to well. Eskers and outwash deposits are found in areas where meltwater channels are present. Glacial flutings, which consist of long, parallel, southeasterly trending ridges and grooves, are prominent in the central part of the area. The ridges are 1 to 6 metres high and 65 to 130 metres wide at the base, and consist of till (Ellwood, 1961). These glacial flutings have strongly influenced the surface drainage and most likely affect groundwater flow in this region. The geologic framework of the Lindbergh area is schematized in Figure 2.7. As suggested by this diagram, the framework for groundwater flow in the Lindbergh area is complex, and this will certainly affect the geometry of the flow systems.

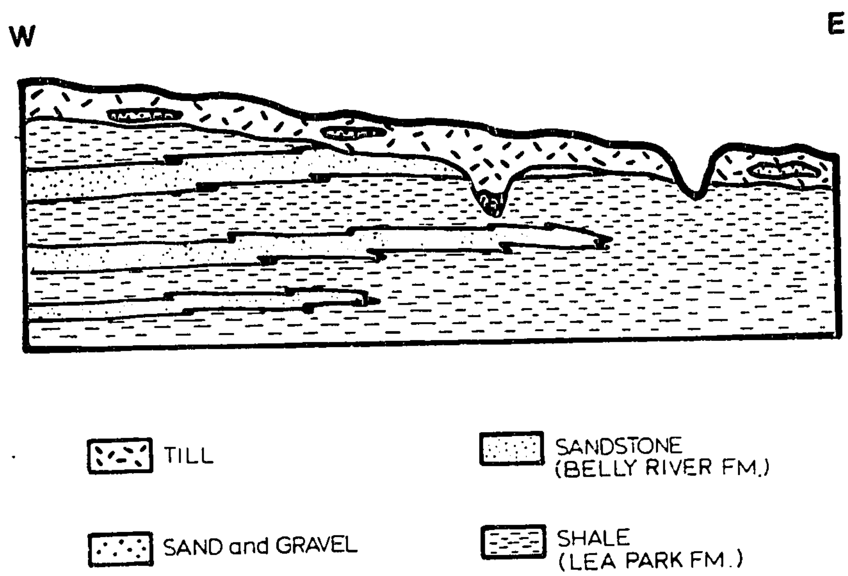


Figure 2.7. Schematic cross-section of the geologic framework

2.4. Summary

The characteristics of the hydrogeological environment of the Lindbergh area are summarized by the following:

(1) significant regional topographic relief (< 250 metres) and pervasive local topography are observed throughout the study area;

(2) surface drainage systems are poorly integrated and have been influenced by Pleistocene glaciation;

(3) major topographic lows coincide with surface drainage courses while major topographic highs coincide with erosional remnants of the Belly River Formation;

(4) approximately 70 percent of the total annual precipitation occurs between the months of May to September;

(5) two main soil types are found and a broad transitional zone exists between them;

(6) most of the area is cultivated, although local natural vegetation may be observed;

(7) the geologic framework is heterogeneous, consisting of clayey till, sand and gravel, sandstone, and shale.

3. FIELD MAPPING OF GROUNDWATER FLOW FEATURES

Three areas were chosen for detailed mapping of manifestations of groundwater flow. These areas, labelled as 1, 2, and 3, are outlined in Figure 3.1. Within each area, three tasks were carried out, namely: (1) mapping of groundwater flow features, (2) a well survey, and (3) the collection of water samples for chemical analysis. The results of the first two tasks are discussed in this section and the latter in chapter 5.

Area 1, located in the west-central part of the study area, covers approximately 90 km^2. It is characterized by numerous lakes and sloughs, springs, and a northwest-southeast trending topographic low. Area 2 is situated northeast of region 1 and covers 79 km^2. It is distinguished by knob and kettle topography, with the exception of a relatively low relief zone in the northeast corner, where glacial flutings are present. An east-west trending buried channel is present in this region. Area 3 is located in the southeast part of the study area and covers an area of 82 km^2. It is characterized by the presence of a deep buried channel and by major topographic relief due to the Vermilion river valley. Springs have been reported in this area by local farmers.

Manifestations of groundwater flow were mapped via automobile and pedestrian traverses. Where possible, traverses followed the direction of groundwater flow. Each site containing pertinent groundwater-related information was labelled and described. A list of these field observations, with their locations, is included in Appendix 2. The traverses were planned with the aid of aerial photographs, topographic maps and information retrieved from published literature. Abundant rain during field mapping caused some features to be either obliterated or masked, thus restricting the detail to which some areas could be mapped.

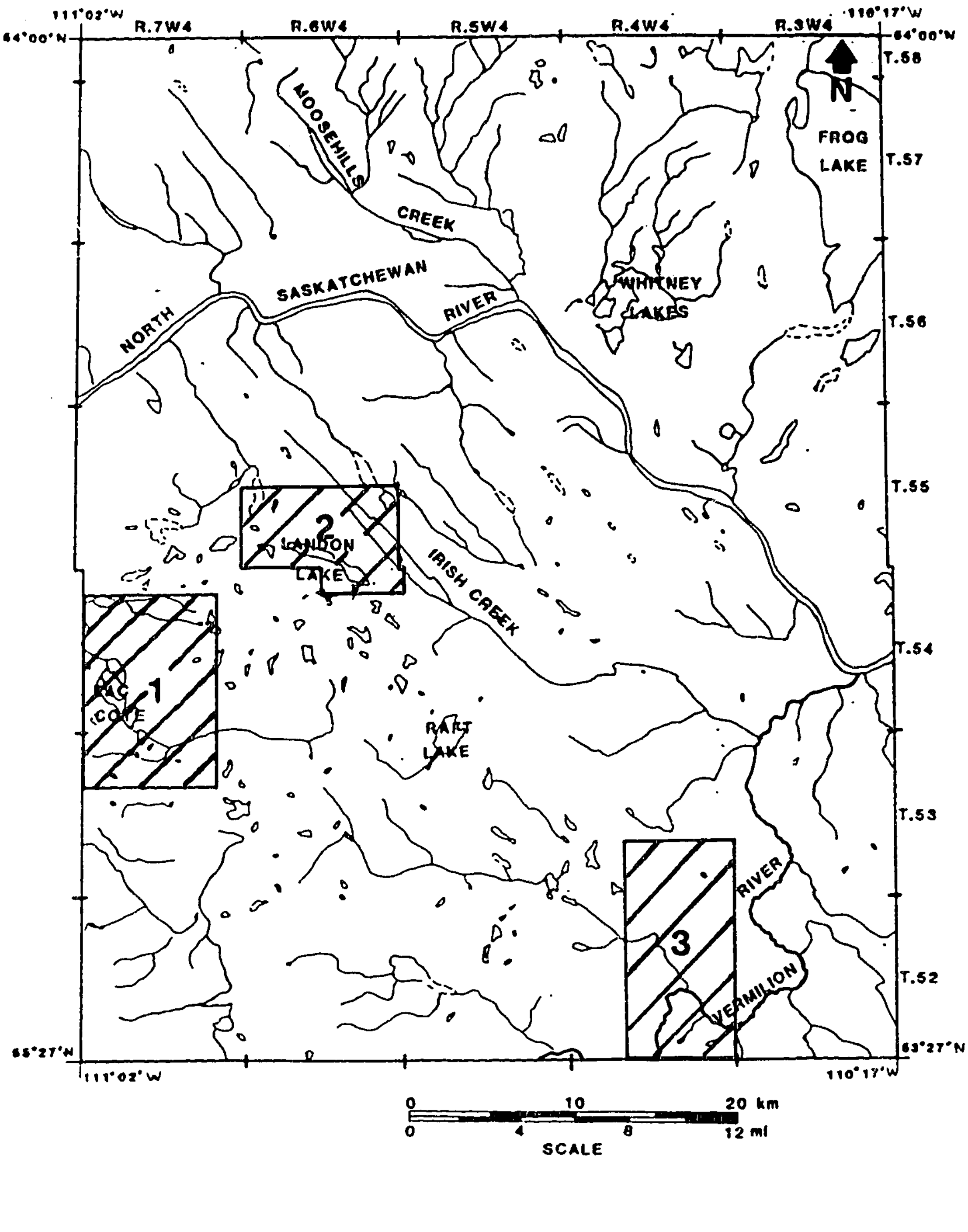


Figure 3.1 Location map of the three field mapping areas

3.1. Types of groundwater manifestations

In the 1960's, the works of Meyboom (1962), Tóth(1962,1963), and Freeze and Witherspoon (1967) led to the following general conclusions:

(1) water in the subsurface moves along flow paths of well-defined groundwater flow systems;

(2) groundwater flow systems have identifiable regions of recharge and discharge;

(3) the flow paths of groundwater and the degree of development of flow systems are controlled by the physiography and geology of a drainage basin;

(4) an interactive relationship exists between groundwater and its environment.

Tóth (1966a) and Meyboom (1966b) subsequently identified a series of hydrogeological phenomena which they attributed to cause-effect relationships between groundwater and the hydrogeologic environment. They postulated that groundwater flow conditions could be predicted from the mapping of these phenomena.
Groundwater manifestations are natural or man-made features which may, directly or indirectly, reflect groundwater flow conditions.

The types of groundwater manifestations observed in the Lindbergh area are listed in Table 3.1. Several schemes have been devised to classify groundwater manifestations (Meyboom, 1963; Tóth, 1966b; Clissold, 1967), but this author opted for a classification in terms of the hydraulic regions of the groundwater drainage basins. The generation of these manifestations is best understood in the context of the hydrological cycle, in which a series of dynamic subsystems are causally-connected. The interaction between subsystems results in the establishment of specific sets of environmental, physical, and chemical conditions in each hydraulic region, which favour the development of certain manifestations and prohibit the generation of others.

Table 3.1. Manifestations of groundwater flow in the Lindbergh area

A. **MANIFESTATIONS OF GROUNDWATER RECHARGE:**

DRY DEPRESSIONS
XEROPHYTIC VEGETATION

B. **MANIFESTATIONS OF GROUNDWATER DISCHARGE:**

SPRINGS
SEEPAGES
SALT PRECIPITATES
"SOAP HOLES"
SLOUGHS
MARSHES
DAMP SOIL PATCHES
PHREATOPHYTIC VEGETATION
HALOPHYTIC VEGETATION
DUGOUTS
STUNTED CROP GROWTH
GULLIES

C. **INCONCLUSIVE MANIFESTATIONS:**

WILLOW RINGS
MESOPHYTIC VEGETATION

A schematic groundwater basin is illustrated in Figure 3.2 to explain the conditions which prevail in each hydraulic region, and the types of groundwater manifestations observed. The following discussion relates to this figure.

In the recharge area, there is downward groundwater flow, away from the water-table. For this reason, that portion of precipitation which infiltrates into the land surface is largely lost to the groundwater flow system and evapotranspiration is reduced. This situation creates a moisture deficiency at the land surface, or a negative water budget. These conditions are conducive to the growth of xerophytic and mesophytic plants, and to the development of dry depressions.

Xerophytes are those plants which are adapted to grow in areas with a limited water supply, or moisture deficiency. Examples of xerophytes found in the Lindbergh area are: sage (*Artemesia*); snowberry (*Symphocarpos*) and silverberry (*Eleagnus commutata*). Mesophytes grow in moist but aerated soil conditions. They are generally distributed throughout the groundwater basin and, hence, are only indicators of groundwater flow conditions when found in association with other manifestations. Recharge sloughs, or dry depressions, commonly have a solid bottom covered with a uniform growth of mesophytic and xerophytic grasses. These depressions accumulate water in early spring during snowmelt, but the water soon infiltrates into the ground and is carried downward along the flow path of groundwater.

The discharge area is characterized by upward movement of groundwater, toward the water-table. In this part of the basin, precipitation and increased evapotranspiration lead to a moisture surplus, or positive water budget at the land surface. Several manifestations observed in the Lindbergh area are attributed to groundwater discharge. They include springs, seepages, salt precipitates, phreatophytes, halophytes, soap holes, gullies, dugouts and stunted vegetation. These manifestations are defined in the following paragraphs.

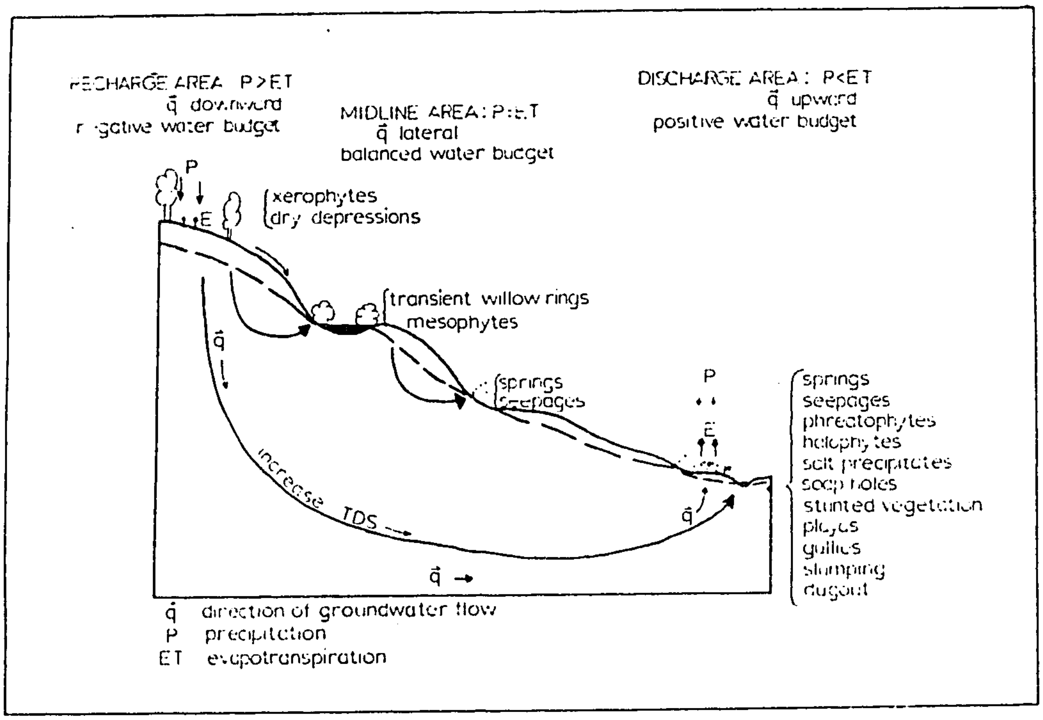


Figure 3.2. Schematic groundwater basin illustrating the prevailing conditions in each hydraulic region and the types of manifestations observed.

Springs are natural openings of the land surface from which a discernible amount of groundwater is discharged (Tóth, 1966b). By definition, they are direct indicators of groundwater discharge. In the Lindbergh area, their occurrence is primarily controlled by the topography and geology. Springs are encountered in areas of low topography, as well as in areas where zones of higher hydraulic conductivity (e.g. sand lenses) intersect the land surface. They are commonly associated with seepages. The latter are essentially the same phenomenon, but in this case flow cannot be discerned (Tóth, 1966b). Damp soil patches also qualify as seepages if they remain wet for extended periods of time between rainfalls, while surrounding soil is dry.

Salt precipitates result from salinization processes by which groundwater acts as a solvent, mobilizer, and transporting agent for salts originating from the geological framework. The salts accumulate along the flow path of groundwater and may precipitate at, or near the land surface, if the rate of upward flow is exceeded by potential evapotranspiration rates (Pawluk, 1983). Salts which accumulate at the land surface form crusts or flats. Salic horizons result from salt accumulation below the land surface. These salic horizons may be recognized by a vegetation cover of halophytes.

Halophytes consist of salt-tolerant plants, which grow on saline soils, where the conditions are unfavourable for other vegetation types. Foxtail barley (*Hordeum jubatum*) and gumweed (*Grindelia squarrosa*) are the most common halophytes in the Lindbergh area. They grow prolifically on saline soils. Red samphire (*Salicornia rubra*) and saline plantain (*Plantago eriopoda*) are more highly tolerant to salts and are found growing on salt encrustations. Soil salinization also adversely affects crop growth. "Burnt crops," or stunted plants, are attributed to discharging water with a high sodium sulphate content.

Phreatophytes are important indicators of groundwater discharge. These plants partly obtain their water supply from the saturated zone (Meinzer, 1923) and hence, indicate that the water-table is close to the land surface. Willows (*Salix*), baltic rushes

(*Juncus balticus*) and horsetails (*Equisitum*) are some of the most common phreatophytes observed in the Lindbergh area.

"Soap holes" are defined as *"part of the land surface characterized by a local weakness of limited extent underlain by a viscous admixture of sand, silt, clay, and water""*(Tóth, 1966b, p.42). They represent moderate discharge of groundwater through unconsolidated material of a heterogeneous nature. Where there is sufficient upward movement of groundwater to counteract the downward force of gravity, the weight of the grains is neutralized, and a zone of weakness is created (Figure 3.3). The development of soap holes also requires that the unconsolidated material be saturated with water, and that there be sufficient permeability, hydraulic gradient, and water supply (Tóth, 1966b).

Only one soap hole was observed in the field mapping regions. It consists of an extensive flat area in an amphitheatre-like depression, covered with phreatophytic vegetation such as baltic rushes (*Juncus balticus*) and western dock (*Rumex occidentalis*). A liquidy greenish-black mud oozes out of a cracked surface, indicating reducing conditions. This soap hole has been in existence at least since the 1920's, when the area was homesteaded. The thickness of the zone of weakness exceeds 5 metres.

Discharge sloughs are characterized by open water or a marshy bottom. They are often surrounded by willows (*Salix*) and poplars (*Populus*), as well as other phreatophytes such as cattails (*Typha*) and baltic rushes (*Juncus balticus*). Prolific growths of foxtail barley (*Hordeum jubatum*) are frequently observed in the proximity of discharge sloughs.

Gullies form in areas prone to erosion. They are often observed at the sites of springs and seepages, where the upward movement of groundwater creates zones of weakness, or erosion.

Dugouts are man-made manifestations of groundwater flow. They are predominantly found in discharge areas, because in these regions the water-table is closer to the land surface. In the Lindbergh area, several springs have been converted into

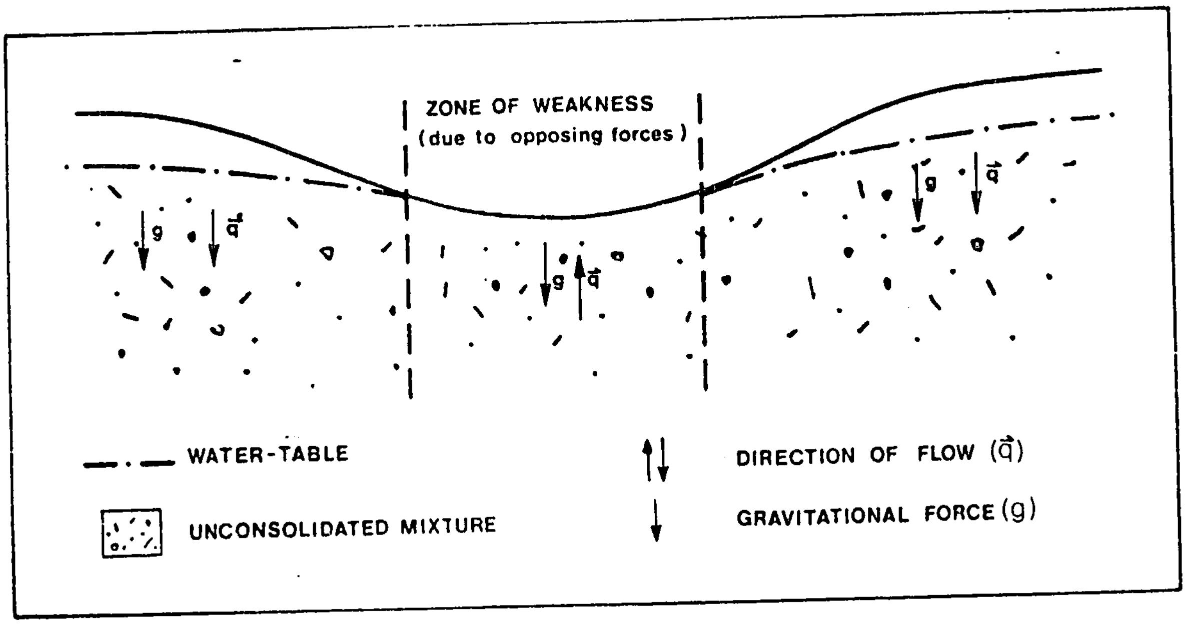


Figure 3.3. Schematic illustration of the prevailing conditions at a soap hole

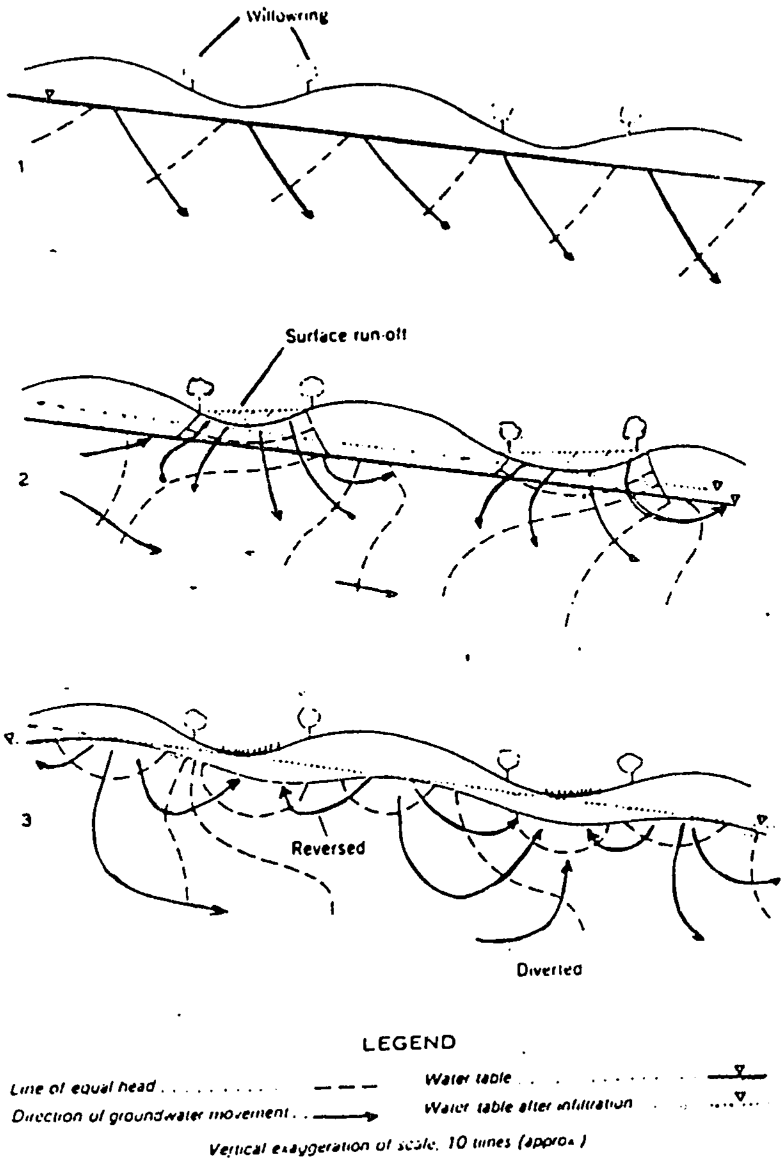
dugouts by farmers.

Unless observed in conjunction with other groundwater manifestations, two types of groundwater features are indeterminant. These are mesophytic plants and willow rings. The general distribution of mesophytes does not directly indicate groundwater flow conditions. Their association with other groundwater manifestations is necessary for an accurate determination of the groundwater flow conditions . Willow rings, or transitional sloughs, are characterized by a ring-shaped growth of poplars and willows. They act as the focal point of both recharge and discharge. Meyboom (1966) suggests that during a one-year period the following conditions can be observed (Figure 3.4):

1) downward flow during the winter;
2) development of a groundwater mound underneath the slough during the spring with an associated flow pattern of lateral and vertical dissipation;
3) an inverted water-table relief during the summer and fall, owing to a cone of depression around the phreatophytes in the ring and dry bed.

The midline area extends between known areas of recharge and discharge. No manifestations clearly distinguish this part of the basin from other hydraulic regions. In the Lindbergh area, midline regions are generally cultivated.

The association of groundwater manifestations with other manifestations is important in groundwater flow mapping. Interpretations are strengthened by the presence of more than one type of manifestation. Table 3.2 summarizes the association of groundwater flow manifestations observed in the Lindbergh area. For example, springs were observed in conjunction with seepages, salt precipitates, phreatophytes, halophytes, and gullies. On the other hand, dry depressions were observed along with xerophytes and mesophytes.



(after Meyboom, 1966b)

Figure 3.4. Transient groundwater flow conditions surrounding willow rings

Table 3.2 Association of the various groundwater manifestations in the Lindbergh area

	Dry depressions	Xerophytes	Springs	Seepages	Salt precipitates	Soap holes	Sloughs	Marshes	Damp soil	Phreatophytes	Halophytes	Dugouts	Stunted vegetation	Gullies	Willow rings	Mesophytes
Dry depressions	X	X														X
Xerophytes	X	X														X
Springs			X	X	X				X	X	X	X		X	X	
Seepages			X	X	X			X	X	X	X	X		X		X
Salt precipitates			X	X	X	X	X	X	X	X	X		X	X	X	
Soap holes					X	X				X	X					
Sloughs					X		X	X		X	X					X
Marshes				X	X		X	X		X	X					
Damp soil			X	X	X				X				X			
Phreatophytes			X	X	X	X	X	X		X	X	X		X	X	
Halophytes			X	X	X	X	X	X		X	X		X		X	
Dugout			X	X						X		X				X
Stunted vegetation					X				X		X		X			
Gullies			X	X	X					X				X		
Willow rings			X		X					X	X				X	X
Mesophytes	X	X		X			X					X			X	X

Plates I to VI illustrate a variety of groundwater manifestations observed in the Lindbergh area. A description of the site is included with each photograph.

3.2. Interpretation of the results

Groundwater flow conditions in the three areas mapped were established by field mapping of groundwater features. These interpretations were supported by observations based on hydraulic head distribution maps constructed from field measurements of water levels. Each area was subdivided into hydraulic regions reflecting the observed groundwater flow conditions and classified according to Table 3.1.

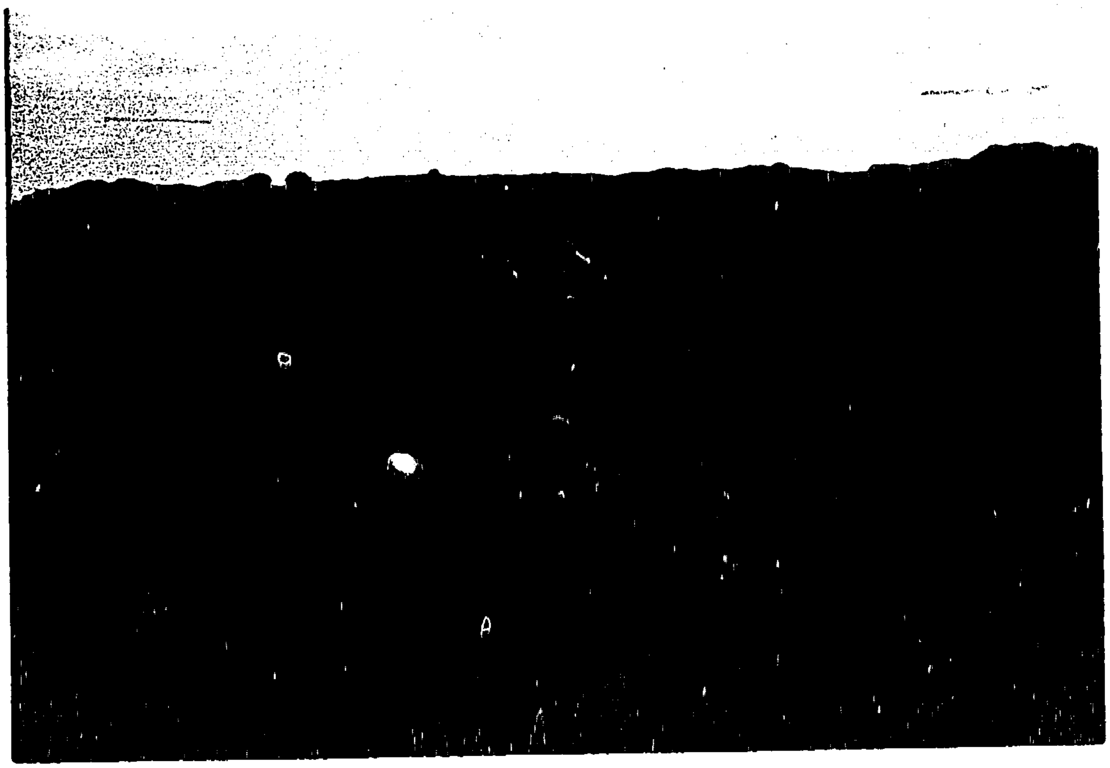
Figure 3.5 illustrates the observed groundwater flow conditions in Area 1. The letters R, D, and M correspond to recharge, discharge, and midline areas, respectively. The cross-sections outlined refer to hydrogeological cross-sections which will be discussed in Chapter 4.

An extensive discharge zone was interpreted over approximately 60 percent of Area 1. This zone is characterized by a northwest-southeast trending topographic low and hummocky local relief. Springs and seepages were observed at three locations (No's. 47, 55, 72b) in this zone. They were located near streams and found in association with phreatophytes such as horsetails (*Equisitum*). Salt precipitates were the most widespread groundwater discharge features mapped in this zone. They were particularly common in areas with hummocky local relief. Commonly, salt precipitates were observed as discrete patches in fields (No's. 28, 29b, 65, 69, 73). A ring of salt precipitation surrounded a slough at observation point 20 (see Plate III).Vegetation zoning, from the centre of the slough outward, was associated the salt precipitates at this location. As exemplified in Figure 3.6, a ring of phreatophytes was found closest to the slough, followed by halophytes, and then mesophytes. The salt precipitates were mapped within the halophytic vegetation band. Vegetation zoning was also observed at

PLATE I

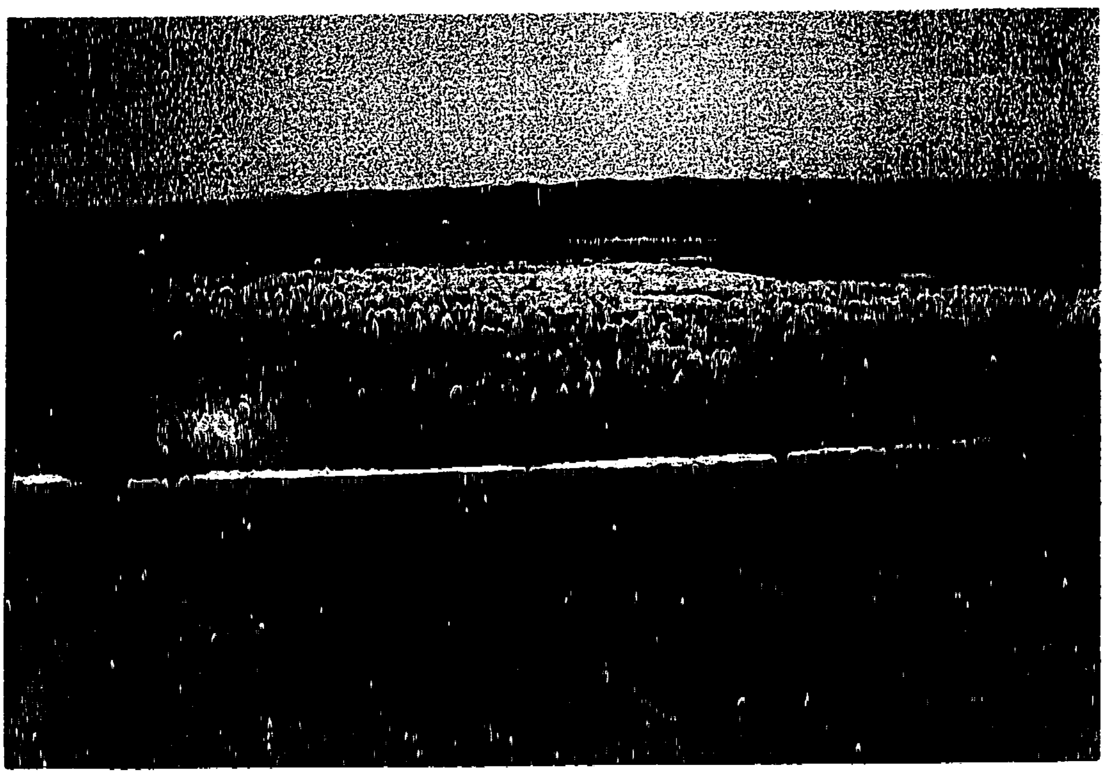
SPRINGS AND SEEPAGES. Springs and seepages discharge from fine to medium grained lenticular sands embedded in till, along a cutbank of the Vermilion river valley. Note the presence of salt precipitates (white) and gullies. Iron stains are also present although not evident on photograph. The Vermilion River valley is located to the left of this picture.

PLATE II



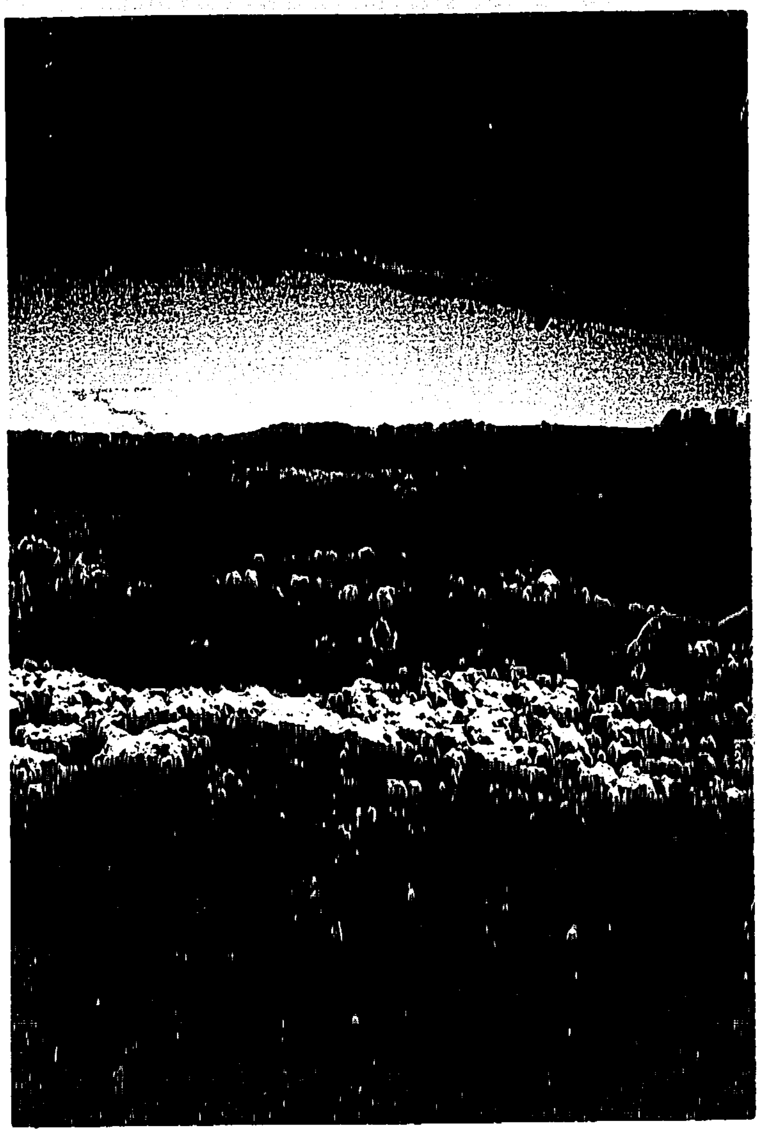
FLAT-TYPE SOAP HOLE. It is characterized by a vegetation cover of phreatophytic grasses, such as sedges, rushes and western dock. A greenish-black liquidy mud oozes out of cracks in the land surface. This indicates reducing conditions. The area is fenced in because the ground enclosed is unstable. Salt precipitates and foxtail barley (*Hordeum jubatum*) are observed in the vicinity of the soap hole.

PLATE III



SALT PRECIPITATES. A halo of salt precipitates surrounds a discharge slough. Phreatophytic grasses grow in the slough. Red samphire (*Salicornia rubra*) grows on the salt ring, and foxtail barley (*Hordeum jubatum*) on the innser side of the ring. Note that slough is in a local topographic depression. Salt precipitates and phreatophytes are absent from hillslopes and hilltops.

PLATE IV



SALT PRECIPITATES AND HALOPHYTES. Salt precipitates located in a broad topographic low. Note the presence of red samphire (*Salicornia rubra*) on top of the salt encrustation and of foxtail barley (*Hordeum jubatum*) and gumweed (*Grindelia squarrosa*). Other salt precipitates are located in the same broad topographic low.

PLATE V

DISCHARGE SLOUGH . Note vegetation zoning. Phreatophytes are located in a ring around the slough, and in the slough, followed by a prolific growth of foxtain barley (*Hordeum jubatum*) on the broad flat, and then by mesophytes on the hillslopes.

PLATE VI

HALOPHYTES AND SALT PRECIPITATES. Saline plantain (*Plantago eriopoda*) grows on top of a salt flat in a ditch. Note the absence of other vegetation.

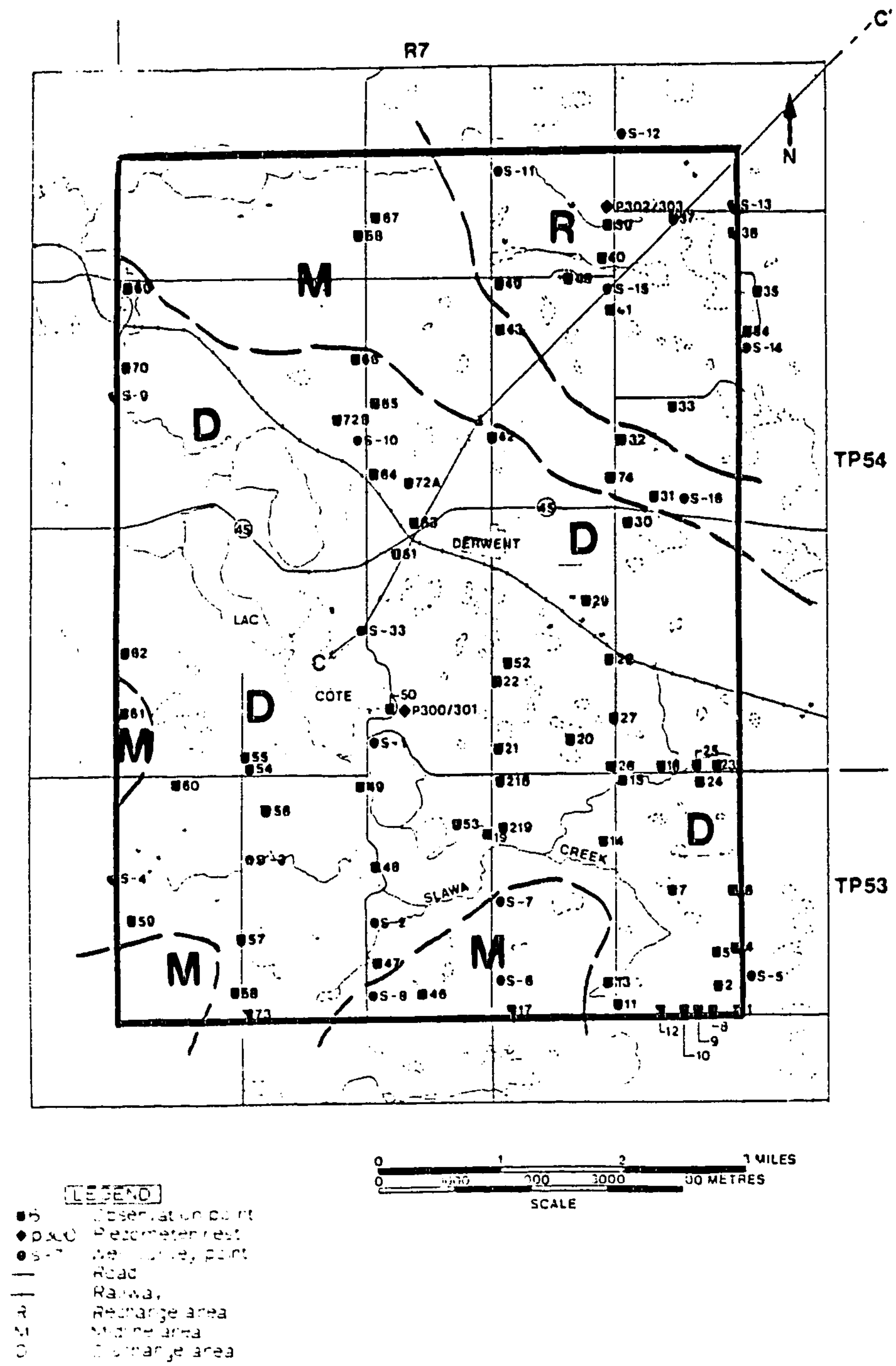


Figure 3.5. Groundwater flow conditions in area 1

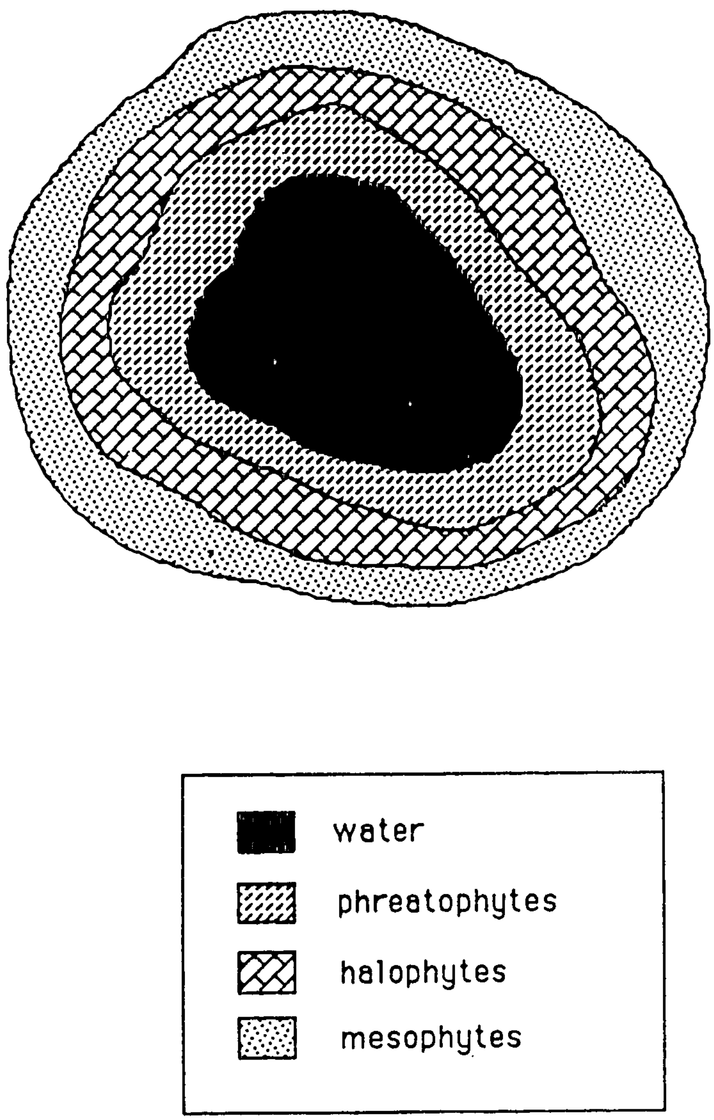


Figure 3.6. Schematic illustration of vegetation zoning associated with discharge sloughs

other sloughs where salt precipitates were absent, and based on the evidence presented above, this phenomenon was interpreted as an indicator of groundwater discharge. Discrete patches of salt were also mapped at various locations along the length of Slawa Creek (No's 47,13,15,16,23,24,25,26), in the southern part of Area 1 (Figure 3.5). This stream is further characterized by marshy edges and prolific growths of halophytes such as foxtail barley (*hordeum jubatum*) and gumweed (*Grindelia squarrosa*). Slawa Creek is interpreted as an effluent stream on the basis of this evidence.

The northern part of Area 1 is characterized by a lack of groundwater discharge features. This area is more elevated than the southern portion. Willow rings are common in this area (No's. 32, 33, 40, 43). Vegetation zoning around the sloughs is characteristically absent. The northeast corner of the region is postulated as a recharge zone, although strong supporting evidence such as dry sloughs and xerophytes were not observed. This interpretation is primarily based on the elevated topography of the area and the absence of groundwater discharge manifestations.

The water level measurements obtained from the well survey in Area 1 are plotted and contoured in Figure 3.7. The significance of hydraulic head measurements will be discussed in detail in Chapter 4, but in general, groundwater flows from areas of higher hydraulic head to areas of lower hydraulic head. In Figure 3.7, the hydraulic heads decrease from the northeast and from the southwest toward the central part of the region, creating a potentiometric low, which also corresponds to a topographic low (see Figure 3.1). Strictly speaking, flow systems cannot be delineated on the basis of the areal distribution of hydraulic heads, but this configuration suggests that the overall directions of groundwater flow are northeast-southwest in the northeast two-thirds of the area and southwest-northeast in the southwest third of the area, toward the interpreted discharge zone.

Figure 3.8 illustrates the groundwater flow conditions interpreted in Area 2. As

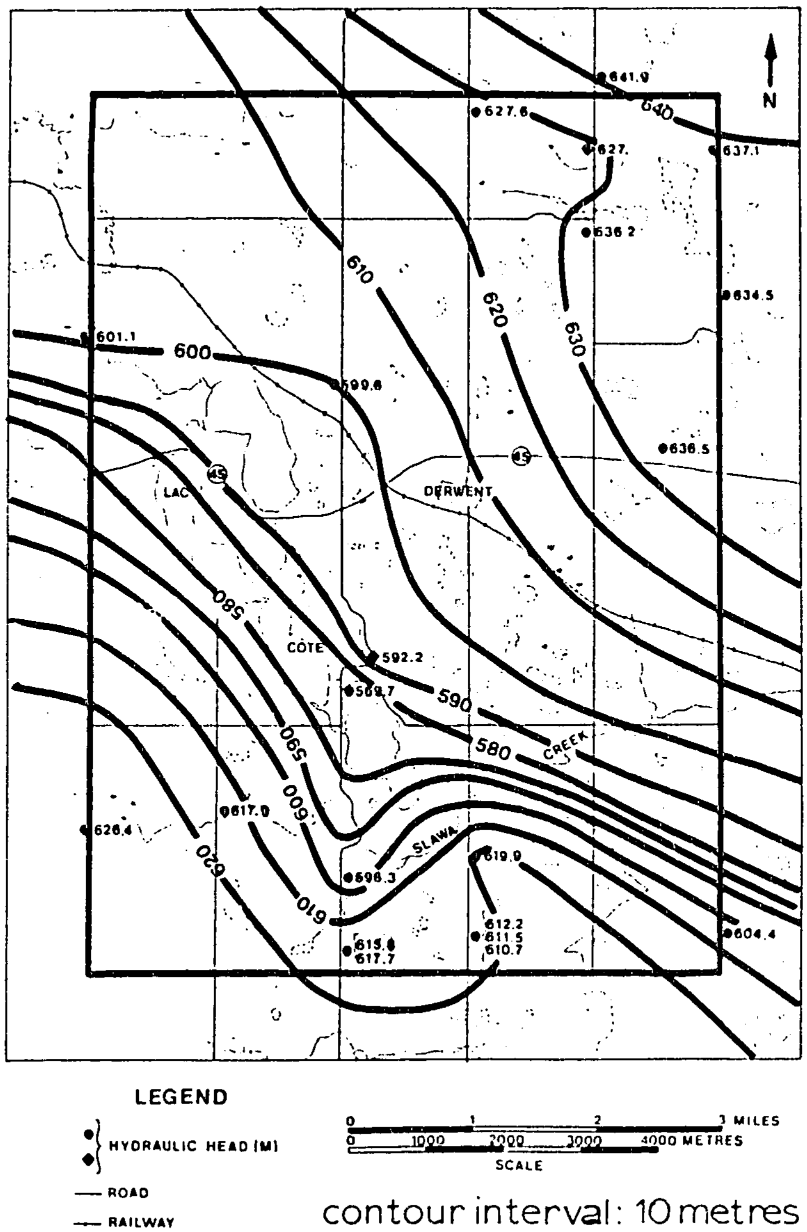


Figure 3.7. Areal distribution of hydraulic heads in area 1

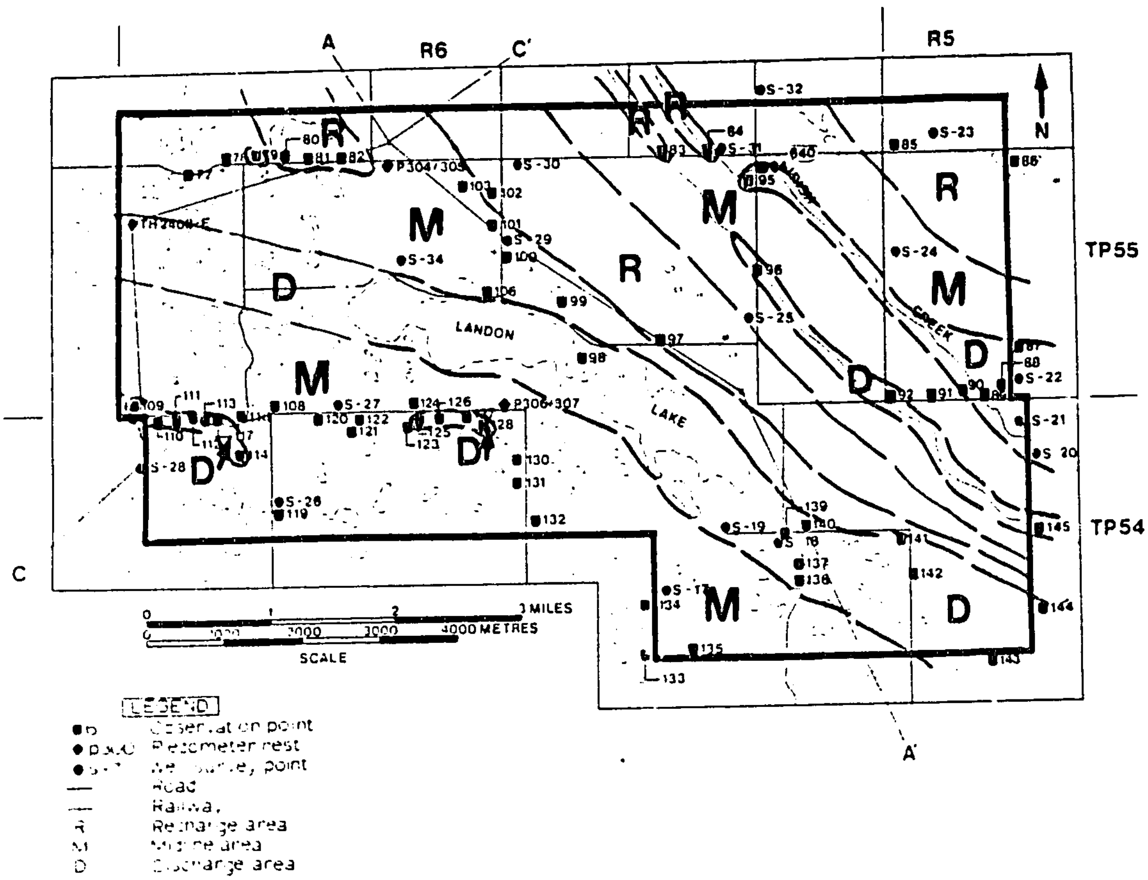


Figure 3.8. Groundwater flow conditions in area 2.

indicated, the recharge and discharge zones are preferentially oriented in a northwest-southeast direction. This orientation of the hydraulic regions is interpreted to result from glacial fluting, as suggested in Chapter 2, wherein recharge areas formed along the ridges of the flutings and discharge zones developed in the grooves. Within the discharge zones, discharge sloughs (No's. 122, 125, 126, 127, 128, 130), salt precipitates (No's. 109, 110, 111, 112, 113, 117, 124, 127), and halophytes and phreatophytes (No.98) were observed. Several of the "discharge sloughs" in this area were dry, with a phreatophytic cover, and occasionally halophytes and salt precipitates. These seemingly contradictory manifestations of groundwater flow were interpreted as effects of depression-focussed transient flow conditions in local flow systems, as suggested by Meyboom (1966b). Lissey (1971) observed similar behavior in several sloughs in Manitoba and attributed it to "interrupted regional flow" (Figure 3.9a). Numerical simulations of lake-groundwater interactions by Winter (1976, 1978) suggest that recharge conditions may exist at one end of the lake and discharge conditions at the other end, if a more permeable aquifer is present at the base of the basin, downslope from the lake (Figure 3.9b).

Recharge conditions dominate in the northeast part of Area 2. Groundwater recharge manifestations were observed at two locations (No's. 83,84). Narrow discharge zones occur along the southern part of Irish Creek. In addition to the undulating topography created by glacial flutings, there is a topographic slope from northwest to southeast. It appears that these two streams behave as influent streams in the upslope part of the basin and effluent streams in the downstream end. This dual behavior of some surface streams has also been observed by Lissey (1971) in Manitoba.

Hydraulic head values (Figure 3.10) in Area 2 are generally higher than those measured in Area 1, as would be expected due to the higher topography. Potentiometric highs are located on each side of Landon Lake, where topographic highs are present.

(A)

(B)

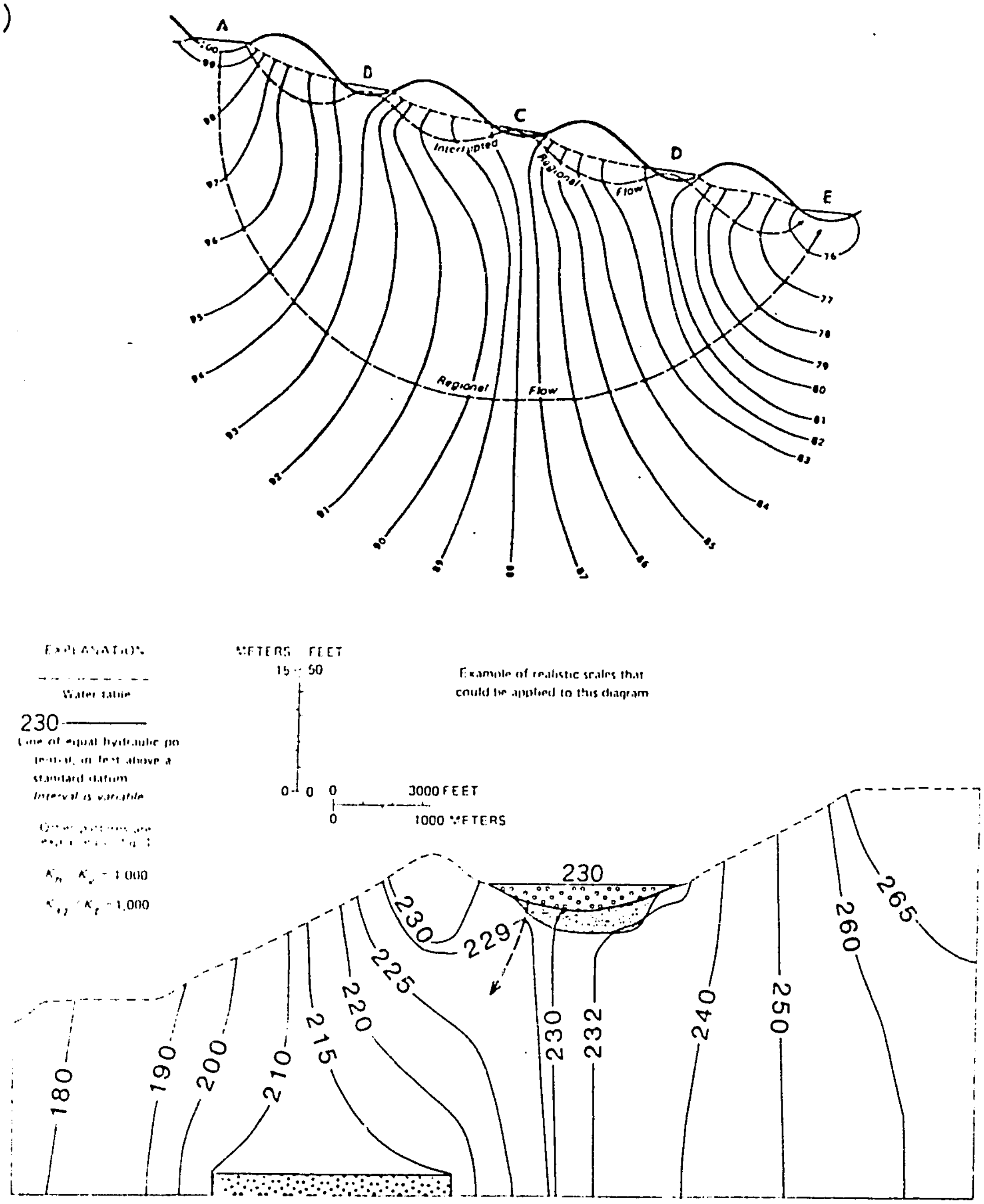


Figure 3.9 Interrupted regional groundwater flow in hummocky topography: (a) Lissey's (1971) model; (b) Winter's (1976) model

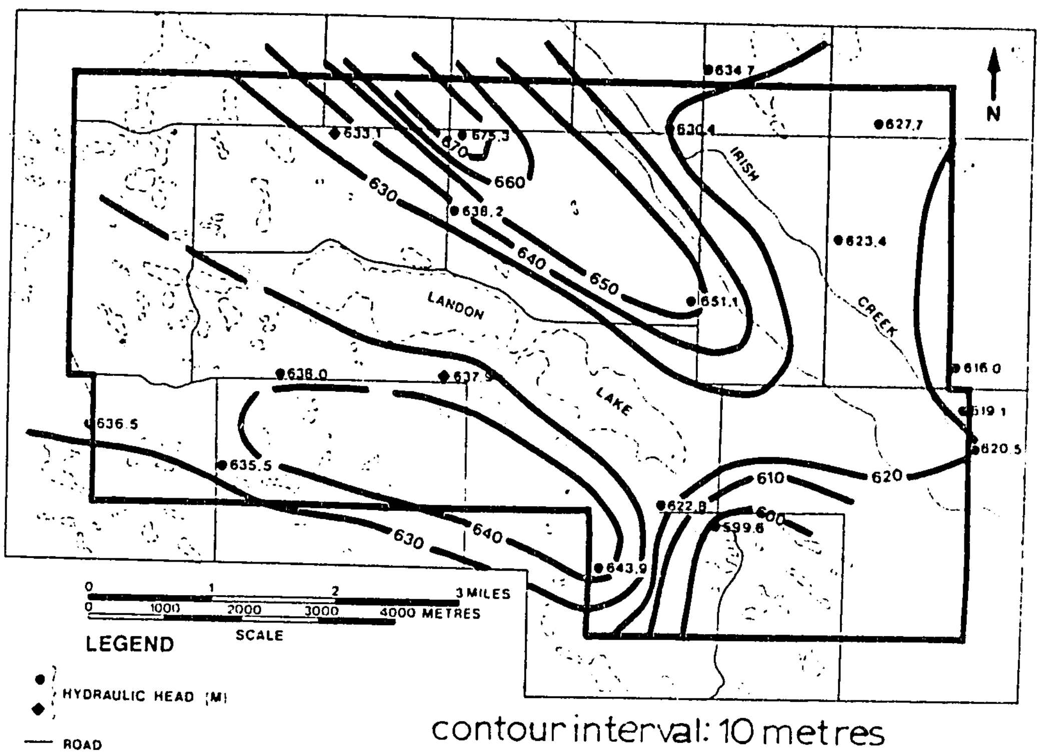


Figure 3.10. Areal distribution of hydraulic heads in area 2

The contour patterns suggest that there is groundwater movement from the highs toward the southwest, northeast, and southeast.

Groundwater flow conditions in Area 3 are shown in Figure 3.11. This area displays the greatest degree of regional relief, in comparison to the previous two mapping areas. The Vermilion River, which is located in a large river valley, flows in an easterly direction through the southern part of the study area. Sloughs are scattered throughout, but are not as common as in the other mapping regions.

Springs were mapped at several locations in Area 3 (Figure 3.11;No's. 150b, 188, 189, 193, 198, 199, 200). The physiographic and geologic settings vary for different springs. For instance, spring 150b was located in a lake west of the study area. The presence of the spring is inferred from the land owner's observation that one part of the lake never freezes during the winter. Springs 198 and 200 were found along streams and were associated with phreatophytes. Spring 199 is located in a coulee of the Vermilion River valley. It is situated approximately 15 metres above the valley floor. It is a low yielding spring (1 litre/min) in a small gully covered with phreatophytes and mesophytes. A bored well is located 5 metres downslope from the spring. Its water-level is within less than one metre of the land surface. Downslope from the well is a dugout with water within 0.5 metre of the land surface. The proximity of the water levels to the land surface in the well and the dugout supports the argument that a relationship exists between springs and groundwater flow. Upward movement of groundwater allows for water to be discharged at a discrete point where the water table intersects the land surface. At least 13 springs were reported by a land owner at observation point 188. These springs are located in coulees along the Vermilion River valley. A spring was also observed on a tributary of the Vermilion River (No. 189). This spring discharged at an approximate rate of 3-5 litres/min and had a very high iron content causing red staining of the surrounding area. The discharging water caused the

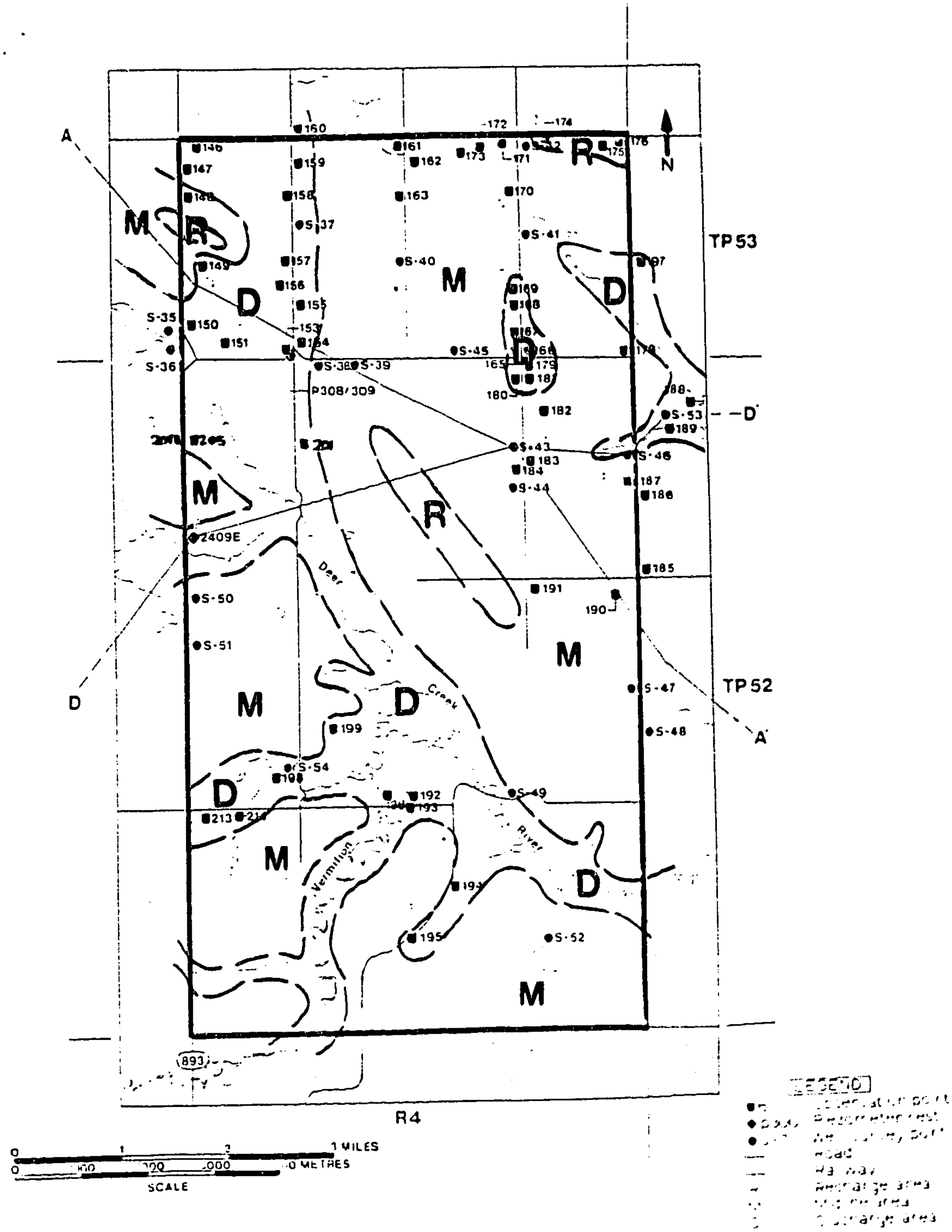


Figure 3.11. Groundwater flow conditions in area 3

flooding of a willow ring and of surrounding ground. The central part of the willow ring behaves as "quick-ground." It is believed that this is due to opposing stresses as in the case of the soap hole. Newly formed springs are located at a cutbank of the Vermilion River (see Plate I). These springs are associated with seepages, gullying, salt precipitates and iron staining. They are too recent for any vegetation to have developed. Seepage areas are more evident on the photograph, although water also trickles from discrete points. This location demonstrates that springs depend both on the physiography and the geology. The springs and seepages discharge from lenticular sand bodies embedded in till, thus showing a geologic control. The location of the springs near a regional topographic low show the physiographic control.

The coexistence of salt precipitates with springs and seepages further strengthens the interpretation that the former are manifestations of groundwater discharge. Salt precipitates were also observed as discrete patches in fields (No's. 158, 165, 166, 176, 194, 202) and in ditches (No. 179), or near streams, along with halophytes (No. 209).

From the distribution of the groundwater discharge manifestations, it appears that there is a northwest-southeast trending regional discharge zone, as well as a regional discharge area along the Vermilion River valley. The recharge zones outlined in Figure 3.11 were inferred from the topography. No recharge manifestations were observed, as these topographic highs were located in cultivated fields.

The distribution of hydraulic head from wells surveyed in Area 3 (Figure 3.12) indicates that the overall lateral directions of groundwater flow are from a potentiometric high in the east-central part of the mapping region, toward the Vermilion River to the south and east.

3.3. Summary

The main conclusions drawn from field mapping of groundwater flow features in

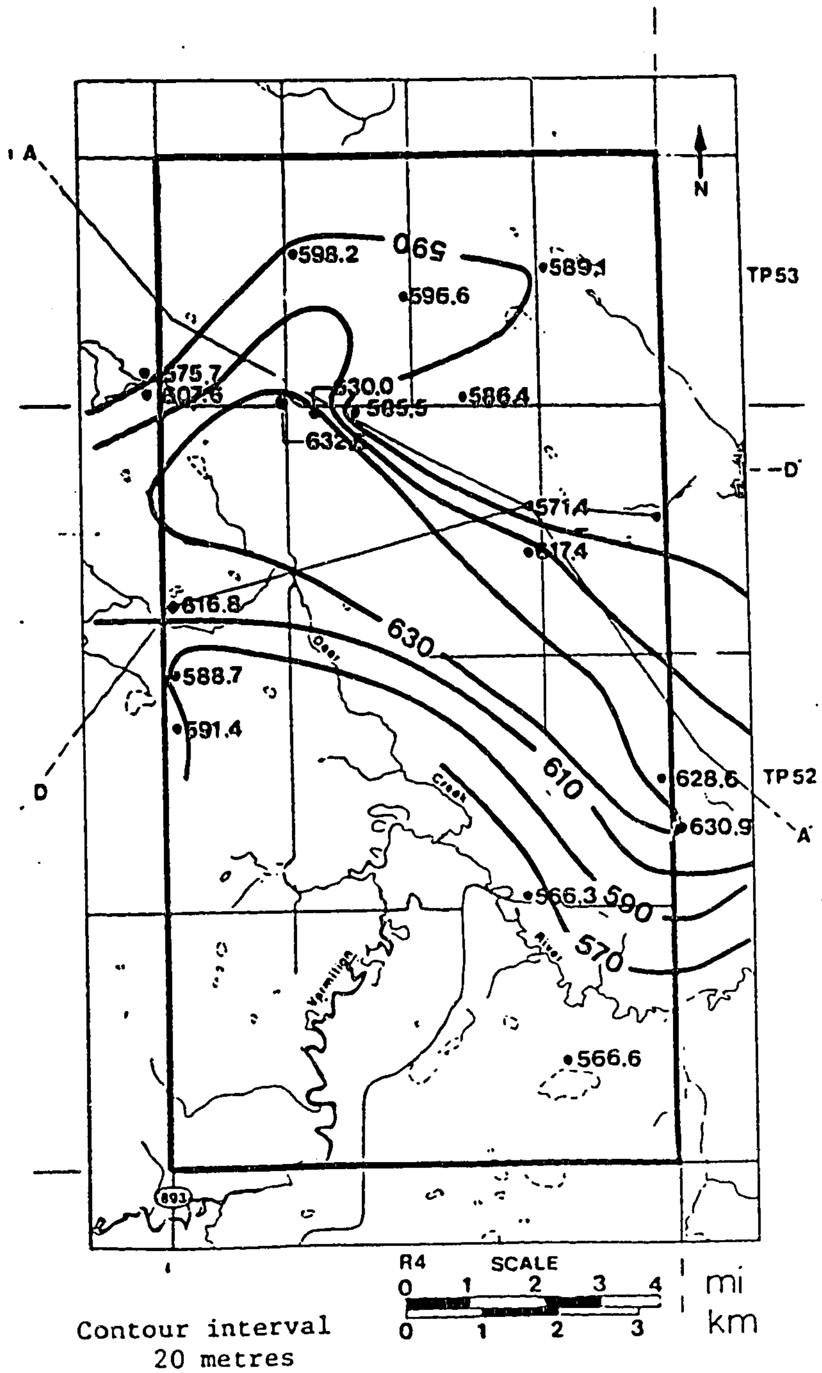


Figure 3.12. Areal distribution of hydraulic heads in area 3.

Areas 1, 2, and 3 may be summarized as follows:

(1) approximately 60 percent of Area 1 is a discharge zone, possibly of regional magnitude;

(2) salt precipitates tend to develop in areas with hummocky topography;

(3) in the absence of salt precipitates, vegetation zoning may indicate groundwater discharge conditions;

(4) Area 2 is predominantly a regional recharge zone with superimposed local flow systems;

(5) the local flow systems in Area 2 have developed as a result of glacial fluting;

(6) several sloughs in Area 2 indicate depression-focussed transient groundwater flow conditions in local flow systems;

(7) groundwater discharge conditions prevail along the tributaries of the Vermilion River in area 3, as well as in the Vermilion river valley;

(8) groundwater recharge areas are generally inferred from the topography because manifestations of groundwater recharge are uncommon.

4. REGIONAL GROUNDWATER FLOW IN THE LINDBERGH AREA

4.1 Theoretical aspects

The following discussion is intended as an overview of the theoretical aspects of regional groundwater flow, although some of these concepts were introduced previously. Much of what follows is drawn from Tóth (1963) and Freeze and Witherspoon (1967).

First, consider Darcy's empirical law for flow through a porous medium, written as:

$$Q = KA\frac{dh}{dl} \qquad (1)$$

where Q is the rate of flow (m^3/s), K is the hydraulic conductivity of the medium (m/s), A is the cross-sectional area (m^2) perpendicular to flow, h is the hydraulic head (m) and l is the distance along the flow path (m). The term dh/dl, or hydraulic gradient, represents the rate of change in hydraulic head along the flow path.

The hydraulic head, h, is a measurable quantity, defined as:

$$h = z + \frac{P}{\gamma} \qquad (2)$$

where z is the elevation (m) of the point of interest relative to a standard datum, P is the pressure at that point (N/m^2), and γ is the weight density (N/m^3) of the water, which is directly proportional to the mass density of the water and the acceleration due to gravity.

In groundwater studies, the hydraulic head is commonly determined from the measurement of non-pumping water levels in wells and piezometers. In this context, the hydraulic head is equal to the sum of two components: the elevation of the point of interest, z, or elevation head, and the pressure head, P/γ or Ψ, which corresponds to the height of the water column (m) in the well or piezometer above the point of measurement (Figure 4.1).

Another factor in Darcy's law (Eq. 1) which needs to be more clearly defined is the hydraulic conductivity, K. This parameter is a function of both medium and fluid properties. It is defined as:

$$K = \frac{k \rho g}{\mu} \qquad (3)$$

where k is known as the intrinsic permeability, ρ is the density of the water, g is the acceleration due to gravity, and μ is the dynamic viscosity. The parameter k is a function of the medium, whereas ρ and μ are properties of the fluid.

As indicated by Darcy's law (Eq. 1), flow is induced by a head loss. Mathematical models have shown that variations in the topography can create a hydraulic gradient and, thus, induce the flow of groundwater. Tóth (1963) modelled flow in hypothetical groundwater basins for which changes were made to the regional slope, the local relief and the depth of the basin. He found that, depending on the boundary conditions, three levels of groundwater flow systems may develop, namely local, intermediate, and regional flow systems (Figure 4.2). Local flow systems are those systems in which recharge and discharge areas are adjacent. Intermediate flow systems do not have adjacent recharge and discharge zones, but are not associated with major groundwater divides and streams. Regional flow systems are characterized by a recharge area at the principal groundwater divide and a discharge point at the lowest stream in the basin.

Tóth's (1963) theoretical models show that:

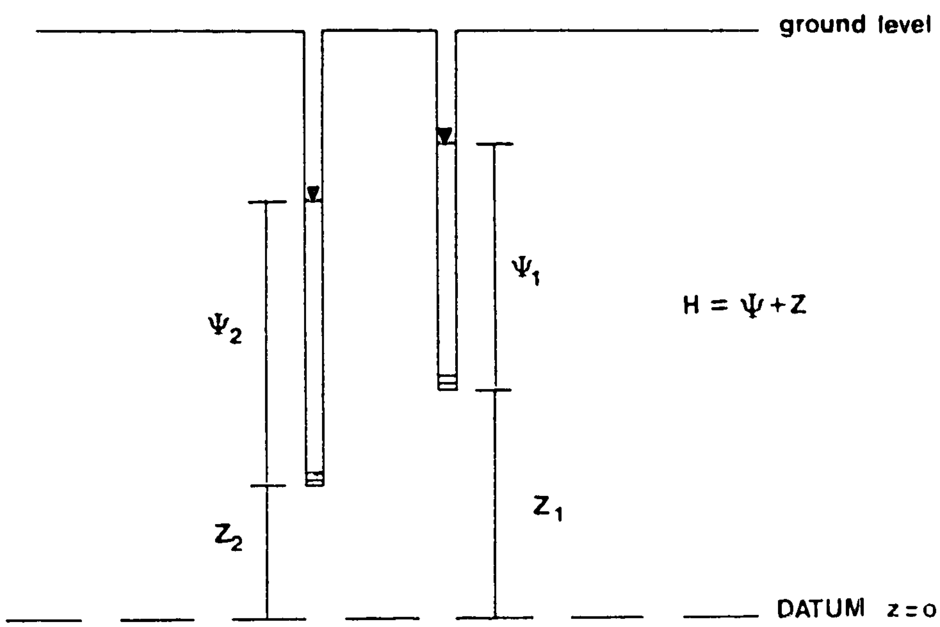
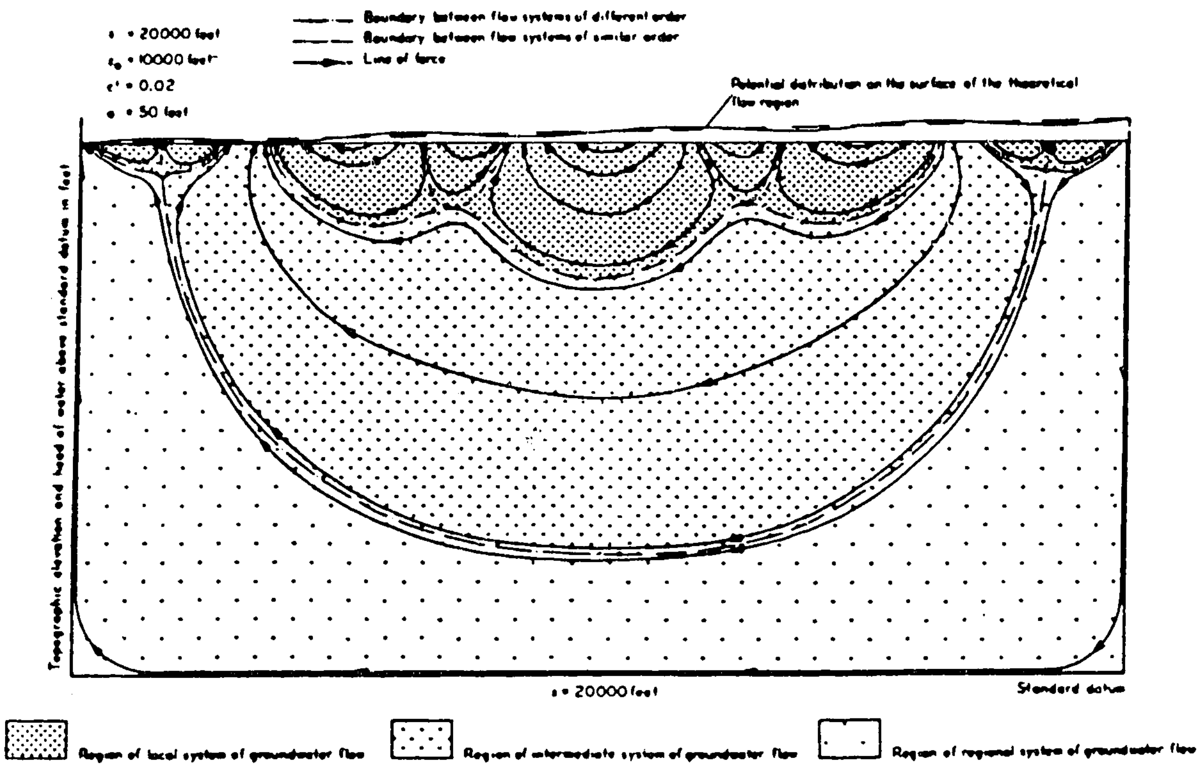


Figure 4.1. Components of the hydraulic head



(after Tóth, 1963)

Figure 4.2. Hiearchy of nested groundwater flow systems in a drainage basin

(1) both the regional slope and the local relief affect groundwater flow;

(2) regional flow systems prevail in regions with negligible local relief but where there is a regional slope;

(3) where there is significant local topography, local flow systems develop;

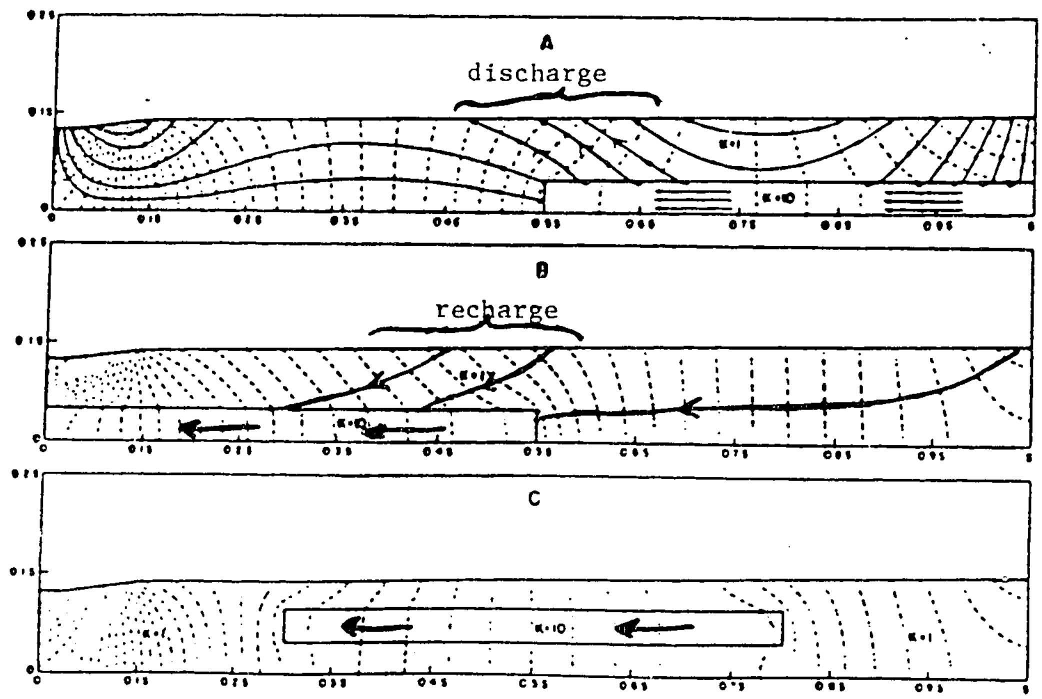
(4) there is a direct relationship between the degree of local relief and the depth of local flow systems; and finally,

(5) the basin depth to basin length ratio plays a role in flow system development, that is, regional flow systems tend to develop in deep groundwater basins whereas shallow and intermediate flow systems develop in shallow basins.

Consider Darcy's law once again (Eq. 1). As indicated by this equation, there is a direct relationship between the flow rate, Q, and the hydraulic conductivity, K. This relationship is particularly significant in heterogeneous and anisotropic media, wherein the hydraulic conductivity varies depending on the position of a point in space.

In shallow groundwater basins the density and the dynamic viscosity of the water may be assumed constant. Consequently, the hydraulic conductivity variations must be due to lateral and vertical permeability changes. These changes are caused by the spatial arrangement of the geological framework.

The effects of permeability variations on groundwater flow have been investigated from a theoretical perspective by several workers. Tóth (1962) has shown that the presence of a high permeability lenticular body in an otherwise homogeneous medium causes a distortion of the flow field. This aspect has been more extensively investigated by Freeze and Witherspoon (1967). Their study shows that the positioning of the high permeability lense in the basin dictates the manner in which groundwater flow is affected. This statement is best explained through the use of examples (Figure 4.3). For instance, if the lense is located in the upstream part of the basin, a micro-recharge zone is created in this part of the basin. Conversely, if the lense is located in the downstream part of the



(after Freeze and Witherspoon, 1967)

Figure 4.3. Effects of permeability differences at depth on groundwater flow

basin, a micro-recharge zone is created in the discharge area. Finally, no significant effect is observed if the lense is situated in the midline area, because groundwater flow is lateral in this region.

The effects of stratification, or layered heterogeneity, have also been investigated (Freeze and Witherspoon, 1967). These authors generated numerically simulated flow nets for systems exhibiting layered heterogeneity. The results of their study show that the greater the contrast between permeabilities, the more significant is the effect on groundwater flow. Anisotropy, which is caused by the alignment of clay minerals, may also be responsible for preferential directions of groundwater flow. Under these conditions, the hydraulic conductivity varies in different directions.

These theoretical aspects of groundwater flow are relevant to the study of groundwater movement in the Lindbergh area. The physiography and geology of this region (Chapter 2) suggest that several factors influence the nature and distribution of groundwater flow systems. For instance, the degree of local relief varies from one area to another. Local flow systems most likely dominate the areas with strong local relief, and may be altogether absent in areas with minor local topography. Likewise, the geologic framework is of a heterogeneous nature and, as such, must affect the flow paths of groundwater.

Two tasks were carried out to examine regional groundwater flow in the Lindbergh area: (1) the interpretation of the hydraulic head distribution from raw data and, (2) two-dimensional numerical modelling of groundwater flow. The methods and results of each task are discussed individually in the following two sections.

4.2. Interpretation of the hydraulic head distribution

4.2.1. Areal distribution

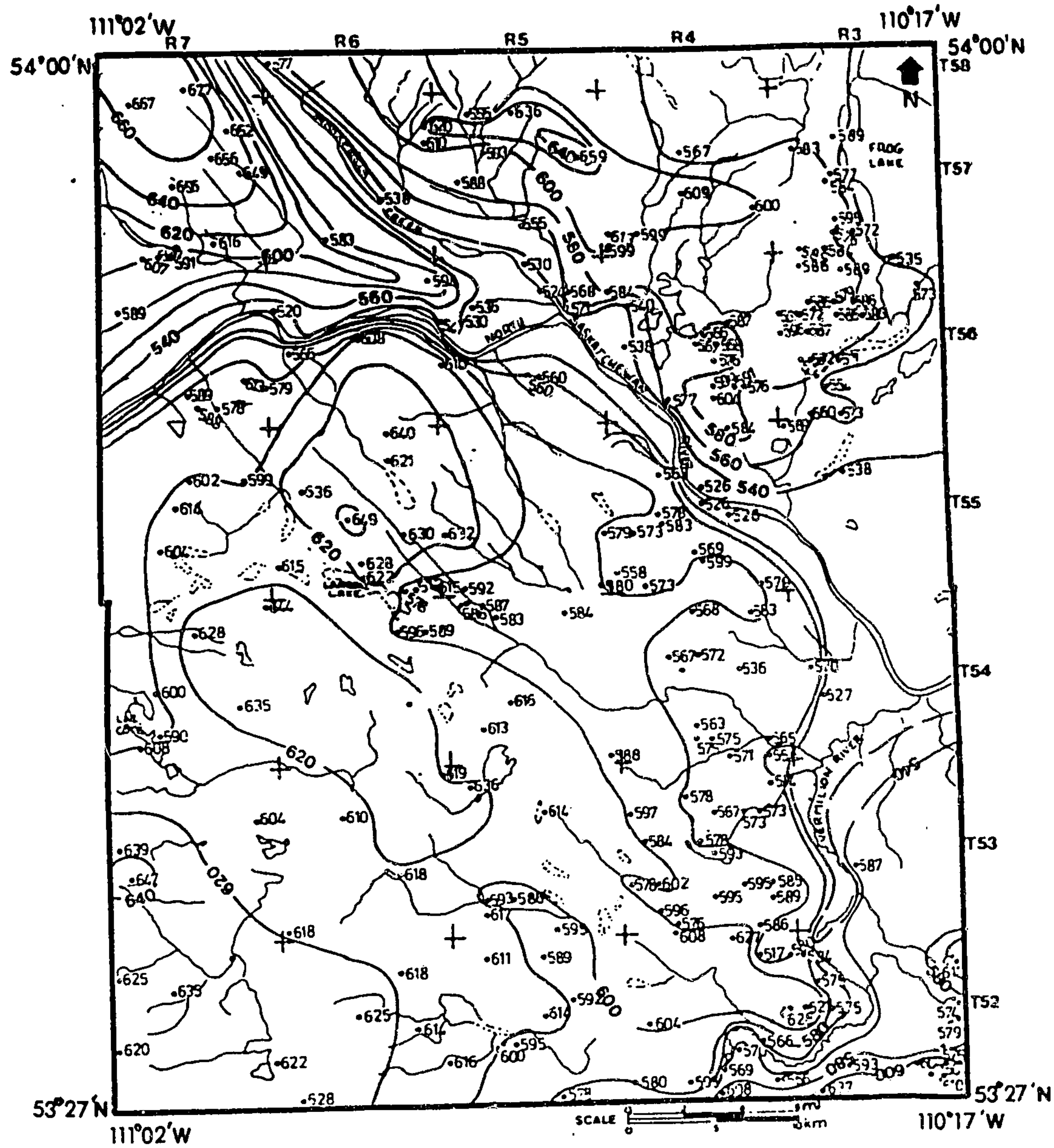
Due to the magnitude of the study area, hydraulic head values were largely determined from static water levels reported on water well reports (Appendix 1). Water level measurements taken during a well survey in the three mapping regions were also included.

The chief purpose of interpreting the hydraulic head distribution is to establish regional groundwater flow conditions. For this reason, it is necessary to examine the three-dimensional distribution of hydraulic heads. With this in mind, a hydraulic head distribution map and four hydrogeological cross sections were constructed.

The areal distribution of hydraulic heads is displayed in Figure 4.4. Only water level measurements from screened wells are considered for this map to insure more accuracy with respect to the potentiometric distribution. Screened wells have a small length of intake relative to the thickness of the aquifer and, thus, can best approximate point measurements. A 20-metre contouring interval was used because it was commensurate with the degree of accuracy in determining topographic elevations.

When the hydraulic head distribution (Figure 4.4) is compared to the topography of the Lindbergh area (Figure 2.3), there is a striking ressemblance between topographic and potentiometric patterns. For instance, topographic and potentiometric highs coincide in several locations including Twp. 52, Rge. 3; Twp. 54, Rge. 6; and Twp. 57, Rge. 7. Likewise, major topographic and potentiometric minima follow similar trends, that is, along the North Saskatchewan and Vermilion Rivers, as well as the Moosehills Creek.

In principle, one cannot delineate the boundaries of groundwater flow systems on the basis of the areal distribution of hydraulic heads alone. On the other hand, the contour patterns reflect overall directions of groundwater flow. The similarities between the



contour interval : 20 metres

Figure 4.4 Areal distribution of hydraulic heads in the Lindbergh area topography and the hydraulic head distribution support the theory that the topography poses a major control on groundwater flow, as suggested by previous workers (Tóth, 1963; Freeze and Witherspoon, 1967).

The relationship between the topography and the hydraulic head distribution may be used to subdivide an area into hydrogeological regions , which are bordered by interpreted groundwater discharge zones.This approach is advantageous because it provides the worker with a first approximation of the distribution of groundwater flow systems. An examination of the physiography in each hydrogeological region may be useful in predicting the number of intermediate or regional flow systems present.

Five hydrogeological regions were identified in the Lindbergh area. They are illustrated in Figure 4.5, along with the topography, and in Figure 4.6, with the hydraulic head distribution. As shown in Figure 4.5, the boundaries of the hydrogeological provinces are located along three major topographic lows, i.e. the North Saskatchewan River, Vermilion River and Moosehills Creek, and a more subtle topographic low in the southern portion of the study area. These limits also coincide with potentiometric lows (Figure 4.6). Hydraulic heads are generally below 540 metres along the three major topographic lows mentioned above, and they are in the vicinity of 600 metres along the minor topographic low in the southern part of the study area.

The following discussion pertains to the areal characteristics of each hydrogeological region, as interpreted from the hydraulic head distribution and the topography.

Hydrogeological region 1 is located in the northwest corner of the Lindbergh area. It is bordered to the east by Moosehills Creek and to the south by the North Saskatchewan River. There is a significant degree of regional relief (>150 m) but minimal local relief (Figure 4.5). The main topographic high consists of the Moose Hills (Twp.57, Rge.7) while the major lowlands are Moosehills Creek and the North Saskatchewan River. There is a relatively steep topographic gradient, particularly eastward. Hydraulic heads range

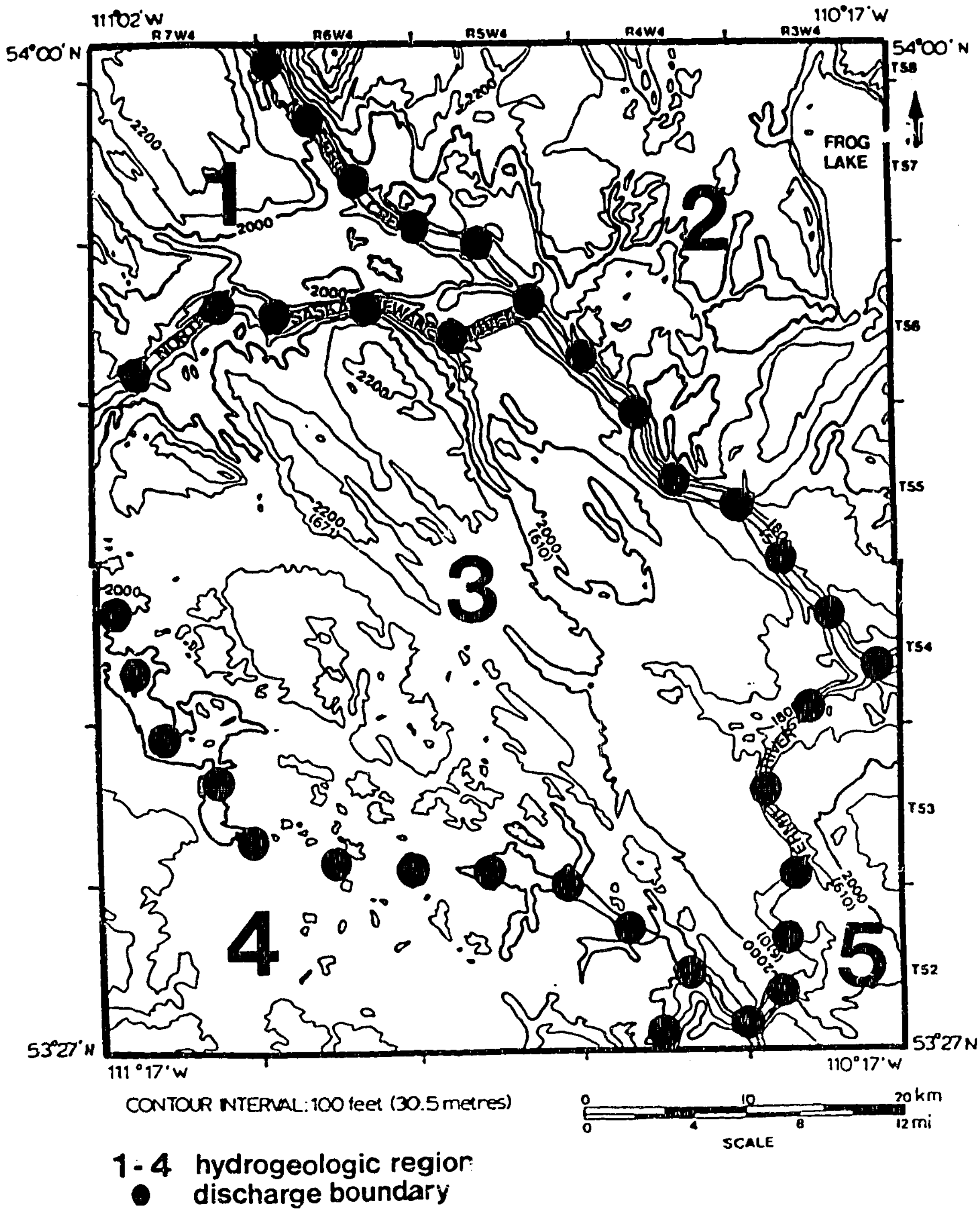
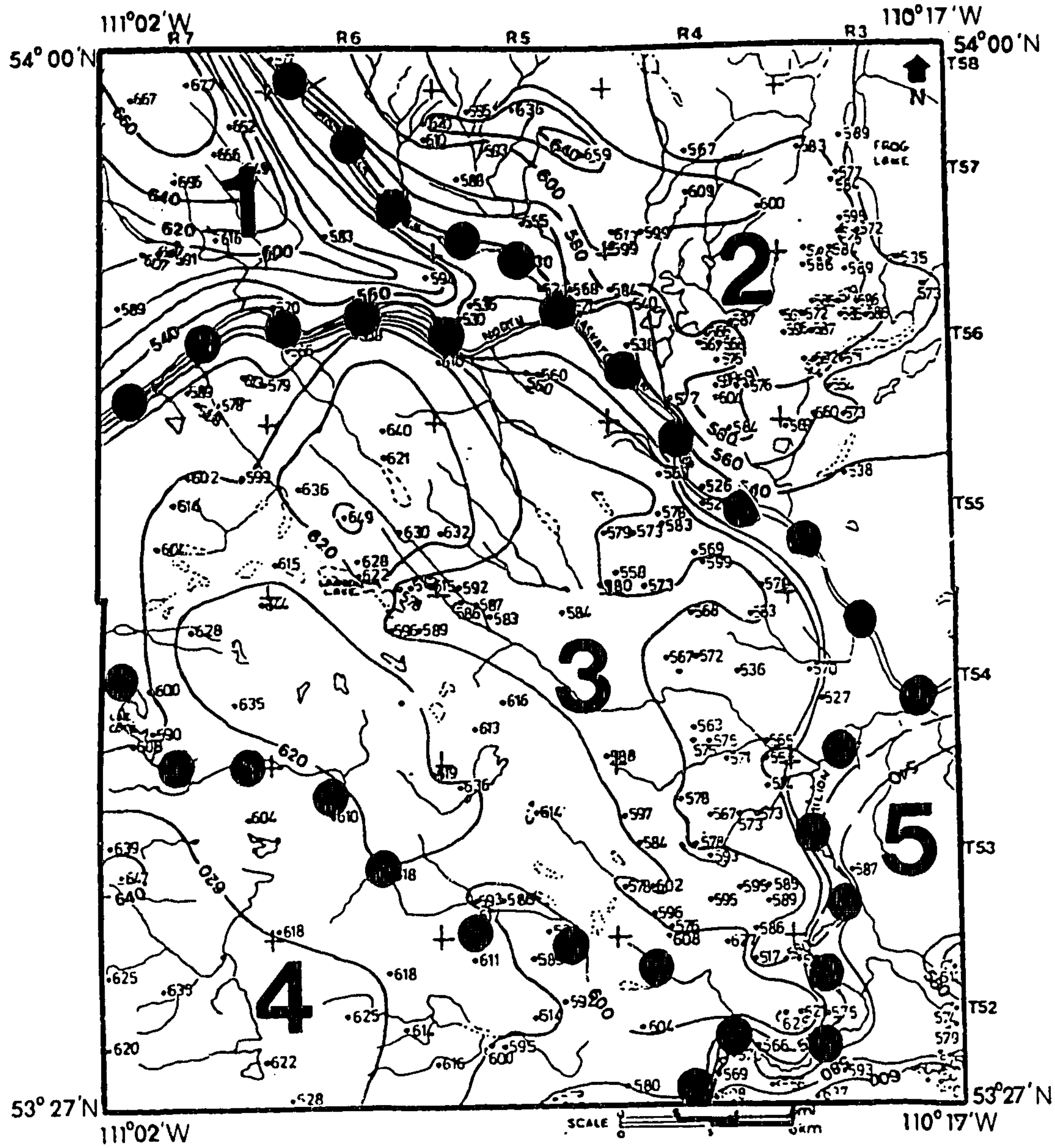


Figure 4.5 Topography in the five hydrogeological regions



contour interval : 20 metres

1-4 hydrogeologic region

● discharge boundary

Figure 4.6 Hydraulic head distribution in the five hydrogeological regions between 520 and 677 metres (Figure 4.6). The highest values are found in the Moose Hills area, whereas the lowest values are located along the North Saskatchewan River and Moosehills Creek. There is a relatively steep hydraulic gradient from the upland toward Moosehills Creek, and, to a lesser degree, toward the North Saskatchewan River. This distribution closely resembles the topographic gradient of this region. These observations, combined with the fact that there is minimal local relief, suggest that there is a predominance of regional and/or intermediate flow systems in hydrogeological region 1 and a scarcity of local flow systems. The depth of the groundwater basin determines which magnitude of groundwater system can develop.

Hydrogeological region 2 is located east of Moosehills Creek and north of the North Saskatchewan River (Figure 4.5.). It is also characterized by a large degree of regional relief (160 m) but there is more local topography than in hydrogeological province 1. A major topographic high, referred to as Moose Hills, is located in Twps. 57-58, Rge. 6. There is a steep topographic slope from this hill toward Moosehills Creek. Broad uplands are separated by minor topographic depressions, owing to the lakes and numerous streams which dissect the landscape. A comparison of Figures 4.6 and 4.5 shows that the hydraulic head distribution generally follows topographic trends. The well distribution is uneven and, therefore, the degree of confidence with respect to contouring varies from area to area. Some interpretations have been made on the basis of the topographic expression because of a lack of data in certain parts of the hydrogeological region. Hydraulic heads vary between 524 and 659 meters. The highest values are from wells located on uplands whereas the lowest values are found along Moosehills Creek and the North Saskatchewan River, as would be expected. Relatively low values are also observed along the western edge of Frog Lake and in the Whitney Lakes Provincial Park region (Twp. 58, Rge. 4). On the basis of all the observations mentioned above , the following groundwater flow conditions are proposed to exist in hydrogeological region 2. There is a main recharge area in the Moose Hills (Twp. 57, Rge. 6). Other recharge areas are associated with smaller topographic highs. In accordance with the definition of a hydrogeological region, the main discharge zones are located at the boundaries of the hydrogeological region. Relatively low hydraulic head values west of Frog Lake and south of Whitney Lake suggest that these regions may be discharge zones for intermediate or local flow systems. The overall directions of groundwater flow are from the uplands toward Moosehills Creek, the north Saskatchewan River and Frog Lake. There also appears to be some flow northward, as indicated by a decrease in hydraulic head in this direction from the central part of the hydrogeological region.

Hydrogeological region 3 is the most extensive of the five regions in the Lindbergh area (Figure 4.5). It is bordered to the north by the North Saskatchewan River, to the east by the Vermilion River, and to the south by a minor topographic low extending from Lac Côté to the Vermilion River. The topographic character of this region suggests that several groundwater flow systems are present. A number of broad uplands (e.g. Twp. 54, Rge. 6; Twp. 55, R. 5; Twp. 55, Rge. 6; Twp. 56, Rge. 6) are associated with Belly River outlyers. These plateaus commonly have 30-60 metres of relief. Another feature which should be noted is the knob and kettle topography of the southern part of Region 3 (Twp. 53, rges. 5-7). This topographic feature results from hummocky disintegration moraine (Ellwood, 1961), creating a high degree of local relief. Northward of the knob and kettle topography there is a strong northwest-southeast orientation of the physiographic features, due to glacial fluting. This feature likely affects groundwater flow locally.

Only regional trends in the hydraulic head distribution can be detected for hydrogeological region 3 from Figure 4.6. The data control is insufficient to detect local variations. From a regional perspective, there appears to be groundwater movement in all directions from to main areas of recharge. One potentiometric high is located north of Landon Lake (Twp. 55, Rge. 6) and the other northeast of Lac Côté (Twp. 54, Rges.

6-7). These areas also correspond to topographic highs, as suggested in Figure 4.5. The hydraulic head contours are widely spaced in province 3, except near the North Saskatchewan and Vermilion Rivers. This suggests that there is a small regional hydraulic gradient and, hence, that regional groundwater flow is not a very significant component of this region. All evidence points to a predominance of intermediate and local flow systems. For instance, there is little regional slope but extensive local relief. Broad, gentle uplands characterize the topographic highs rather than steep hills as in hydrogeological regions 1 and 2. Theoretical models (Tóth, 1963) have shown that areas with negligible regional slope but substantial local topography are likely to develop groundwater flow systems of smaller order.

Hydrogeological region 4 is situated in the southwest corner of the study area (Figure 4.5). This region is distinguished by relatively high elevations (610-640 m), a lack of regional relief and minimal local topography. It is bordered to the north by the minor topographic low discussed previously and to the east by the Vermilion River. This river also flows to the south of the hydrogeological region. There is little regional variation in the hydraulic head distribution (Figure 4.6). For the most part, hydraulic heads range between 600 and 640 metres, except along the boundaries of the region where they may be as low as 578 metres. From the potentiometric distribution there appears to be some lateral movement of groundwater northward and eastward from the western edges of the study area (Twp. 53, Rge. 7).

Finally, the fifth hydrogeological region is located east of the Vermilion River, in the southeast corner of the study area (Fig. 4.5). This region is characterized by a significant regional slope toward the Vermilion and North Saskatchewan Rivers, comparable to that of hydrogeological region 1. Furthermore, there is minimal local relief. There is a hill in Twp. 53, Rge. 3 which slopes northward and westward, and a hill in Twp. 52, Rge. 3, which slopes northward. The topographic expression is reflected in the hydraulic head distribution (Figure 4.6). Potentiometric highs coincide with topographic highs (Twp. 53, Rge. 3; Twp. 52, Rge. 3) and a potentiometric minimum is situated along the Vermilion River. This suggests that there is a lateral component of flow toward the Vermilion River.

4.2.2. Hydraulic head distribution along selected hydrogeological cross-sections

Having discussed the areal distribution of hydraulic heads in the Lindbergh area, it is imperative that we examine this distribution in the (x-z) directions. As stated earlier, groundwater flow systems cannot be identified solely from areal distributions of hydraulic head. It is essential that the vertical component flow be accounted for.

Four hydrogeological cross sections, labelled A-A', B-B', C-C' and D-D' (Figures 4.9 to 4.12; in pocket) were constructed for this purpose (Figure 4.7). They were compiled from water well drillers reports, Alberta Environment test holes, oil exploration E-logs and structure test holes. Each cross section contains a wide range of information, from well lithologies to water levels and estimated hydraulic heads. The depth to the water table is estimated from a survey of shallow (<16 m) open-hole, or water-table wells. It appears that the water-table is usually within 8 metres of the land surface, at an average depth of 3.5 metres.

Cross section A-A':

Hydrogeological cross section A-A' (Figure 4.8, in pocket) extends from the northwest to the southeast extremity of the study area. It traverses hydrogeological regions 1,3 and the edge of region 5. This cross section is oriented so as to closely follow the steepest topographic gradient, in order to mimic the pathways of regional groundwater flow.

The topographic surface along A-A' has a significant amount of regional relief, with

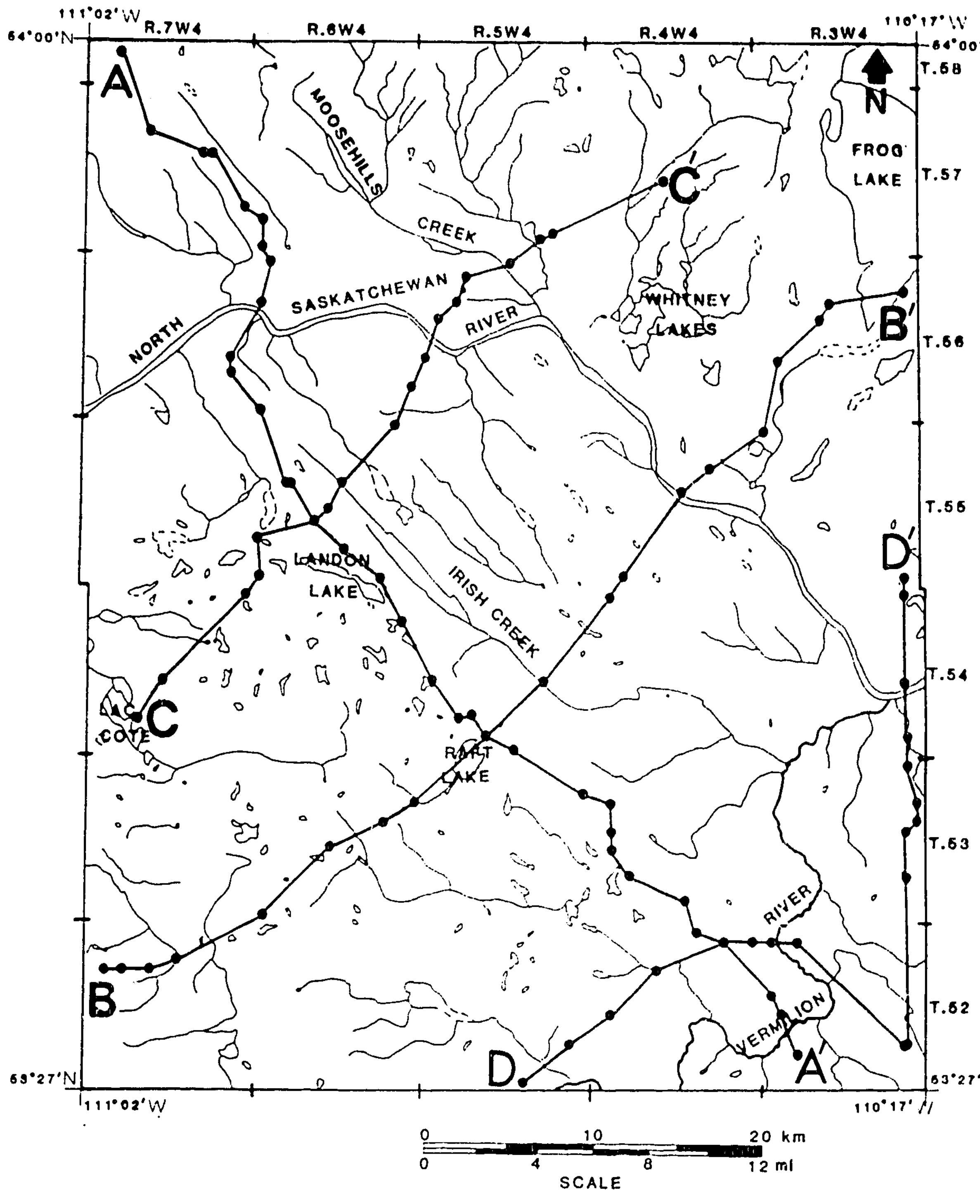


Figure 4.7 Location of the hydogeological cross-sections

elevations ranging between 575 and 675 metres. The undulating character of the land surface indicates that there is also some local topography. These characteristics suggest that there is a potential for the generation of a hierarchy of nested flow systems.

The geologic framework also plays a key role in determining flow paths of groundwater. Cross section A-A' follows the edge of the Belly River/Lea Park contact, and hence, only outlyers of Belly River sandstone are present (wells 3, 7, 16, 17, 20). The base of the deepest layer of Belly River sandstone can effectively be considered as an impermeable basement for the shallow groundwater flow systems under study. It is underlain by a great thickness of Lea Park shale (>200 m) which, in turn, is underlain by shales of the Colorado Group (Table 2.2). Where the Belly River Formation is absent, surficial deposits rest directly atop the Lea Park Formation. In this situation, using the same argument as in the previous case, the bedrock surface may be considered as an impermeable basement for groundwater flow systems. This situation is further investigated in section 4.4 which deals with mathematical modelling of groundwater flow. The surficial deposits consist of an admixture of clay till and localized pockets of sand and/or gravel, varying between 10 and 100 metres in thickness. These deposits are thickest where preglacial channels are incised in the bedrock surface (wells 18, 32).

In hydrogeological region 1 (wells 1 to 9), hydraulic heads decrease with elevation from the Moose Hills to the North Saskatchewan River. This trend supports the theory that the topography provides the ultimate control on groundwater flow, as advanced by Tóth (1963).

The Belly River Formation is present in region 1. Assuming that the base of the deepest sandstone tongue acts as an impermeable basement, this implies that the maximum depth of groundwater flow systems is 125 metres in this region. There is a general lack of local relief in this hydrogeological region, with the exception of a terrace north of the North Saskatchewan River (wells 7, 8). This characteristic of the topography, combined with the relatively steep regional slope, suggests that a regional flow system prevails in this part of the study area. A local flow system may have developed as a result of terracing.

There are several groundwater flow conditions in hydrogeological region 3. The southern side of the North Saskatchewan River Valley, between wells 10 and 13, is a near mirror image of the northern slope, with its relatively steep topographic gradient and terrace at 600 metres elevation. The expected drop in hydraulic heads toward the river is observed.

The topography is flat between wells 13 and 16. This is an elevated plateau which exists due to an underlying bedrock high. The existence of the bedrock high is attributed to the outlyer of Belly River sandstone which is more resistant to erosion than shale. On the basis of the hydraulic head values there appears to be a groundwater divide between wells 13 and 16.

Hydraulic heads decrease between wells 16 and 18, and then increase toward well 24. This drop in head values toward well 18 may appear anomalous at first glance because it does not coincide with a topographic low. This situation may be explained by the presence of a high permeability buried channel at this location. Cross section A-A' intersects this east-west trending buried channel at an oblique angle (see Figure 2.7) in Township 55, Range 6W4. Groundwater appears to move toward the channel from the north and south and is carried along the aquifer in an eastward direction. The hydraulic head distribution map (Figure 4.4) shows a decrease in hydraulic head in this direction.

Although hydraulic heads increase from wells 18 to 24, there is a drop in topographic elevation between wells 18 and 20, followed by an increase in topography, which coincides with a bedrock high caused by the presence of a Belly River remnant (wells 20, 25).

The topography and hydraulic head distribution indicate that a groundwater divide is present in the vicinity of well 24. It is situated on a topographic high and hydraulic heads decrease in both directions from this point.

Between wells 25 and 33, there is an increase in local relief and bedrock topography. There are also several sand lenses in this region, as evidenced by the well lithologies. These characteristics appear to affect the hydraulic head distribution. For instance, the head values decrease between wells 29 and 30, whereas the topography increases. Similarly, hydraulic heads increase from well 30 to 31, while the elevations decrease. This somewhat contradicting potentiometric distribution is interpreted to be due to the heterogeneity of the medium and the increased local topography. These factors are likely to generate groundwater flow systems of different orders of magnitude, as suggested by previous workers (Tóth, 1963; Freeze and Witherspoon, 1967).

A deeply entrenched buried channel is located at well 32. Hydraulic heads decrease substantially toward this buried channel, suggesting that groundwater moves toward the channel, as is the case at well 18.

There are no hydraulic head values to indicate a decrease in hydraulic head toward the Vermilion River (wells 33, 34, 35), but on the basis of the sharp topographic slope it may be assumed that there is downward movement of groundwater toward the river. This assumption is supported by the areal distribution of hydraulic heads (Figure 4.6), and field mapping which shows that the Vermilion River Valley is a narrow groundwater discharge zone (Chapter 3).

The maximum depth for any given flow system in region 1 was is 125 metres. This statement holds true for the other hydrogeological regions as well. A perusal of the geological framework along cross section A-A' suggests that most groundwater flow systems have an approximate depth of 75 metres, and are unlikely to exceed 125 metres depth.

<u>Cross section B-B'</u>:

Hydrogeological cross section B-B' (Figure 4.9 , in pocket) extends from the southwest to the northeast parts of the Lindbergh area, between Township 52, Range 7W4 and Township 56, Range 3W4. It intersects cross section A-A' in Township 54, Range 5W4 on a topographic high, and traverses hydrogeological regions 4, 3, and 2, respectively.

The land surface shows a significant degree of relief. There are several broad uplands along this cross section. Elevations range between 525 metres at the North Saskatchewan River, and 675 metres at the southwest extremity of the cross section.

B-B' approximately follows the regional dip of the strata. The Belly River Formation is present in the western part of the cross section, between wells 1 and 10. The subcropping Belly River sandstone tongues coincide with bedrock and topographic highs.

There is a correlation between the thickness of surficial deposits, the bedrock surface and the bedrock geology. Where the Belly River Formation is present, there is a relatively thin cover of surficial material (10-20 m) and the bedrock surface is more elevated. To the north, the bedrock surface drops off and the till thickness increases to 80 metres. It is important to make note of this relationship because the depth of the groundwater flow system depends on the bedrock geology and bedrock topography. On the basis of the geological interpretation along cross section B-B' the maximum groundwater basin depth is 110 metres in the southwest portion of the section, where the Belly River Formation subcrops, and 80 metres in the northeast half, where the Lea Park Formation subcrops.

The hydraulic head distribution in hydrogeological province 4 (wells 1 to 7) indicates that there is groundwater movement from the topographic high toward the boundary of the province, as hydraulic heads decrease in this direction. The lower hydraulic head in well 1 (H = 619 m) than in well 3 (H = 635 m), while it is located at a higher elevation, may be explained by the fact that it is a deeper well. In a recharge area, such as this hill, there is a strong downward component of groundwater flow, and hence hydraulic heads decrease with depth under the recharge area.

There are two major topographic highs in hydrogeological region 3. One of these uplands surrounds wells 8 and 9 and one is at the intersection of cross sections A-A' and B-B'. They are separated by Raft Lake, located in a minor topographic low. Hydraulic heads decrease southward and northward from this region, indicating groundwater movement in both directions, toward the hydrogeological region boundaries.

On the basis of the lithologies of wells 9, 10 and 12 it may appear that the Lea Park shale is part of the groundwater basin where the Belly River Formation is absent. However,these wells are open holes and, therefore, the groundwater may be from overlying units. There is a possibility that the shale is fractured, but in this study the bedrock surface is considered as an impermeable basement where the Lea Park Formation subcrops because, as mentioned previously, this Formation is of great thickness in comparison to the overlying sediments.

In hydrogeological region 2, hydraulic heads decrease from the central part (well 18) toward the North Saskatchewan River (well 14) and toward Frog Lake (well 20, 21), indicating groundwater movement in these two directions. Groundwater flow systems are confined to the surficial deposits in this portion of the cross section.

Cross section C-C':

Hydrogeological cross section C-C' (Figure 4.10, in pocket) parallels B-B' but is located to the northwest. This cross section is interesting in that it traverses 3 major groundwater discharge boundaries, namely the Lac Côté region, the North Saskatchewan River and Moosehills Creek. It intersects hydrogeological regions 3, 1, and 2, from southwest to northeast. B-B' intersects A-A in Twp. 55, Rge. 6.

The southwest portion of the cross section, as outlined in Figure 4.11, was selected for groundwater modelling. The reasons for this choice and the results of the computer modelling are dealt with in section 4.4.

The topographic surface along cross section C-C' shows a great deal of relief.

Regionally, elevations range between 575 and 675 metres. The lowest elevations are found in the broad valley formed between the North Saskatchewan River and Moosehills Creek. The highest elevation is found at well 8, but there are several other secondary topographic highs, such as in between wells 3 and 4, 10 and 11, 18 and 19.

Erosional remnants of Belly River sandstone are present southwest of the North Saskatchewan River, and absent to the northeast (wells 3, 6, 7, 8, and 10). These outlyers are associated with bedrock highs, as they are more resistant to erosion. The bedrock surface appears to follow the same trends as the topography. For example, both the land surface and the bedrock surface drop sharply near the North Saskatchewan River Valley. The relationship between the till thickness and the bedrock geology is not as obvious here as for cross section B'-B'. There appears to be thinning of the quaternary deposits on bedrock surface highs, but there is also local thickening (well 8). The latter characteristic is probably due to glacial fluting, as described by Ellwood (1961).

Based on the geological interpretation, the maximum depths for groundwater flow systems associated with subcropping Belly River or Lea Park Formations are 100 metres and 80 metres, respectively. The latter value is based on the thickness of the till in the northeast part of B-B' (Figure 4.10, in pocket) because there is a lack of geological control in the northeast portion of C-C'.

The hydraulic head distribution indicates that there is groundwater movement from topographic highs toward the three major groundwater discharge zones mentioned earlier. Consider the hydraulic conditions from southwest to northeast along C-C'. Between wells 1 and 8, the hydraulic head distribution points to an overall southwestward movement of groundwater, from the topographic high located at well 8 to the Lac Côté region (wells 1 and 2). Hydraulic heads decrease from 649 to 590 metres in this direction. There is a minor topographic low between wells 4 and 7. Hydraulic heads decrease toward the centre of this depression, suggesting groundwater flow toward this low. Based on the topography, this may be a discharge zone for a local or intermediate flow system.

From well 8 to the North Saskatchewan River the topography is first undulating and at a relatively high elevation (650-675 m) and then declines sharply near the river. There is a lack of information in between wells 8 and 11 to accurately determine the groundwater flow conditions, but considering the topography and the geology, groundwater appears to move downward below the hill (well 8) until it reaches the sandstone aquifer. It is then carried laterally northward through the aquifer. A decrease in hydraulic head with depth (wells 11, 12) shows that there is downward flow of groundwater in the flank of the river valley, toward the North Saskatchewan River.

Between wells 12 and 18 there is a large valley upon which two smaller valleys are superimposed. The latter two are the North Saskatchewan River and Moosehill Creek valleys. Cross section C-C' traverses near the conjunction of these two drainage channels and, therefore, their valleys almost join. As can be seen from the cross section, there is significant local relief in this broad valley. This characteristic favours the development of local (or intermediate) groundwater flow systems between these two streams. The hydraulic head distribution (wells 13, 14, 15, 16) supports this suggestion, as hydraulic heads decrease toward areas of lower topography.

The topography increases significantly northeast of Moosehills Creek (120 m), and then starts to decline further northeast. Hydraulic heads (wells 18, 16) decrease toward the meltwater channel, strengthening the argument that it is a regional groundwater discharge zone.

There is enough topographic relief (local and regional) along C-C' for a hierarchy of nested flow systems to exist. As mentioned earlier, part of this cross section was selected for groundwater modelling. It is on the basis of the comparison of the results of the modelling with the actual data that groundwater flow system delineation will be conducted in Chapter 6. So far, the groundwater flow conditions have been described along the various cross sections, but no attempt has been made to identify individual flow systems. It is necessary to determine the hydraulic parameters and model groundwater flow before this can be accurately done.

Cross section D-D'':

This last cross section (Figure 4.11, in pocket) is located in the southeast corner of the Lindbergh area. It trends southwest-northeast for the first part (wells 1 to 11) and then north-south (wells 11 to 19), intersecting cross section A-A' in Township 52, Range 4W4 (well 5).

Hydrogeological cross section D-D' traverses parts of hydrogeological regions 4, 3, 5 and 2. It encounters a significant degree of topographic relief, both on a local and regional scale. Two major rivers are crossed, namely the Vermilion and North Saskatchewan Rivers. The boundary between hydrogeological regions 4 and 3 is only expressed as a minor topographic low along this cross section.

The lowest elevations (500-525 m) are found at the river courses mentioned above, and the highest elevation (650 m) is located on a broad hill situated between the two rivers.

The subcropping geology consists mostly of Lea Park shale, with the exception of an erosional remnant of Belly River sandstone in Township 52, Range 4W4 (well 3). The thickness of the overlying surficial deposits generally ranges from 10 to 35 metres, but exceeds 100 metres at the location of a deeply entrenched buried channel in Township 52, Range 4W4 (Figure 2.7). At least 35 metres of sand and gravel are present at the base of this channel, making it an important aquifer in the Lindbergh area.

Using the same arguments as for the previous cross sections, the depth range for groundwater flow systems is 10-100 metres, with an average depth of 30 metres. There are two locations where the producing zone is the Lea Park shale (wells 10, 16). This again brings up the suggestion that the Lea Park Formation is part of the groundwater basin. However, as stated earlier, the Lea Park Formation may be considered as impermeable for practical pruposes due to its extreme thickness.

The hydraulic head distribution along D-D', beginning with the portion of the cross section located to the west of the Vermilion River (wells 1 to 7). Since there are only four hydraulic head measurements here, groundwater flow directions must also be inferred from the physiographic setting. The topographic surface suggests that groundwater flow is toward the west and the east, from a topographic high located at well 3. This suggestion is supported by the fact that the hydraulic heads are lower in wells 1, 5 and 7 than in well 3. On the other hand, the lower hydraulic head in well 5 (H = 517 m) than in wells 3 and 7 suggests that there is some downward movement of water toward the buried aquifer. The areal distribution of hydraulic heads in the southeast corner of the study area (Figure 4.4) suggests that the water is carried in a northwest direction along this aquifer.

The hydraulic head distribution in that part of the cross section east of the Vermilion River and south of the North Saskatchewan River (wells 8 to 16) indicates that groundwater flow is from a topographic high located in Township 53, Range 3W4, toward the rivers mentioned above. Hydraulic heads decrease from this topographic high toward the west and the north . Furthermore, the decrease in hydraulic head with depth indicates that groundwater flow is downward under the large hill. On the basis of the topography, it would appear that several orders of magnitude of groundwater flow systems are present, but that regional groundwater discharge zones are confined to the river valleys.

North of the North Saskatchewan River, southward movement of groundwater is assumed on the basis of the topography, since there is only one hydraulic head measurement.

4.3. Estimation of hydraulic conductivity values

In the Lindbergh, the four main hydrogeological units consist of till, unconsolidated sand and gravel, sandstone, and shale. Hydraulic conductivity values for sand and sandstone were estimated from bail tests and pump tests, while those of till and shale were assumed from the literature. The estimated hydraulic conductivity values were integrated into the groundwater flow model, which will be discussed in section 4.4.

Bail tests were performed at five piezometer sites in the Lindbergh area. Each site included two piezometers drilled at different depths, distanced by approximately 1.5 metres. Details of the piezometer installations are provided in Appendix 3.

The following procedure was followed at each site. First, undisturbed water levels were measured in both piezometers. Then, one of the piezometers was bailed at a constant rate using a 1 litre bailer. Bailing rates ranged between 0.8 l/min and 1.1 l/min, and the duration of the bailing varied between 15 and 60 minutes. Recovery water levels were measured immediately after bailing stopped, and for a period of 90 minutes. The response was also measured in the second piezometer during the recovery. In all cases, no change in the water level was observed in the second piezometer. Time-drawdown curves were constructed and transmissivity values calculated using the Jacob straight-line method (Cooper and Jacob, 1946), whereby:

$$T = \frac{2.3Q}{4\pi\Delta s} \qquad (4)$$

where Δs is the residual drawdown per log cycle (m), Q is the bailing rate (m^3/s) and T is the transmissivity (m^2/s). Hydraulic conductivities were subsequently determined using an estimate of the aquifer thickness:

$$K = \frac{T}{b} \qquad (5)$$

where K is the hydraulic conductivity (m/s), T is the transmissivity (m^2/s) and b is the thickness of the aquifer (m). Time-drawdown curves for each of the piezometers tested are presented in Figure 4.12. A comparison of the time-drawdown curves shows that the curve profile for piezometer 300 is markedly different than the curve for piezometers 302, 305, 306, and 308. The formenr was drilled into sandstone , while the latter were drilled in to sand. From the bail test, the hydraulic conductivity of sandstone is estimated to be approximately 1×10^{-6} m/s (Table 4.1), while hydraulic conductivity values for sand range between 6×10^{-6} m/s and 8×10^{-6} m/s.

Two pump tests were performed by Alberta Environment staff on two observation wells (2408-E, 2410-E). Both wells were completed in sandstone. Water level measurements were recorded during recovery in well 2408-E and during pumping for well 2410-E. Time-drawdown curves were constructed (Figure 4.13) for both wells and the transmissivities determined from the Jacob straight-line method (Cooper and Jacob, 1946). Hydraulic conductivities were then estimated on the basis of presumed aquifer thicknesses (Table 4.1). Both pump tests yielded similar hydraulic conductivity values for sandstone, in the range of 2.4×10^{-5} m/s (2408-E) to 3.4×10^{-5} m/s (2410-E).

Recovery tests were strictly performed on sand and sandstone units. For estimates of hydraulic conductivity values of till ansd shale, there writer referred to the literature. The most relevant study was that of Maclean (1974) in which he estimated hydraulic conductivities of various materials in the Vegreville area, approximately 100 kilometres east of the Lindbergh area. He estimated an average hydraulic conductivity value of 3.0×10^{-9} m/s for till on the basis of recovery tests and core analyses. The hydraulic conductivity of shale was estimated at 3.0 x 10-11 m/s.

Overall, the values of the hydraulic conductivities obtained from aquifer tests in this study were comparable to those of previous authors (Maclean, 1974; Stanley and Assoc.,

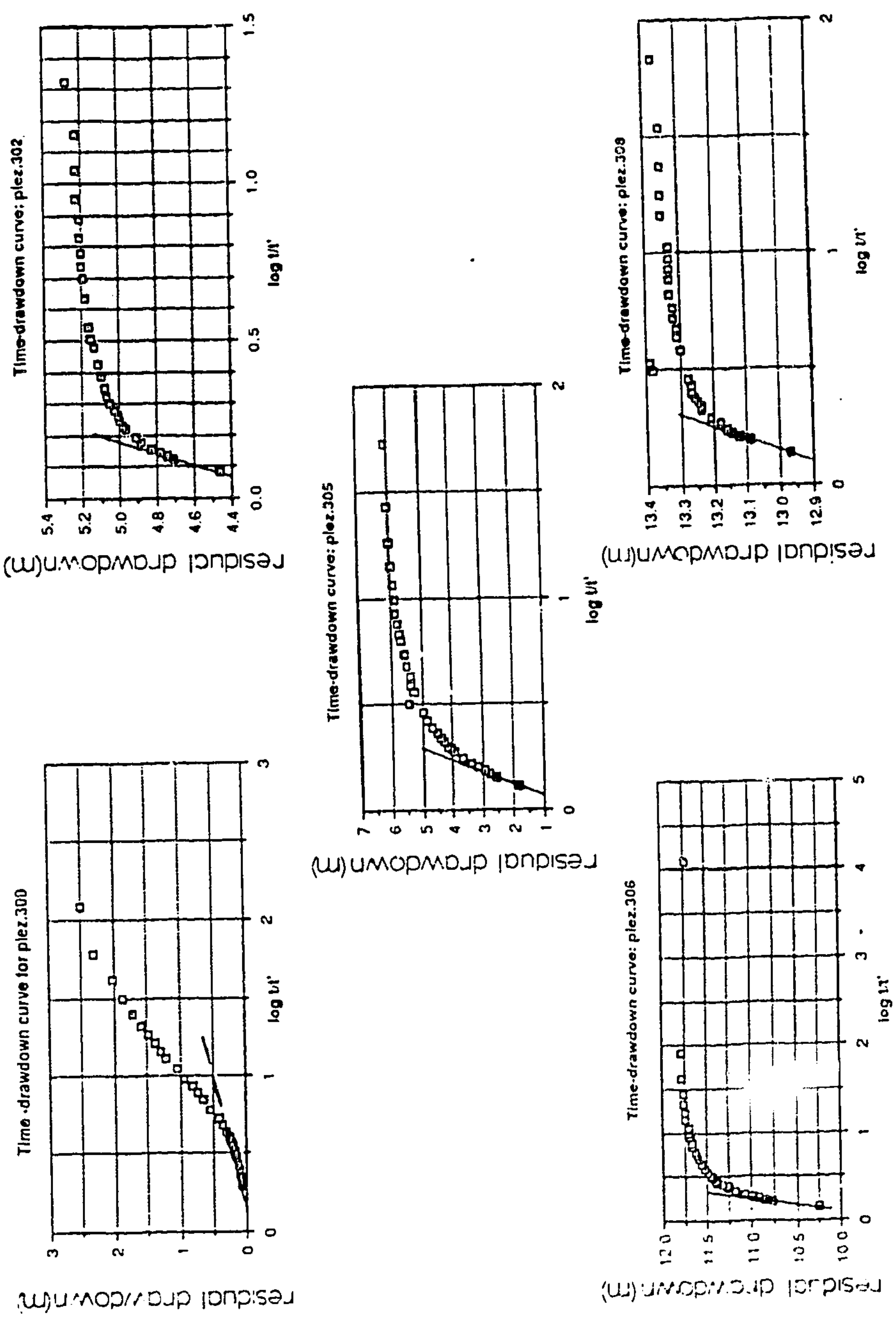
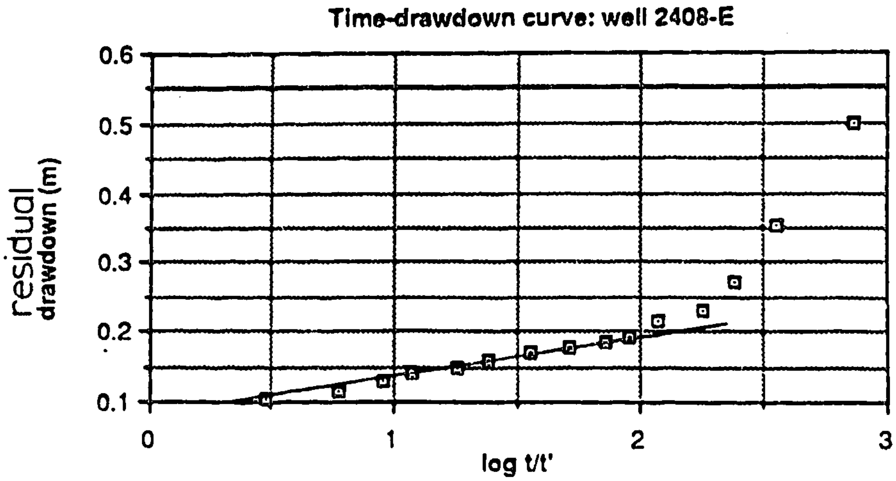


Figure 4.12. Time-drawdown curves for bailing tests

Table 4.1. Summary of the results obtained from bail tests and pump tests on piezometers and wells in the Lindbergh area

Piezometer No.	Location	Lithology	Q (m^3/s)	Δs/log cycle (m)	T (m^2/s)	b (m)	K(m/s)
300	SW-4-54-7W4	sandstone	1.67×10^{-5}	0.53	5.77×10^{-6}	0.61	9.46×10^{-6}
302	09-26-54-7W4	sand	1.33×10^{-5}	2.90	8.39×10^{-7}	1.52	5.51×10^{-7}
305	13-09-55-6W4	sand	1.83×10^{-5}	12.90	2.81×10^{-7}	0.15	1.87×10^{-6}
306	01-04-55-6W4	sand	1.56×10^{-5}	6.30	4.53×10^{-7}	?	-
308	01-04-53-4W5	sand	1.83×10^{-5}	2.25	1.18×10^{-6}	1.52	7.76×10^{-6}
2408-E	NW-07-55-6W4	sandstone	2.65×10^{-4}	0.07	1.31×10^{-4}	5.49	2.39×10^{-5}
2410-E	SW-28-53-4W4	sandstone	2.65×10^{-4}	0.47	1.03×10^{-4}	3.05	3.05×10^{-5}



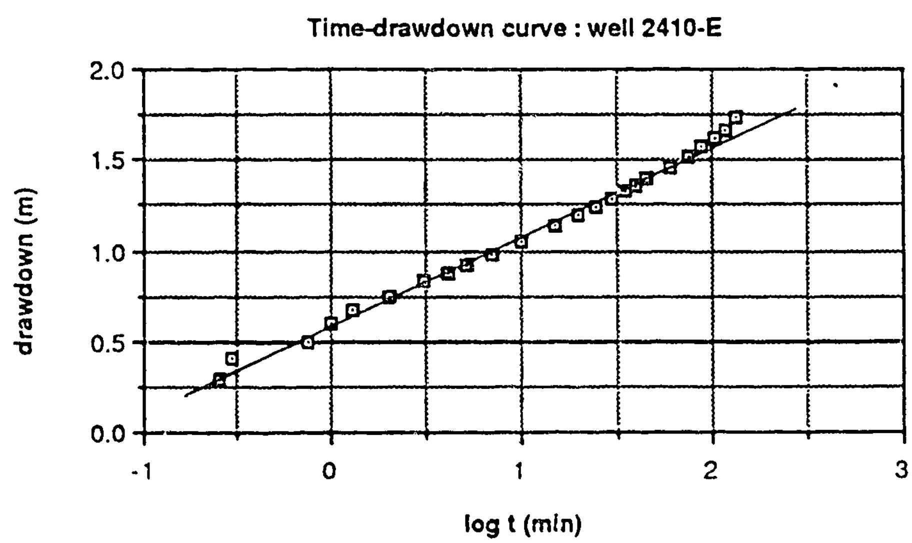


Figure 4.13. Time-drawdown curves for pump tests

1981,1985) in nearby areas. Based on the recovery tests and the literature search hydraulic conductivity values were estimated for each of the four hydrogeologic units. These values are summarized in Table 4.2.

4.4. Two-dimensional modelling of groundwater flow

4.4.1. Methodology

The primary goal of the thesis was to study the relationships between groundwater flow and its environment. Mathematical modelling of groundwater flow is an important aid in understanding these relationships.

A two-dimensional Galerkin finite element model for solving a steady state distribution was selected for this study (Frind, 1971). The main objectives of the numerical modelling were to: (1) study the effects of the topographic relief on groundwater flow; (2) study the effects of higher permeability zones on groundwater flow; (3) determine if the Lea Park Formation is an effective impermeable basement; and (4) estimate the depths of groundwater flow systems

The southwestern portion of hydrogeological cross section C-C' (Figure 4.10, in pocket) was selected for groundwater flow modelling. This part of the cross section transects field mapping regions 1 and 2, and therefore the theoretical flow pattern may be compared to field evidence of groundwater flow conditions (discussed in section 4.5).

The model selected to simulate groundwater flow conditions assumes that the region of flow is heterogeneous and isotropic. The partial differential equation which describes flow in a two-dimensional heterogeneous and isotropic medium is:

$$K\frac{\partial^2 h}{\partial x^2} + K\frac{\partial^2 h}{\partial z^2} = 0 \qquad (6)$$

Table 4.2. Estimated hydraulic conductivities for the hydrogeologic units

Hydrogeologic unit	Lithology	estimated K (m/s)
1	till	3.0×10^{-9}
2	sand	3.0×10^{-6}
3	sandstone	3.0×10^{-5}
4	shale	3.0×10^{-11}

where K is the hydraulic conductivity of the medium (m/s), h is the hydraulic head in the medium (m), x and z are the space coordinates (m).

The boundary conditions of the model are as follows (Figure 4.14a). The right vertical boundary which coincides with the crest of the highest hill along C-C' is assumed to be impermeable. Also, a bottom impermeable boundary is located at an arbitrary elevation in the Lea Park Formation below the topographic surface. The left vertical boundary is also assumed to be impermeable as it is located at the boundary between hydrogeological regions 3 and 4. Since the water level data are insufficient to describe the water table in the required detail, the water table is presumed to coincide with the land surface. The top boundary is treated by specifying a hydraulic head equal to the elevation of the land surface at each node along the boundary.

A finite element grid which approximates the topographic surface and the interpreted geologic framework as closely as possible was designed. The region was subdivided into four hydrogeologic units based on estimated hydraulic conductivities (Figure 4.14b) and then further partitioned into 152 triangular elements with 100 nodes (Figure 4.14c).

The hydraulic conductivities assigned to each of the four hydrogeologic units are listed in Table 4.1. These values were estimated from recovery tests, pump tests, and from the literature.

4.4.2 Results

The model utilized (Frind, 1971) estimated the hydraulic heads at each node in the grid given a set of boundary conditions. These hydraulic heads were contoured at a

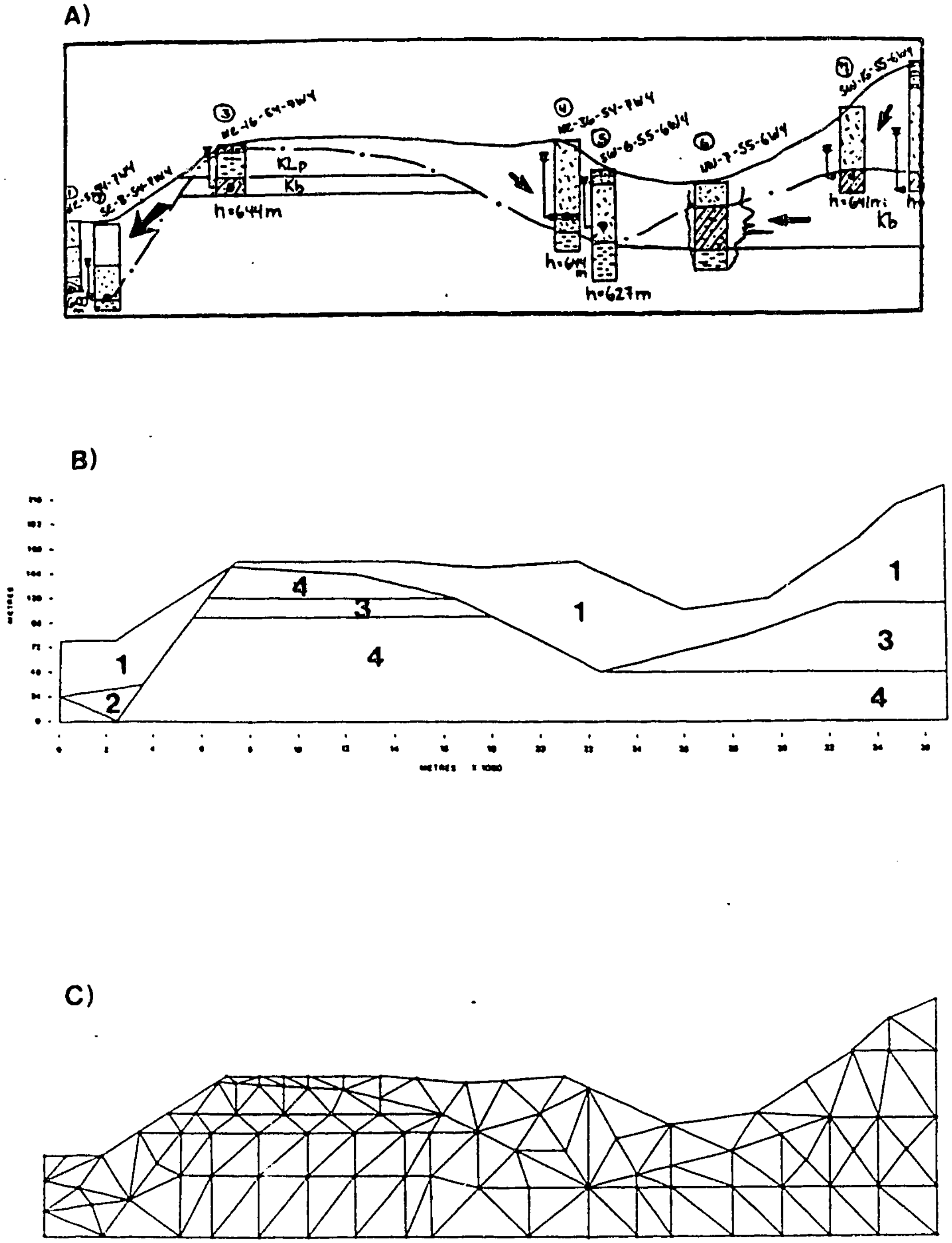


Figure 4.14. Two-dimensional groundwater modelling region and grid design

10-metre interval and flow lines were drawn in on the basis of the hydraulic head distribution. The law of orthogonality between flow lines and equipotential lines in a flow net does not apply here, as there is a vertical exaggeration of 41.7 times.

The simulated groundwater flow conditions are presented in Figure 4.15. From the simulated hydraulic head distribution it is evident that there is a relationship between the topographic surface and groundwater flow, as is expected from the theory (Tóth, 1963). The model also shows that there is little hydraulic gradient in areas of minor topographic relief. The presence of a higher permeability body (e.g. sand or sandstone) at depth modifies the potentiometric distribution within the region of flow. Whereas there appears to be a strong vertical component of flow in the overlying till, groundwater movement is lateral in the Belly River sandstone units.

On the basis of this model, the Lea Park Formation may be considered as an effective impermeable basement for shallow groundwater flow systems. There is no vertical hydraulic gradient within the Lea Park shale underlying the Belly River Formation. On the other hand, there is a vertical gradient within the shale above the thin sandstone unit in the left part of the region. The thickness of the shale unit appears to be a controlling factor in determining whether the Lea Park Formation may be presumed to be impermeable.

Finally, this model suggests that this part of the basin is dominated by intermediate and local flow systems. It appears that the depth of the groundwater basin is insufficient for regional flow system development along this section.

The writer recognizes the fact that the model is simplistic. It is two-dimensional and assumes that the medium is isotropic. Furthermore, an arbitrary elevation was used as an impermeable basement rather than a known geologic boundary. Nevertheless, this model is adequate in demonstrating the relationships between groundwater flow and its environment and provides useful results which may be compared to actual data.

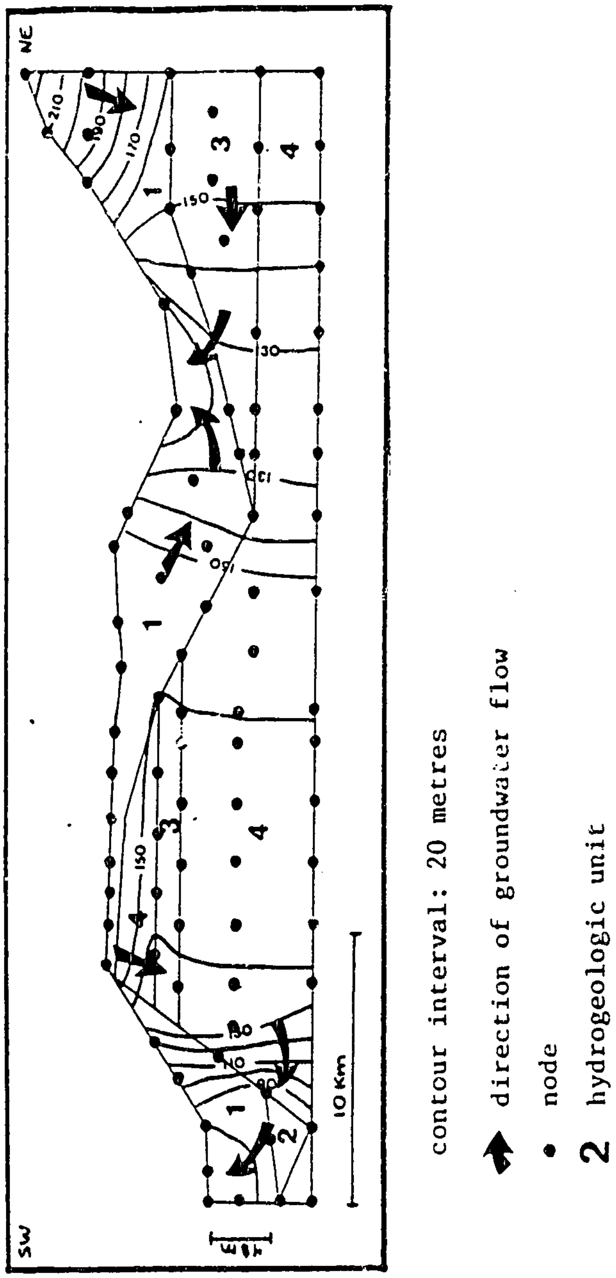


Figure 4.15. Simulated groundwater flow pattern for the modelling region

4.5. Comparison of the groundwater flow model with the field mapping results

The portion of hydrogeological cross-section C-C' which was selected for groundwater flow modelling transects field mapping areas 1 and 2, and therefore, a direct comparison of the results is possible. The following discussion refers to figure 4.16, where the two sets of results are compared.

The hydraulic regions interpreted from the field mapping of groundwater flow conditions concur with the results of the flow modelling. The recharge zone in Area 2 coincides with an area of strong downward flow on the groundwater flow model. The interpreted recharge area in Area 1 also corresponds to a zone of downward flow.

The large discharge zone identified from field mapping in Area 1 is more widespread than predicted from the flow model. There are several possible explanations for this discrepancy. For instance, some of the discharge manifestations mapped within the discharge zone may be associated with a local flow system located in the midline region of an intermediate groundwater flow system. On the hand the discrepancy may result from the limitations of the model itself, which were discussed in the previous section.

The field mapping results generally agree with the flow patterns of the simulated flow model, thus strenghthening the argument that mapping groundwater flow manifestations is useful in determining flow conditions. Groundwater flow system boundaries may be inferred from the mapping of groundwater manifestations.

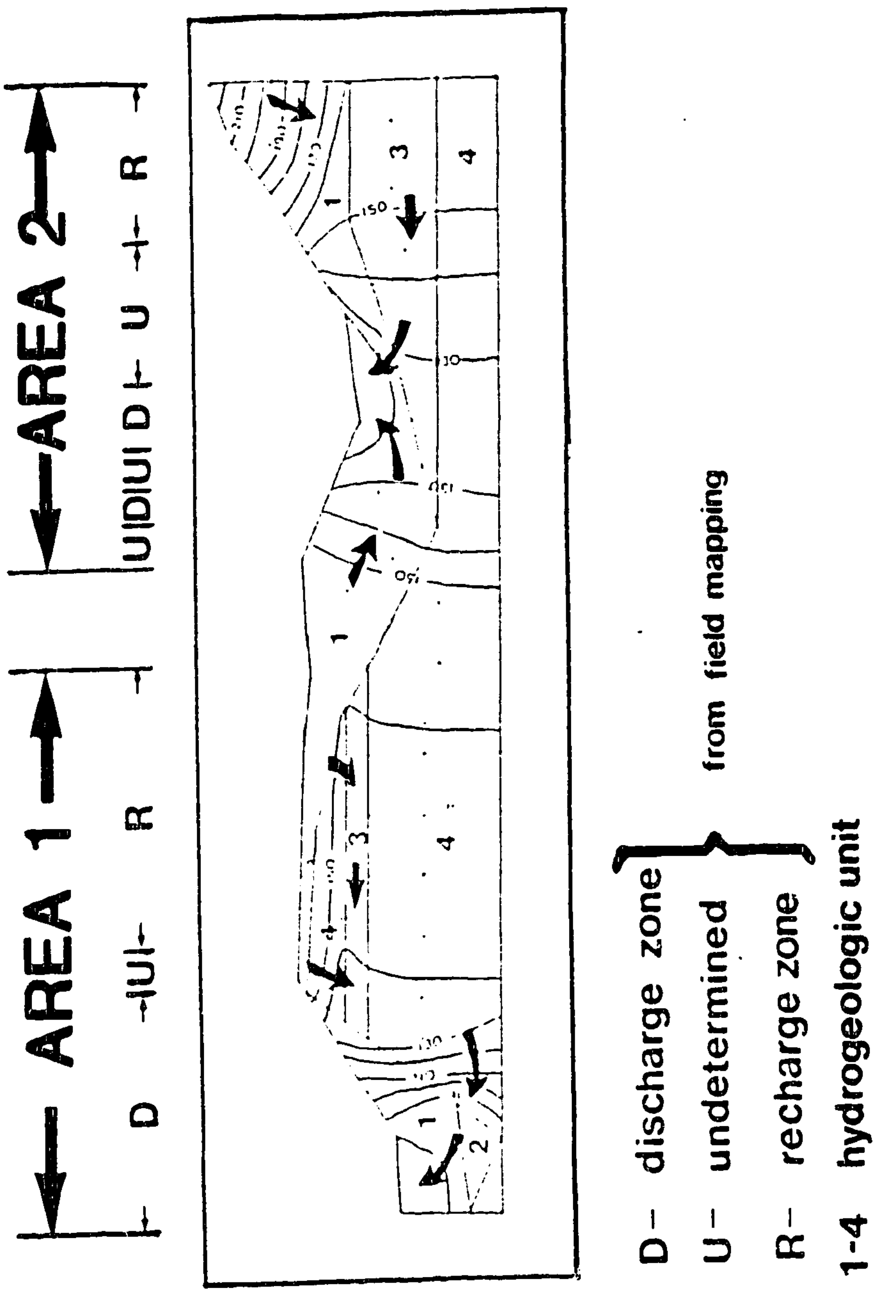


Figure 4.16. Comparison of the field mapping results and groundwater flow model

5. HYDROGEOCHEMISTRY OF THE LINDBERGH AREA.

5.1. Introduction and procedures

The chemical evolution of groundwater as it travels through the geologic environment must also be addressed in this study, as it directly impacts the groundwater quality. The chemical composition of groundwater is determined primarily by the antecedent water quality, climatic influences, the mineralogical composition of the rocks and the flow patterns in the hydrogeologic basin (Tóth, 1984). Climatic, geologic, and vertical zonations can be observed as a result of the controls imposed on the groundwater chemistry (Schoeller, 1962). Climatic zoning is attributed to the fact that the chemical concentration in water is directly proportional to the amount of precipitation. This form of zonation is a continent-wide phenomenon, and thus should not be of significant influence on a local basis. Geologic zoning occurs because groundwater composition is controlled by the mineralogy of the formation and the solubility of the minerals. Vertical zonation is attributed to the existence of groundwater flow systems. As groundwater moves along the flow path, there is an increase in the distance travelled and the residence time of the groundwater. Temperature and pressure changes with depth affect the solubility of the minerals and the thermodynamic equilibrium of the system.

This chapter is limited to a discussion of the effects of geology and groundwater flow on groundwater chemistry. Variations in water chemistry due to climatic influences are not expected in the Lindbergh area for the reasons mentioned previously.

Chemical analyses of groundwater sampled from drift and bedrock aquifers were obtained from the files of the Groundwater Information Service of Alberta Environment. These analyses (218 samples) were tested for accuracy by calculating the cation-anion balance. An additional 17 groundwater samples were collected during field mapping and submitted for routine chemical analysis. Values for the major ions (Na^{+}, Ca^{2+}, Mg^{2+}, K^{+}, HCO_3^{-}, SO_4^{2-}, Cl^{-}) for all chemical analyses, reported in mg/l, were converted to meq/l for mapping purposes and statistical analysis, and to percent meq/l for plotting on Piper trilinear diagrams (Piper, 1944). The Piper trillinear plots were generated using a computer program which reads the chemical analyses in mg/l, converts the values to meq/l, checks the analyses for cation-anion balance, and plots the analyses (Crowe, 1979).

5.2. Effects of geology on groundwater chemistry

The chemical compositon of groundwater is largely controlled by factors such as the mineralogical composition of the rocks , the solubility of the component minerals, and the contact area and contact time between rock and water (Tóth, 1984). The travel-time of groundwater along the flow path, which is directly related to the permeability of the rocks, determines the time available for chemical processes such as mineral dissolution, mineral precipitation, ion exchange, etc. to take place. Schoeller (1962) suggests that the chemical composition of groundwater partly reflects a geological zonation due to the controls mentioned above.

In order to establish a link between the groundwater chemistry and the geology, the chemical anayses were grouped into drift and bedrock groundwater samples. Over 80 percent of the chemical analyses were obtained from drift aquifers. The reader recalls from Chapter 2 that the Belly River Formation subcrops only in the western third of the study area (see Figure 2.5), and therefore most water wells were drilled in drift aquifers.

Table 5.1 summarizes the chemical analyses of groundwater in the Lindbergh area, as taken from the tables in Appendix 4. The maximum, minimum, mean and standard deviation are listed for the major ions and total dissolved solids (TDS). In addition, mean

Table 5.1 Range, mean and standard deviation of the major groundwater components of drift and bedrock groundwater samples

a) Drift groundwater samples (n=175)

	Max.	Min.	$\bar{x}$	$\bar{s}$
TDS (mg/l)	2607	240	900	526
Ca (meq/l)	23.10	0.05	5.50	4.10
Mg (meq/l)	15.80	0.10	4.10	3.20
Na (meq/l)	29.80	0.30	6.20	6.90
K (meq/l)	0.60	0.01	0.10	0.10
HCO3 (meq/l)	16.90	2.40	9.10	2.80
SO4 (meq/l)	31.00	0.20	5.50	6.10
Cl (meq/l)	5.80	0.02	0.90	1.80

b) bedrock groundwater samples (n=32)

	Max.	Min.	$\bar{x}$	$\bar{s}$
TDS (mg/l)	1854	307	915	344
Ca (meq/l)	10.60	0.05	2.70	2.40
Mg (meq/l)	5.90	0.10	1.80	1.50
Na (meq/l)	21.40	0.70	11.00	6.00
K (meq/l)	0.20	0.03	0.10	0.04
HCO3 (meq/l)	12.90	5.50	9.40	2.00
SO4 (meq/l)	19.20	0.40	5.50	3.90
Cl (meq/l)	1.80	0.03	0.60	0.70

values for the major ions were plotted on Stiff diagrams (Figure 5.1) to visually demonstrate the differences between drift and bedrock groundwater chemistry. The following discussion refers to Table 5.1 and Figure 5.1.

Based on statistical analysis, there is no significant difference between the groundwater quality of drift waters (mean TDS = 900 mg/l) and bedrock waters (mean TDS= 915 mg/l). On the other hand, there are several differences in the concentrations of the major cations in these groundwaters. Drift waters have lower Na^+, higher Ca^{2+} and higher Mg^{2+} concentrations than bedrock waters. The average Ca/Na ratio is 3.6 times greater in drift groundwater (Ca/Na = 0.25) than in waters from bedrock aquifers (Ca/Na = 0.89). The mean HCO_3^-, SO_4^{2-} and Cl^- concentrations are similar in drift and bedrock waters. The differences in cation concentrations and similarities in anion compositon are shown in the Stiff diagrams drawn for the average drift and bedrock groundwater (Figure 5.1).

As mentioned in section 5.1, the chemical analyses were plotted on Piper Trilinear diagrams (appendix 5). A sample Piper trilinear diagram is shown in Figure 5.2. Four hydrochemical facie were identified, using an arbitrary cutoff of forty percent (SO_4^{2-}+Cl^-) and (Ca^{2+}+Mg^{2+}), in meq/l, as suggested by Ophori (1986). The hydrochemical facies identified are as follows:

(1) Ca-Mg-HCO_3 facies;

(2) Ca-Mg-SO_4-HCO_3 facies;

(3) Na-SO_4-HCO_3 facies;

(4) Na-HCO_3-SO_4 facies.

The results were summarized in the form of histograms, shown in Figure 5.3. Available data

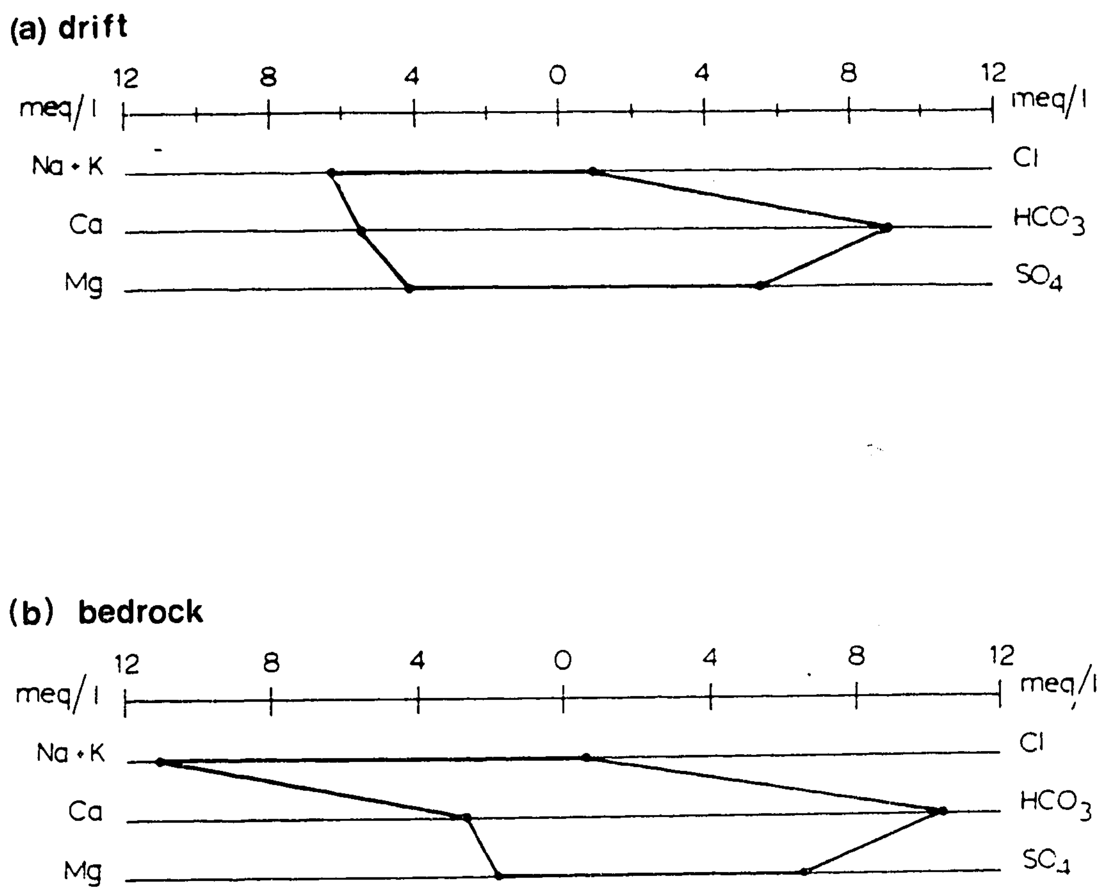
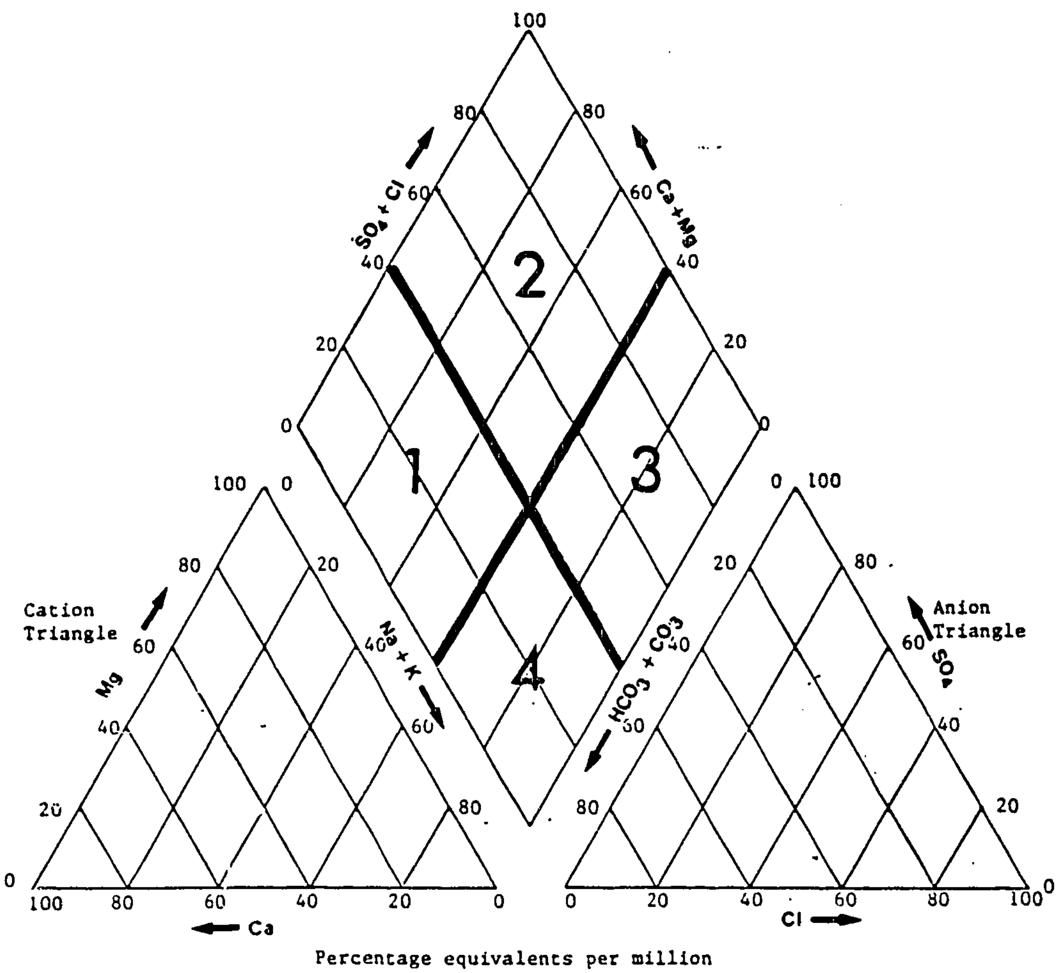


Figure 5.1 Stiff diagrams showing the mean concentrations of major ions, in meq/l, for drift and bedrock groundwater samples.



FACIES :
1 Ca-Mg-HCO_3
2 Ca-Mg-SO_4-HCO_3
3 Na-SO_4-HCO_3
4 Na HCO_3 SO_4

Figure 5.2 Piper-trilinear diagram showing the hydrochemical facies classification

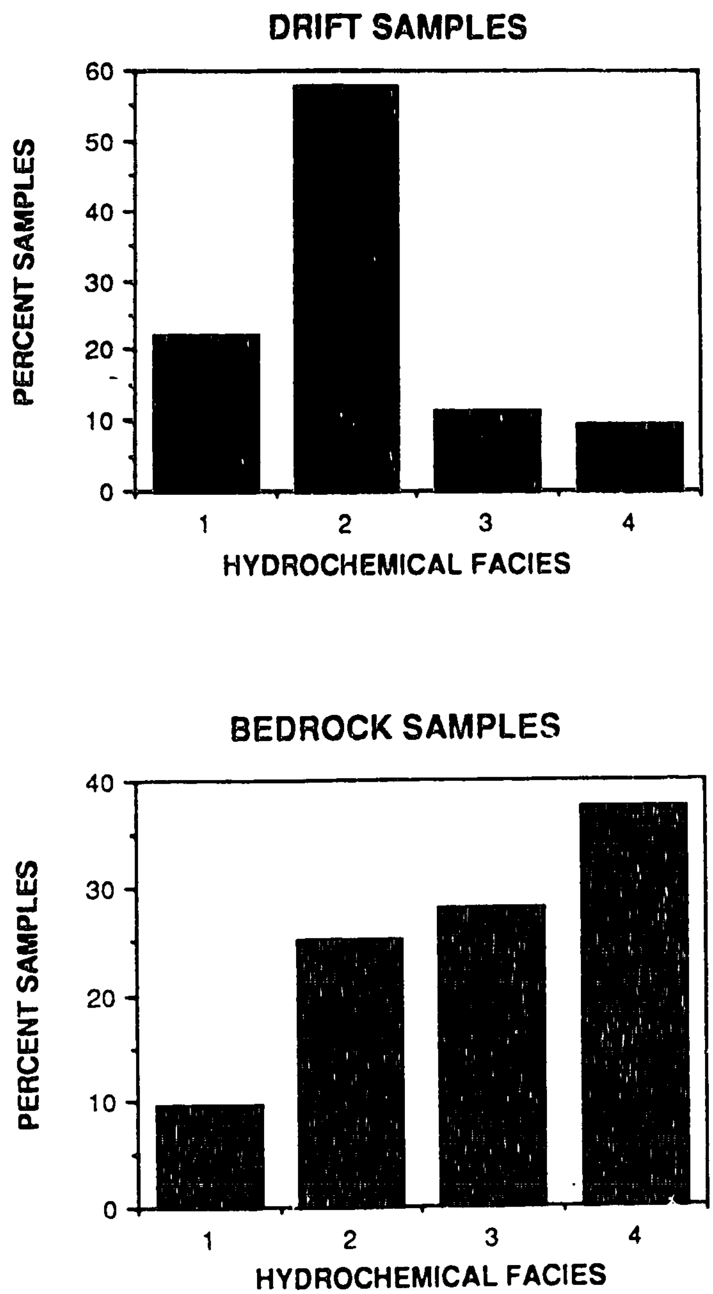


Figure 5.3 Histograms of the hydrochemical facies in drift and bedrock groundwater samples

show that drift and bedrock waters have different hydrochemical facies. Almost 60 percent of drift waters are of hydrochemical facies 2 and 22 percent are of hydrochemical facies 1. Calcium and magnesium are the dominant cations in both these facies. The predominance of hydrochemical facies 2 in drift water also suggests that SO_4^{2-} and Cl^- are important components of these waters. Nearly 70 percent of the groundwaters sampled have (SO_4^{2-} + Cl^-) concentrations exceeding 40 percent in the anion content. Hydrochemical facies 3 and 4 predominate in bedrock waters but are relatively uncommon in drift waters. These facies are characterized by a high sodium and low calcium and magnesium content. Hydrochemical facies 2 is fairly common (25 percent), indicating that calcium is the predominant cation in some bedrock waters.

It is apparent from the hydrochemical facies that the major differences in the chemical composition of drift and bedrock waters are in the cation fraction. The geologic framework does not appear to impose a major control on the anionic components of groundwater. From the interpretation of the hydrochemical facies, one concludes that drift waters typically have high calcium and magnesium concentrations and low sodium concentrations, whereas the opposite is true in bedrock waters. Mineral dissolution and cation exchange are the two main chemical processes believed to account for the differences in the chemical composition of drift and bedrock waters of the Lindbergh area. Mineral dissolution is most active in the drift, where significant quantities of Ca^{2+}, Mg^{2+}, HCO_3^-, SO_4^{2-} and Cl^- accumulate as the result of the weathering of carbonates, silicates and clay minerals as well as the dissolution of soluble salts. Typically, the mineralogical composition of till includes the following minerals (Grisak et al, 1976): (1) silicates, such as quartz, plagioclase, and micas; (2) carbonates, such as calcite and dolomite; (3) clay-minerals, with

Ca-montmorillonite as the dominant clay-mineral; and (4) sulfate and chloride minerals including gypsum, anhydrite, halite and mirabilite. Based on saturation indices, Ozoray et al (1980) found that calcite and clay-minerals, particularly Ca-montmorillonite, were the controlling solid phases in the evolution of groundwater chemistry in shallow aquifers of the Sand River area, which is located immediately north of the study area. The dissolution of these minerals through weathering of the till is believed to be responsible for the high Ca^{2+} concentrations in the drift waters of the Lindbergh area.

Once groundwater enters the Belly River Formation, cation exchange is believed to be the predominant chemical process controlling the groundwater composition.This process depends on the fixation force of the cations. Ca^{2+} has a greater fixation force than Mg^{2+}, which has a greater fixation force than Na^{+}. This means that Ca^{2+} is more easily adsorbed than Mg^{2+} and Na^{+} respectively, and conversely, that Na^{+}can enter into an aqueous solution more easily than Ca^{2+} or Mg^{2+}. Cation exchange may be expressed by the following general reaction (Schwartz and Muehlenbachs, 1979):

$$Ca_{aq}^{2+} + Mg_{aq}^{2+} + \text{Na-clay} = Na_{aq}^{+} + \text{CaMg-clay}$$

This process may explain why bedrock waters are generally low in Ca^{2+} and Mg^{2+} concentrations and enriched in Na^{+} ions.

5.3. Effects of groundwater flow on groundwater chemistry

Groundwater movement is one of the controlling factors on the chemical evolution of groundwater. As groundwater travels along its the flow paths, several chemical processes modify its chemical composition. The most important chemical processes affecting the chemical composition of groundwater in shallow aquifers are mineral dissolution, mineral precipitation, cation exchange,and possibly, sulfate reduction.

Several studies have attempted to demonstrate a relationship between groundwater flow and the chemical composition of groundwater. Chebotarev (1955) observed that as groundwater travels along its flow paths, it tends to evolve from a bicarbonate type water, to a sulfate type, and finally to a chloride type. Back (1960) developed the concept of hydrochemical facies and suggested that groundwater flow patterns determine the vertical and lateral distribution of these facies. Schoeller (1962) observed a vertical zonation in the chemical composition of groundwater and attributed this to groundwater flow. Tóth (1984) suggested that groundwater quality could be related to the hydraulic regime as well as the type of groundwater flow systems.

As a general rule, the following chemical changes are expected in the direction of ground water flow (Tóth, 1984):

(1) increase in TDS;

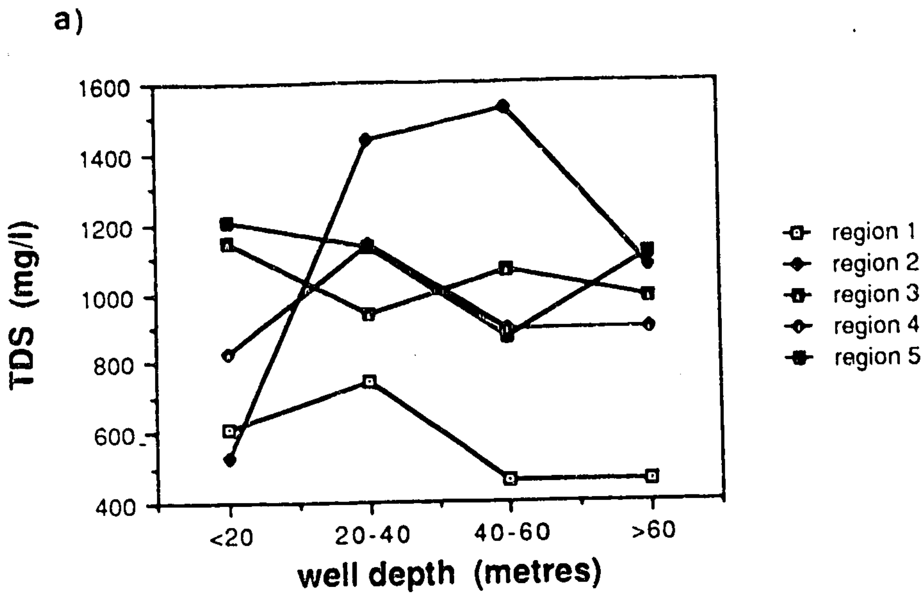
(2) decrease in the Ca/Na ratio;

(3) decrease in the Ca/Mg ratio;

(4) decrease in the SO_4/Cl ratio;

(5) increase in the SO_4/HCO_3 ratio.

Mineral dissolution is the primary process responsible for the increase in TDS in the direction of groundwater flow. In general , lower TDS values are found in recharge areas and higher TDS values are found in discharge areas (Tóth, 1984). Theoretically, one should expect decreasing TDS values with increasing elevation and higher TDS values with increasing well depth. For the purpose of this discussion, the TDS values were averaged for different elevation and depth ranges in each of the five hydrogeological regions (Figure 5.4 (a) and (b)). There is an overall decrease in TDS from the lowest elevations (<575 metres) to the highest elevations (>625 metres) but there is a slight increase in TDS from the lowest



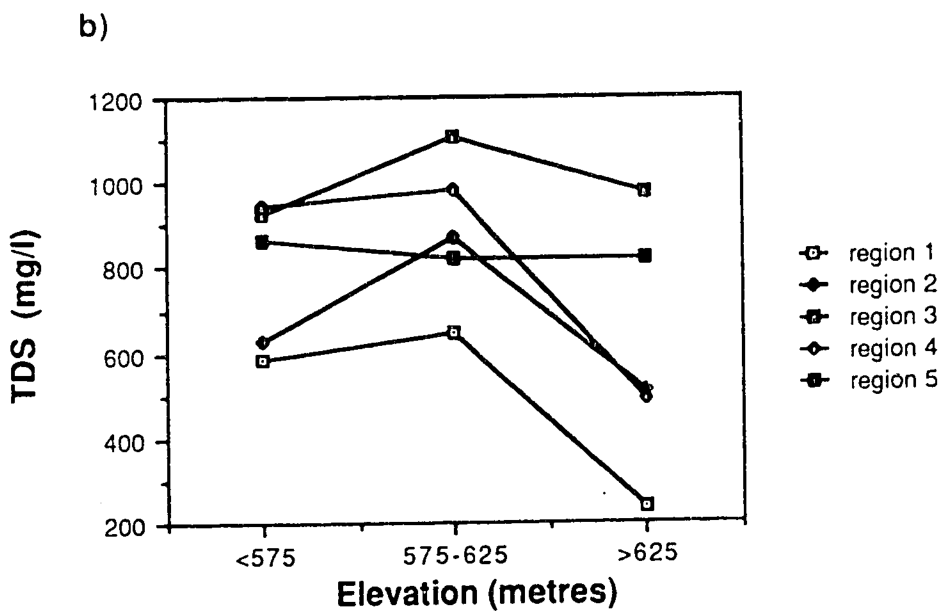
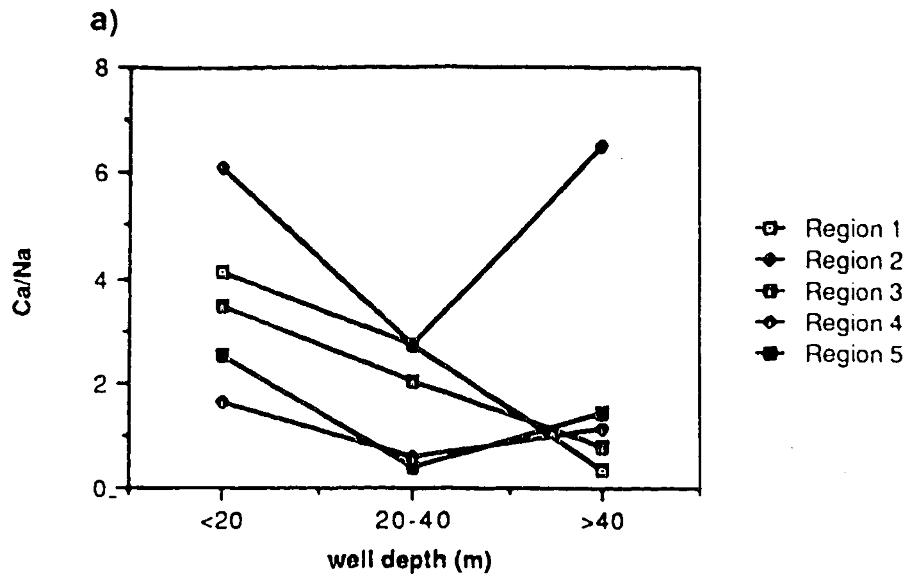


Figure 5.4. Plots of TDS versus (a) well depth and (b) elevation, for each hydrogeological region

elevations to the 575-625 metres elevation range. This increase may be due to the coexistence of different orders of flow systems as a result of the variations in the topographic relief. Groundwater samples were most likely obtained from hydraulic regions of different groundwater flow systems, as well as from different lithologic units. The plot of TDS content versus well depth (Figure 5.4 (b)) suggests that there is no correlation between the TDS content and well depth in the Lindbergh area. Three factors are believed to be responsible for this. First, the majority of the wells are less than 40 metres in depth and therefore, the sample size of deeper wells may be insufficient to a show a meaningful trend. Second, samples were taken from all hydraulic regions. Although the TDS content tends to increase with depth, a groundwater sample taken from a recharge area will generally be lower in TDS than a groundwater sample taken from the same depth in a discharge area, because the groundwater has travelled a greater distance in the latter case. Finally, some of the inconsistencies may be explained by the heterogeneous nature of the geologic framework, which, as was shown in section 5.1, strongly influences the chemical composition of the groundwater.

Decreases in Ca/Na and Ca/Mg concentrations ratios in the direction of groundwater flow (Tóth, 1984) result primarily from the process of cation exchange, whereby Ca^{2+} in the groundwater replaces the Na^{+} and Mg^{2+} in the rocks as groundwater travels along its flow paths. In general, one should observe a decrease in the Ca/Na ratios with increasing well depth and an increase with increasing elevation. There appears to be an overall decrease in the Ca/Na ratio with increasing well depth (Figure 5.5 a) but this trend is not apparent for the Ca/Mg ratio (Figure 5.6 a). As well, plots of Ca/Na and Ca/Mg versus elevation (Figures 5.5 b ands 5.6b) do not show an increase in these ratios with increasing elevation. As in the case of the TDS content , the absence of significant trends is probably due to the sampling of



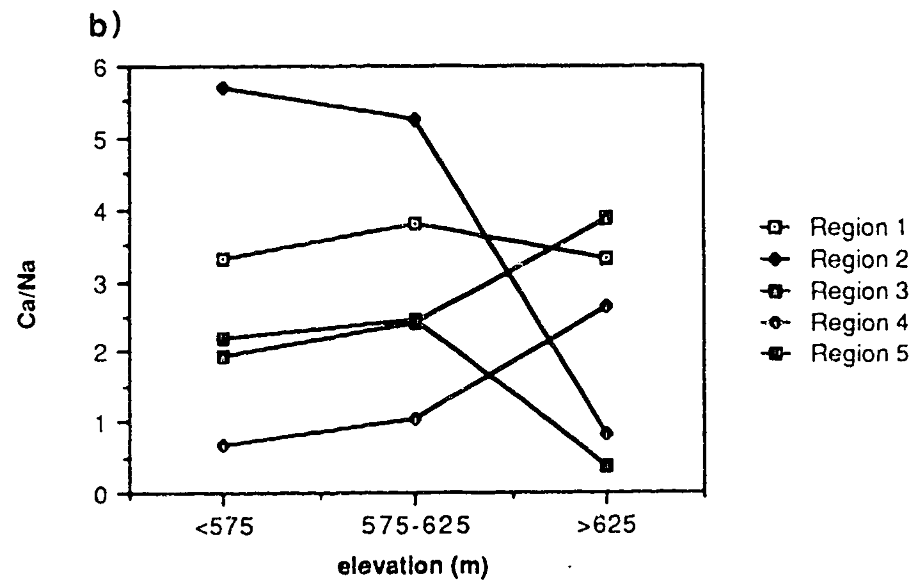
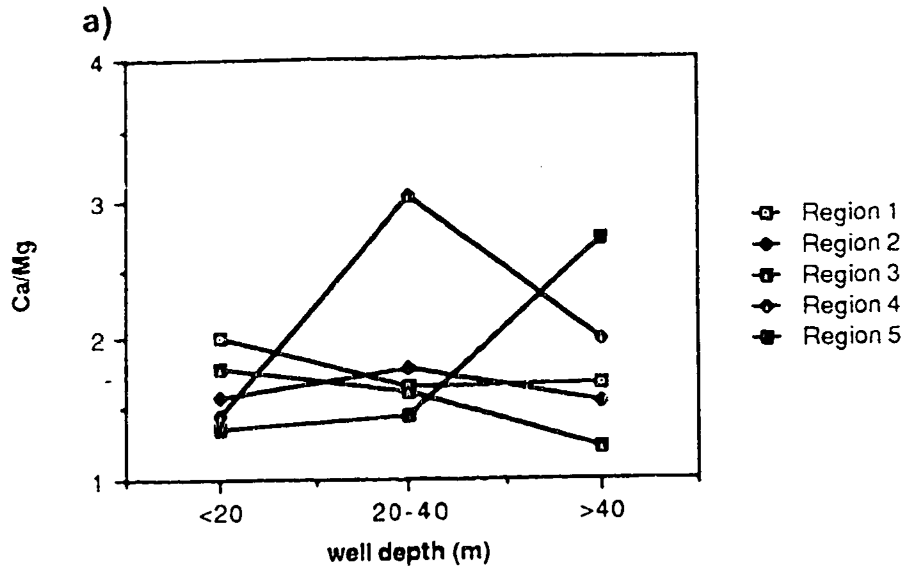


Figure 5.5 Plots of Ca/Na versus (a) well depth and (b) elevation, for each hydrogeological region



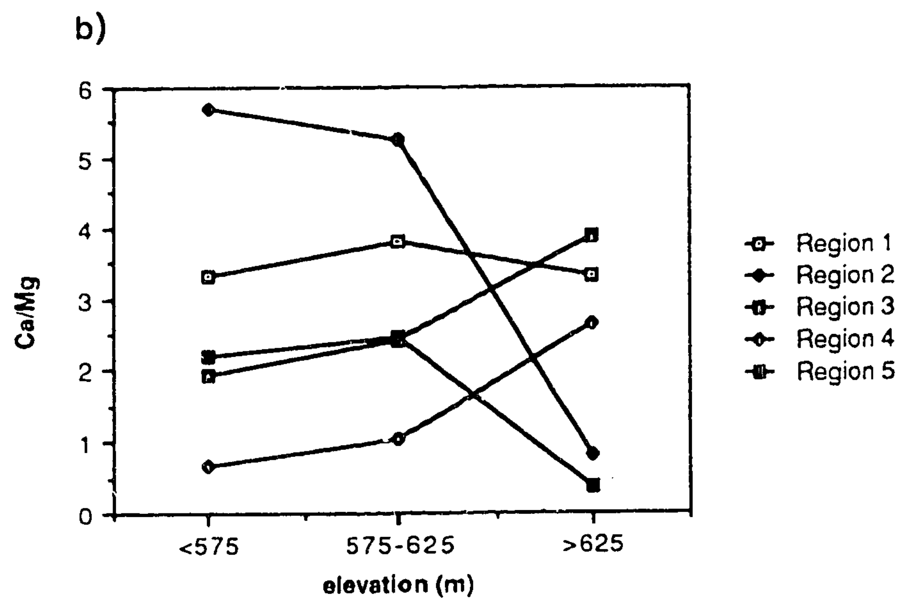


Figure 5.6 Plots of Ca/Mg versus (a) well depth and (b) elevation, for each hydrogeological region

groundwaters from different groundwater flow systems, to the small number of samples from deeper wells, and from the heterogeneous nature of the hydrogeological basin.

The SO_4/Cl ratio decreases in the direction of groundwater flow because of the higher solubility of Cl^- and the possible depletion of SO_4^{2-} due to sulfate reduction. The SO_4/HCO_3 ratio increase due to CO_2 depletion along the flow path. These trends are not apparent on the plots of SO_4/Cl and SO_4/HCO_3 versus well depth and elevation (Figure 5.7 a, b and Figure 5.8 a, b). Again, groundwater sampling from different groundwater flow systems, the sampling distribution and the heterogeneous nature of the rock framework may explain the apparent lack of correlation.

5.4. Summary

The interpretation of the groundwater chemical analyses demonstrated that there is strong correlation between groundwater composition and geology in the Lindbergh area. Typically, drift waters have high Ca^{2+}, Mg^{2+}, SO_4^{2-}, and Cl^- concentrations, whereas bedrock waters are low in Ca^{2+} and Mg^{2+} ions and enriched in Na^+ ions. Mineral dissolution is the main chemical process which can explain the high Ca^{2+}, Mg^{2+}, SO_4^{2-}, and Cl^- concentrations in the drift. These ions accumulate as a result of the weathering of carbonates, silicates and clay-minerals in the till. Cation exchange is the most significant chemical process affecting the chemical composition of groundwater in the Belly River Formation. As groundwater enters the bedrock, the Ca^{2+} and Mg^{2+} ions found in the drift waters are adsorbed to the clay-minerals and the Na^+ ions in the clay-minerals are released into the groundwater.

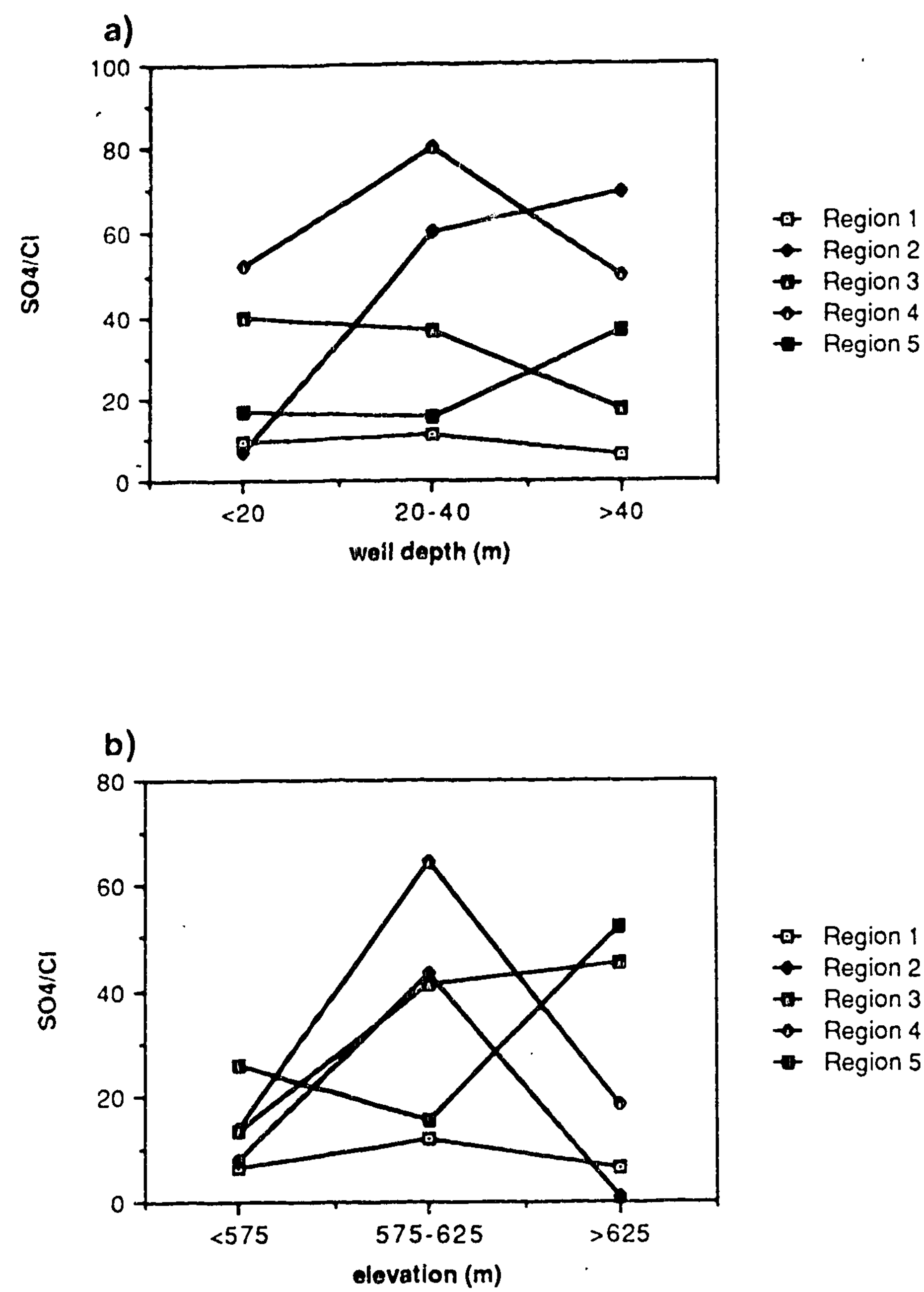
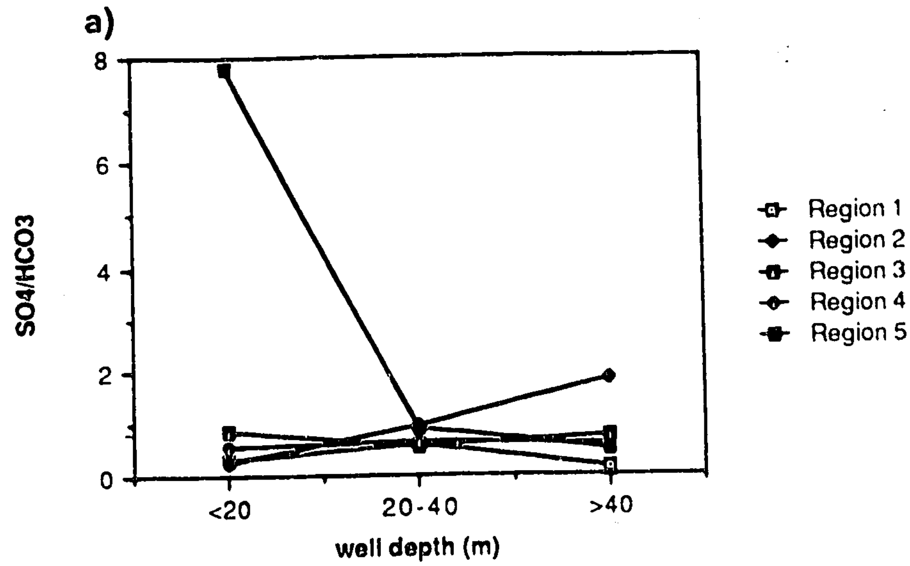


Figure 5.7. Plots of SO_4/Cl versus (a) well depth and (b) elevation ,for each hydrogeological region



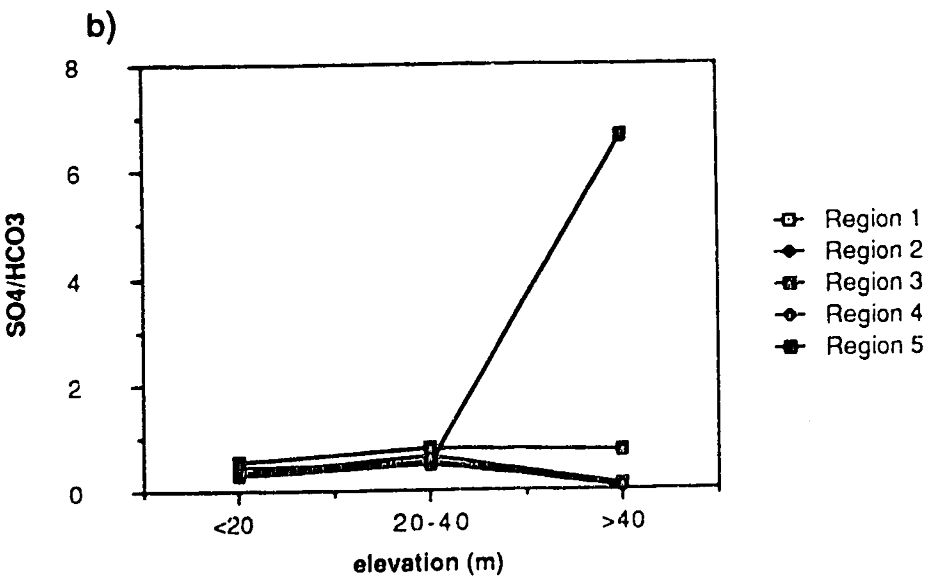


Figure 5.8. Plots of SO_4/HCO_3 versus (a) well depth and (b) elevation ,for each hydrogeological region

This study could not demonstrate a strong relationship between groundwater chemistry and groundwater flow. The TDS content and the Ca/Na, Ca/Mg, SO_4/Cl, and SO_4/HCO_3 ratios were plotted against well depth and elevation in an attempt to show a correlation between groundwater composition and groundwater flow. Three reasons may explain the inconclusive results. First, most of the wells are less than 40 meters in depth, and therefore the sample distribution may not be representative. Second, two groundwater samples taken at the same depth or elevation may have different origins. A groundwater sample obtained from a discharge area will likely have a different chemical composition than a groundwater sample obtained from a recharge area at the same well depth or elevation. Finally, and most importantly, the hydrogeologic basin is heterogeneous and therefore, the effects of the geology must also be taken into account.

In conclusion, in this specific case the effects of the geology on groundwater quality are more clear cut than the effects of groundwater flow. Nevertheless, groundwater chemistry can be used in a qualitative manner to characterize groundwater flow systems.

6. SYNTHESIS AND CONCLUSIONS

6.1. Distribution of groundwater flow systems in the Lindbergh area

Based on the results of this study, a map of groundwater flow systems in the Lindbergh was been produced (Figure 6.1). The flow systems are labelled with a number and a letter. The number refers to the hydrogeological region in which it is located, and the letter distinguishes between flow systems within a particular hydrogeological region. The boundaries of the groundwater flow systems are approximate. Groundwater discharge zones are more accurately defined because they are confined to topographic lows and are often associated with groundwater discharge features. On the other hand, recharge zones are largely inferred from the hydraulic head distribution and the topography. Local flow systems are not represented on this map due to the scale of the study.

Two flow systems are identified in hydrogeological region 1 (Figure 6.1). These flow systems are separated by an intermediate groundwater discharge zone located along a tributary creek of the North Saskatchewan River. This creek is characterized by lower topography, low hydraulic head values and the presence of a spring. Flow system 1a is of regional order. It is recharged in the Moosehills region (Twp 57, Rge 7W4) and discharges along the valleys of Moosehills Creek, the North Saskatchewan River and the intermediate discharge zone. From hydrogeological cross-section A-A' (Figure 4.9, in pocket) it appears that this flow system may have a depth of approximately 125 metres. Flow system 1b is of intermediate order. It recharges on a secondary topographic high located in between the regional topographic highs and lows. Local flow systems do not prevail in hydrogeological region 1 because there is a lack of local relief.

Three groundwater flow systems are inferred in hydrogeological region 2. One is

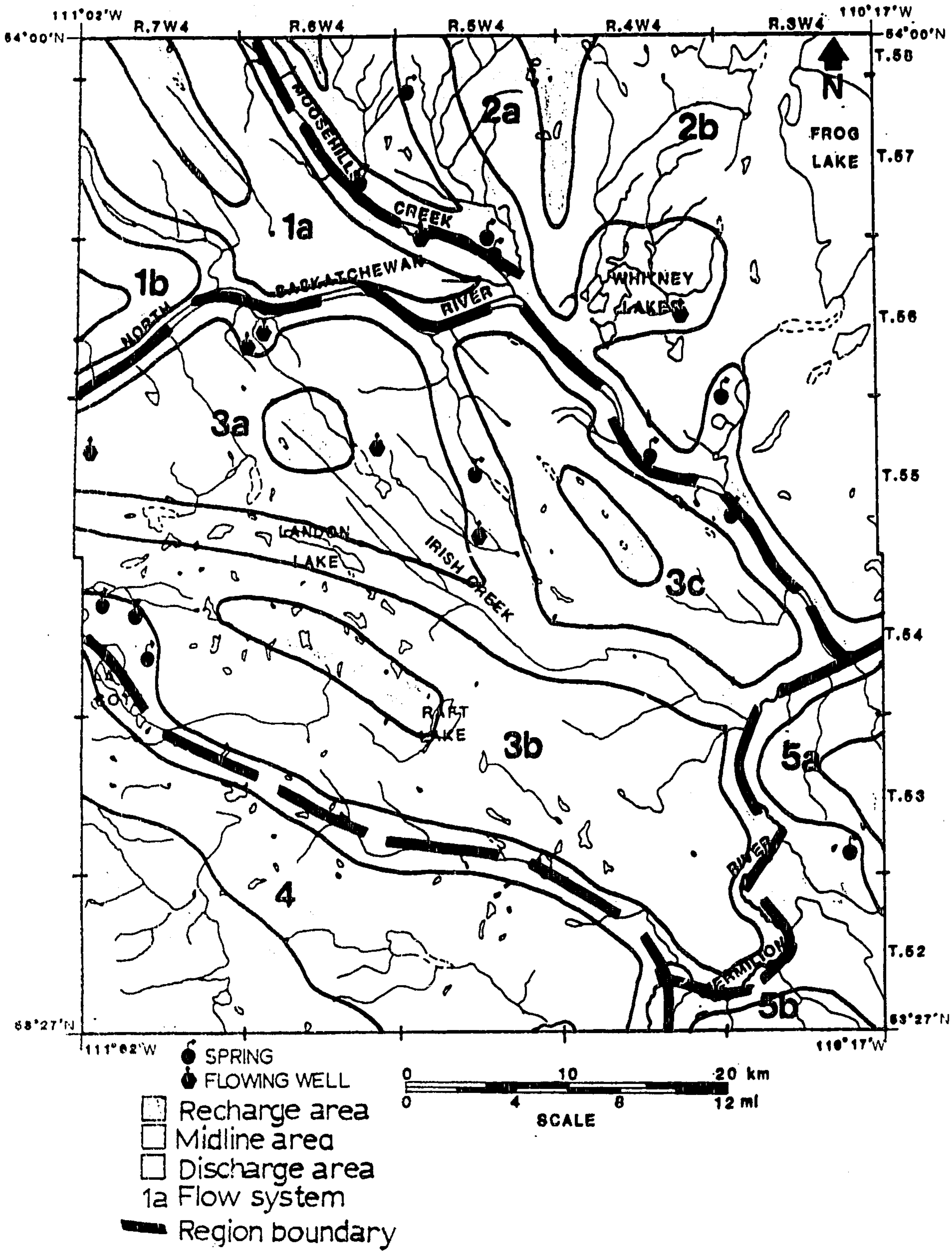


Figure 6.1 Distribution of intermediate and regional groundwater flow systems in the Lindbergh area.

considered as a regional flow system (2a) while the remaining two (2b, 2c) are classified as intermediate flow systems. Flow system 2a is recharged in the Moose Hills (Twp. 58, Rge 6W4) and discharges along Moosehills Creek and an intermediate discharge zone. Local relief is not prominent in this region, and hence, nor are local flow systems. Intermediate flow systems 2b and 2c are characterized by local relief due to the incision of the landscape by several streams, and are characterized by nested local flow systems. The discharge boundary separating flow systems 2a and 2b is postulated on the basis of the topography. The boundary separating flow systems 2b and 2c is inferred from evidence such as low hydraulic head values, high total dissolved solids in the groundwater, and the presence of springs and flowing wells (see Figure 2.4).

Hydrogeological region 3 comprises three main groundwater flow systems (3a, 3b, 3c) within which local flow systems are superimposed. Based on the results of the flow modelling and the interpretation of the geology along hydogeological cross-sections A-A', B-B', and C-C' (Figures 4.9 to 4.11, in pocket), these three flow systems are presumed to be of regional order. Due to the presence of hummocky moraine, local flow systems are common in groundwater flow systems 3a and 3b. Flow system 3a is characterized by a gently sloping topography, and thus by flow systems of higher order. The regional recharge areas for the three flow systems are situated at the highest topographic elevations in each of the flow systems. These zones are delineated on the basis of the topography and the hydraulic head distribution. Closed potentiometric maxima characterize these regions.

Hydrogeological region 4 is part of a regional flow system which discharges along the boundary between regions 3 and 4, and along the Vermilion River valley, which extends to the south of the study area. A broad recharge zone is inferred in the southwest corner of the study area.

Two regional flow systems are interpreted in hydrogeological region 5. The main direction of flow for both flow systems is toward the Vermilion River, but they are separated by an intermediate discharge boundary. This zone is characterized by lower topography, lower hydraulic head values, hydrochemical types 3 and 4 groundwater, and higher TDS values. Local flow systems are uncommon in this area, due to a lack of local topography.

In summary, ten groundwater flow systems of intermediate or regional magnitude are identified in the Lindbergh area. Their delineation and characterization are based on interpretations of the physiography, geology, and hydraulic head distribution. The groundwater chemistry was also taken into account, but not as a prime criteria in identifying individual groundwater flow systems. As discussed in Chapter 5, there are several other factors which mask the effects of groundwater flow on the water chemistry.

6.2 Applications of groundwater-flow systems mapping

Groundwater flow-systems mapping can be used in a wide range of applications which require an understanding of the global hydogeological system. The following examples are but few of the potential applications where this mapping technique can be applied.

In the field of agriculture, groundwater flow-systems mapping may be helpful in areas of crop selection, land reclamation and soil classification. Areas prone to soil salinization, salt precipitation, gullying may be predicted from the study of groundwater flow. An example of a potential use for groundwater flow-systems mapping is illustrated in Figure 6.2. This thematic map, developed from the groundwater flow-systems map, indicates areas which are prone to soil salinization and salt precipitation. These areas correspond to discharge zones, as a direct link between groundwater flow and salt

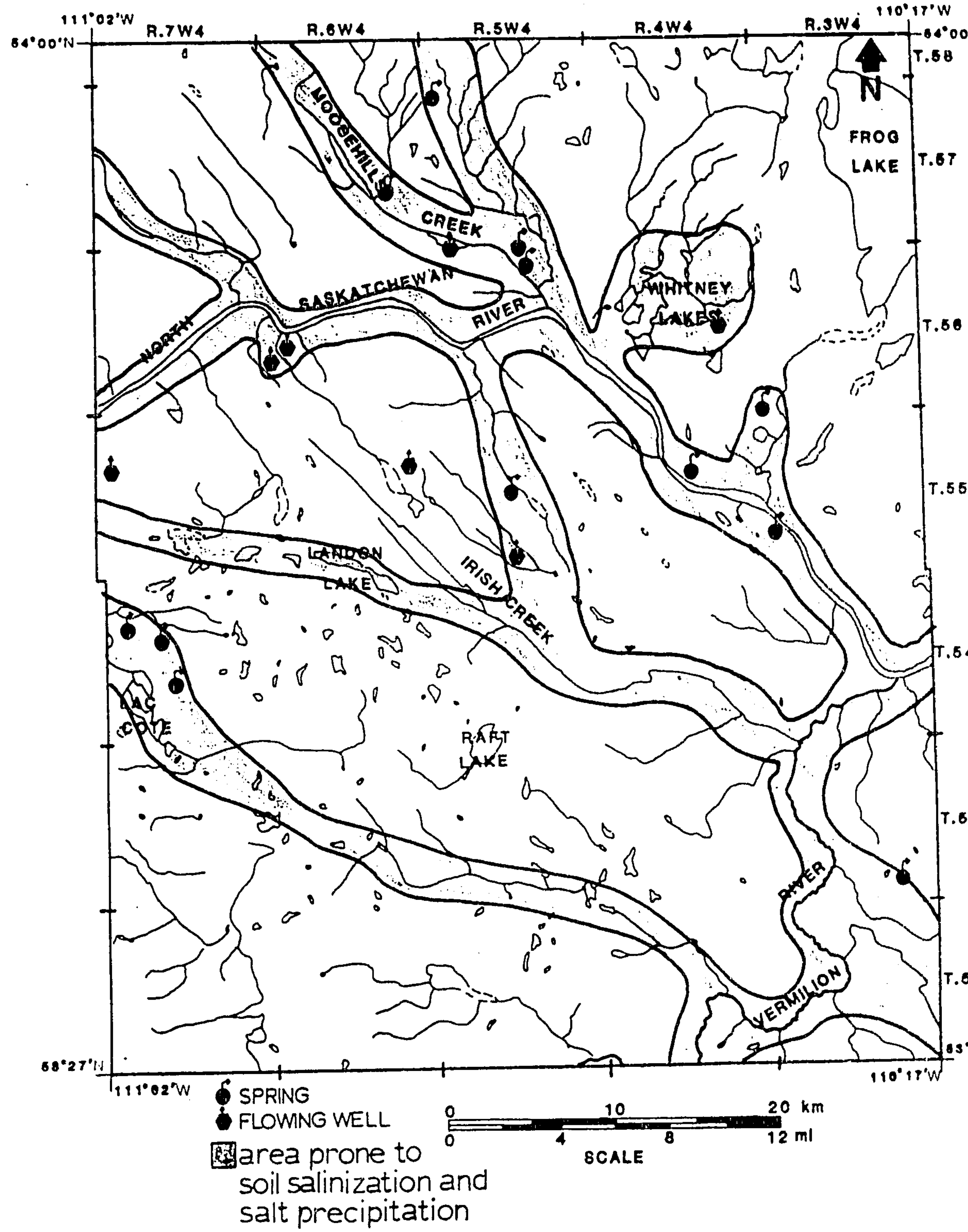


Figure 6.2. Thematic map of groundwater flow: areas prone to soil saliniztion and salt precipitation

precipitation has been established.

Groundwater flow-systems mapping may also aid in the fomulation of groundwater management programs, where the mapping of aquifers is necessary and information on groundwater flow conditions and groundwater quality are beneficial. Studies have shown that optimal groundwater development must take into consideration the entire groundwater basin, and not be restricted to the investigation of high permeability zones (Ophori, 1986).

An example of land use evaluation which demonstrates the necessity of groundwater flow studies is the selection of waste disposal sites. Too often, the locations of such sites area based on an investigation of the hydrostratigraphy without regard to groundwater flow. Recharge areas should be avoided because of the downward flow which can carry leaked contaminants to the groundwater supply. Using a groundwater flow-systems map as a basis, recharge areas can be avoided and and safer sites can be selected for waste disposal .

6.3 Conclusions

The main objective of this study was to study groundwater flow in terms of its relationships with its surrounding environment, using the Lindbergh study as a case study. This task was accomplished using a technique termed groundwater flow-systems mapping. The main conclusions to be drawn from the Lindbergh study are as follows.

The groundwater supply is limited in the Lindbergh area. Groundwater is extracted from the Belly River Formation in the western portion of the study area and from isolated surficial sand and gravel lenses throughout the area. Groundwater should only be used for domestic and agricultural purposes because of its limited availabilty.

Ten groundwater flow systems of regional or intermediate order are found in the Lindbergh area. Their maximum depth is approximately 125 metres. Local flow systems, which have primarily developed due to Pleistocene glaciation, are found in all ten groundwater flow systems.

The base of the Belly River Formation is an effective impermeable basement where it is present. Where the Lea Park Formation subcrops, the bedrock surface may be considered as an impermeable basement. The lateral boundaries of the groundwater flow systems are defined by the topography.

Hydraulic regions of groundwater flow systems can be successfully mapped based on the identification of groundwater flow manifestations. Groundwater flow modelling in the Lindbergh area confirmed the field mapping results.

The groundwater quality is strongly influenced by the geology in the Lindbergh area but the effects of groundwater flow on groundwater quality are not clear cut.

Although groundwater flow-systems mapping is ideal in theory, there are some limitations which should be noted. For instance, there may be a problem with the data availability. The accuracy of the results is commensurate with the amount of information available. The multi-disciplinary approach of this technique may cause problems to an individual worker. In essence, the workermust be a hydrogeologist, hydrologist, soil scientist, chemist, botanist, and groundwater modeller all in one. This problem may be resolved if a team of specialists carry out the study.

In summary, groundwater flow-systems mapping is a viable mapping technique, although it is not widely embraced at present time. It is a logical choice for land use evaluations and groundwater management studies, and it is hoped that more workers will recognize the importance of of looking at all components of the hydrogeological system.

REFERENCES

Back, W. 1960. Origin of hydrochemical facies and groundwater in the Atlantic Coastal Plain. Report XXI, Int. Geol. Congress, Norden. Part I, 87 pp.

Carlson, V.A. 1974. Bedrock topography of the Vermilion map area, NTS 73-E, Alberta. A.R.C. map.

Chebotarev, I.I. 1955. Metamorphism of natural waters in the crust of weathering. Geochim. Cosmochim. Acta, Vol.8, pp.22-28, 137-170, 198-212.

Clissold, R.J. 1967. Mapping of naturally occurring surficial phenomena to determine groundwater flow conditions in two areas near Red Deer, Alberta. M.Sc. thesis, Univ. of Alberta, 125 pp.

Cooper H.H.Jr. and C.E. Jacob. 1946. A generalized graphical method of evaluating formation constants and summarizing well field history. Trans. Amer. Geophys. Union, Vol. 27, pp.526-534.

Crowe, A.S. 1979. Program to plot chemical analyses on a Piper trilinear plot. (unpublished) Univ. of Alberta.

Currie, D.V. and N. Zacharko. 1976. Hydrogeology of the Vermilion area, Alberta. A.R.C.Report 75-5,, 15 pp.

Department of Energy, Mines and Resources. 1975. Survey and Mapping Branch. NTS Topgraphic map sheet 73-E (aerial photography 1970).

Ellwood, R. 1961. Surficial geology of the Vermilion area, Alberta, Canada. Ph.D. thesis, Univ. of Illinois, 131 pp.

Engelen, G.B. 1984. Hydrological Systems Analysis- a regional case study. TNO-DGV, Inst. of Appl. Geosc., report No. OS 84-20, Delft, Netherlands, 43 pp.

Energy Resourses Conservation Board. 1969. Structure contours of the base of the Fish Scales for area No.4. ERCB map.

Environment Canada. 1981-1985. Monthly meteorological records.

Farvolden, R.N. 1959. Groundwater supply in Alberta. (Unpublished report) Alberta Res. Council.

Freeze, R.A. 1969. Regional groundwater flow in the Old Wives LAke drainage basin, Saskatchewan. Dept. of Energy, Mines and Resources, Scientific Series No.5.

Freeze, R.A. and J.A. Cherry. 1979. Groundwater. Prentice-Hall Inc., Englewood Cliffs, New Jersey, 604 pp.

Freeze, R.A. and P.A. Witherspoon. 1967. Theoretical analysis of regional groundwater flow 2. Effect of water-table configuration and subsurface permeability variations. Wat. Resources Res., Vol.3, No.2, pp.623-634.

Frind, E.O. 1971. Finite-element model for steady-state potential distribution in a two-dimensional cross-section. (Unpublished paper) Univ. of Waterloo, Waterloo, Ont.

Grisak, G.E. et al. 1976. Hydrogeologic and hydrochemical properties of fractured till in the Interior Plains Region; *in* R.F. Legget (editor), Glacial Till, an Interdisciplinary Study. The Royal Society of Canada Special Publication No.12, pp. 304-335.

Hume, G.S. and C.O. Hage. 1941. The geology of east-central Alberta. G.S.C. Memoir 232, 101 pp.

Le Breton, G.E. 1963. Groundwater geology and hydrology of East-Central Alberta. A.R.C. Bull. 13, 64 pp.

Leskiw, L.A. 1971. Relationship between soils and groundwater in field mapping near Vegreville, Alberta. M.Sc. thesis, Univ. of Alberta, 138 pp.

Lissey, a. 1968. Surficial mapping of groundwater flow systems with application to the Oak River Basin. Ph.D. thesis, Univ. of Sask., Saskatoon, 106pp.

Lissey, A. 1971. Depression-focussed transient groundwater flow patterns in Manitoba. G.A.C., Special Paper No.9, pp.333-341.

Maclean, A.H. 1974. Soil genesis in relation to groundwater and soil moisture regimes near Vegreville, Alberta. Ph.D. thesis, Univ. of Alberta, Edmonton.

McLean, J.R. 1971. Stratigraphy of the Upper Cretaceous Judith River Formation in the Canadian Great Plains. Sak. Res. Council, Geol. Div., report No.11, 96 pp.

Meinzer, O.E. 1923. Outline of groundwater hydrology- with definitions. U.S.G.S. Water Supply Paper 494, 71 pp.

Meyboom, P. 1962. Patterns of groundwater flow in the prairie profile. Proc. of Hydrol. Symp. No.3, Groundwater, pp.5-20.

Meyboom, p. 1966b. Unsteady flow near a willow ring in hummocky moraine. Jour. of Hydrol., pp.38-42.

Mifflin, M.D. 1968. Delineation of groundwater flow systems in Nevada. Tech. Report, Series H-W. Hydrol. and Wat. Res. Publ. No4, Desert Res. Inst., Univ. of Nevada System, 53 pp.

Moss, E.H. 1955. The Vegetation of Alberta. Bot. Rev. Vol.21, No.9, pp.493-567.

Nauss, A.W. 1945. Cretaceous stratigraphy of the Vermilion area, Alberta, Canada. Bull. of Am. Assoc. Petrol. Geol., Vol. 29, No.11, pp.1605-1629.

Ophori, D.U. 1986. A numerical simulation of regional groundwater flow for basin management; Plains Region, Alberta. Ph.D. thesis, Univ. of Alberta, 327 pp.

Ozoray, G. et al. 1980. Hydrogeology of the Sand River Area, Alberta. A.R.C. Earth Sciences Report 79-1, 10 pp.

Pawluk, S. 1983. Salinization and solonetz formation. in: A.S. Agronomist Monograph: Handbook of Soil Geomorphology, 25 pp.

Piper, A.M. 1944. A graphic procedure in the geochemical interpretation of water analyses. Transactions, Am.Geoph. Union, Vol.25, pp.914-923.

Schoeller, H. 1962. Les eaux souterraines. Masson et Cie, Editeurs, Paris (VIe), 619 pp.

Schwartz, F.W. and K. Muehlenbachs, 1979. Isotope and ion geochemistry of groundwaters in the Milk River aquifer, Alberta. Water Resources Research, Vol.15, No.2, pp.259-268.

Shaw, E.W. and S.R.L. Harding. 1949. Lea Park and Belly River Formations of East-Central Alberta. Bull. Am. Assoc. Petrol. Geol., Vol.33, No.4, pp.487-499.

Stanley and Assoc. 1981. Dome Petroleum Ltd, Lindbergh pilot project, Water source well. (Unpublished report) Edmonton, Alberta.

Stanley and Assoc. 1985. Water resources study, Elk Point area. (Unpublished report) Edmonton, Alberta.

Tóth, J. 1962. Theory of groundwater motion in small drainage basins in central Alberta, Canada. Jour. of Geophys. Res., Vol.67, No.11, pp.4375-4387.

Tóth, J. 1963. A theoretical analysis of groundwater flow in a small drainage basin. Jour. of Geophys. Res., Vol.68, pp. 328-345.

Tóth, J. 1966b. Mapping and interpretation of field phenomena for groundwater reconnaissance in a prairie environment, Alberta, Canada. Bull. I.A.S.H., No.2, 49 pp.

Tóth, J. 1971. Groundwater discharge: a common generator of diverse geologic and morphologic phenomena. Bull. I.A.S.H. XVI (1.3), 23 pp.

Tóth, J. 1984. The role of regional gravity flow in the chemical and thermal evolution of groundwater. Proc. First Can./Amer. Conf. on Hydrogeology, Nat. Water Well Assoc., pp.3-39.

Winter, T.C. 1976. Numerical simulation analysis of the interaction of lakes and ground water. U.S.G.S. Prof. Paper 1001, 45 pp.

Winter, T.C. 1978. Numerical simulation of steady-state three dimensional groundwater flow near lakes. Water Resources Res. Vol.14, No.2, pp. 245-254.

APPENDIX 1

Water well data for the Lindbergh area

Symbols:

No. :	well number
LSD.:	Legal subdivision
SEC.:	Section
TP.:	Township
R.:	Range (West of Fourth Meridian)
EL.:	topographic elevation
w.d.:	well depth
Type:	completion type
w.l.:	depth to water level
elev.:	elevation of water level (hydraulic head)
Litho.:	lithology of completed interval
Y.:	well yield

NO.	LSD	SEC	TP	R.	EL.(m)	w.d.(m)	Type	w.l. (m)	elev (m)	Litho	Y. (l/s)
1	NW	1	52	3	613.26	32.00	c	3.51	609.75	sd	1.7
2	NE	2	52	3	613.26	33.53	c	6.22	607.16	sh	0.8
3	SE	6	52	3	655.32	49.99	c	18.29	637.03	sh	-
4	SE	8	52	3	632.46	49.38	c	39.62	592.84	cl	-
5	SW	11	52	3	613.26	49.99	c	9.14	604.11	sd	1.5
6	SW	12	52	3	613.26	35.97	c	11.89	601.37	tl	-
7	NW	12	52	3	617.22	53.95	c	41.76	575.46	sd	0.3
8	NE	13	52	3	609.60	43.59	c	30.27	579.42	sh	0.7
9	SW	19	52	3	628.50	28.65	c	7.62	620.88	cl	-
10	NE	20	52	3	594.36	10.67	d	3.05	591.31	cl	0.6
11	SE	24	52	3	605.64	56.08	c	31.85	573.79	sd	0.6
12	SE	25	52	3	613.26	15.24	a	10.36	602.89	gr	-
13	NE	25	52	3	620.88	14.94	c	10.06	610.82	sd	<0.1
14	SW	20	52	3	601.98	44.20	c	27.43	574.55	sd/gr	0.7
15	SE	30	52	3	601.98	82.30	c	26.52	575.46	sd/gr	-
16	SW	31	52	3	594.36	26.52	c	10.67	583.69	sh	-
17	SW	36	52	3	620.88	10.06	a	4.57	616.31	cl	0.1
18	SE	2	52	4	617.22	30.48	a	11.89	605.33	sh	0.5
19	SW	3	52	4	617.22	27.13	c	8.84	608.38	gr	-
20	NW	4	52	4	617.22	30.48	b	22.56	594.66	sh	1.1
21	NW	6	52	4	594.36	30.48	b	14.02	580.34	sh	-
22	SW	10	52	4	571.50	30.48	b	7.62	563.88	gr	-
23	SW	10	52	4	571.50	26.21	c	2.38	569.06	sh	15.0
24	SW	10	52	4	571.50	29.26	c	2.76	568.76	sh	7.6
25	SW	10	52	4	571.50	23.16	c	2.68	568.76	sh	6.8
26	16	10	52	4	571.50	42.67	c	2.35	569.06	sh	-
27	16	10	52	4	571.50	41.76	c	1.83	569.67	sh	22.0
28	16	10	52	4	571.50	46.94	c	1.89	569.67	sh	-
29	16	10	52	4	571.50	39.32	c	1.95	569.67	sh	-
30	SE	14	52	4	575.16	27.43	b	10.67	564.49	ss	-
31	NE	18	52	4	628.50	32.61	c	24.08	604.42	sd	7.6
32	NE	34	52	4	630.02	32.92	c	3.05	626.97	sd/gr	11.4
33	SE	35	52	4	613.26	96.01	c	41.15	517.25	sh	3.4
34	SE	3	52	5	594.36	30.48	c	16.46	577.90	sd	-
35	SE	3	52	5	594.36	12.19	b	3.35	591.01	sd	-
36	NE	11	52	5	605.94	48.46	b	19.20	586.74	ss	-
37	SW	16	52	5	617.22	53.04	c	21.95	595.27	sd	2.3
38	SE	17	52	5	624.84	12.19	b	4.88	619.96	cl	0.5
39	SE	17	52	5	624.84	51.21	c	24.69	600.15	sd	2.3
40	SW	22	52	5	617.22	54.56	c	33.53	614.17	sd	1.1
41	NW	23	52	5	640.08	57.61	c	48.16	591.92	sd	0.4
42	SW	32	52	5	632.46	32.92	c	21.95	610.51	gr	1.1
43	SW	34	52	5	609.60	44.81	c	20.21	589.48	sd	0.9
44	SE	6	52	6	643.74	23.47	c?	16.15	627.58	co	0.2
45	NE	8	52	6	632.46	27.43	b	14.63	617.83	cl	0.4
46	SE	10	52	6	640.08	44.50		28.96	611.12	ss/sh	
47	NE	12	52	6	628.50	54.86	c	12.27	616.31	sh	1.1
48	NE	14	52	6	620.88	31.70	c	6.71	614.17	sd	3.8
49	SE	17	52	6	632.46	19.51	b	3.66	628.80	sh	0.8
50	SE	21	52	6	632.46	22.86	c	7.92	624.54	sd/gr	1.0
51	NE	26	52	6	628.50	30.48	c	10.36	618.13	tl	0.6
52	NW	33	52	6	624.84	18.29	b	4.88	619.96	sh	0.4
53	SE	34	52	6	624.84	32.00	b	9.14	615.70	-	0.6
54	NE	4	52	7	651.36	60.05	b	28.04	623.32	sh	0.9

NO.	LSD	SEC	TP	R.	EL.(m)	w.d.(m)	Type	w.l. (m)	elev (m)	Litho	Y. (l/s)
55	NE	8	52	7	640.08	43.28	b	12.80	627.28	ss	1.5
56	NE	12	52	7	628.50	17.07	c	6.71	621.79	sd	0.3
57	NW	17	52	7	662.94	21.34	b	10.06	652.88	-	0.3
58	SW	18	52	7	662.94	65.53	c	42.67	620.27	sd/ss	0.5
59	SE	24	52	7	632.46	24.38	b	9.14	623.32	ss	0.8
60	SE	25	52	7	617.22	30.48	b	13.41	603.81	sh	0.8
61	SW	28	52	7	643.74	22.86	c	9.14	634.59	gr	3.0
62	SE	30	52	7	674.22	79.25	a	54.86	619.35	sh	0.9
63	NW	30	52	7	681.84	64.62	c	56.69	625.14	ss	0.5
64	NE	33	52	7	640.08	36.58	b	19.51	620.57	b/r	0.2
65	NW	34	52	7	632.46	27.13	b	8.84	623.62	sh	0.2
66	NW	2	53	3	632.46	79.25	a	55.29	577.29	sh	0.2
67	NW	3	53	3	594.36	35.05	a	21.03	573.33	sh	0.2
68	NE	10	53	3	647.70	60.96	b?	15.24	632.46	sh	0.3
69	NW	12	53	3	655.32	15.85	b	6.10	649.22	sd	0.2
70	NW	13	53	3	658.98	12.19		8.53	650.44	sd	0.1
71	NW	14	53	3	647.70	17.68	a	7.32	640.38	cl	-
72	SE	15	53	3	632.46	65.84	b	3.66	628.80	sh	<0.1
73	5	16	53	3	586.74	11.58	c	0.00	587.04	sd	-
74	NW	16	53	3	594.36	51.82	a	10.67	583.69	sh	0.3
75	NE	18	53	3	586.74	32.00	b	7.32	579.42	b/r	-
76	NE	24	53	3	632.46	30.18	a	24.08	608.38	gr	0.2
77	SE	25	53	3	617.22	11.89	a	3.66	613.56	cl/sd	0.0
78	SW	28	53	3	586.74	11.89	b	3.35	583.39	gr	-
79	SW	36	53	3	586.74	11.28	a	5.79	580.95	cl	3.0
80	NW	36	53	3	586.74	8.84	a	3.66	583.08	cl	3.0
81	NW	4	53	4	647.70	63.70	c	51.21	596.49	tl	0.5
82	SE	5	53	4	617.22	13.56	a	3.96	613.26	sd	1.1
83	NW	7	.53	4	601.98	46.63	c	24.08	577.90	sd	0.8
84	NW	8	53	4	617.22	21.95	c	15.00	602.28	-	0.1
85	NW	8	53	4	620.88	71.93	c	34.14	586.74	-	1.1
86	SW	10	53	4	617.22	37.49	c	22.68	594.66	sd	0.8
87	NW	11	53	4	601.98	18.29	c	7.01	594.97	-	1.5
88	SW	12	53	4	598.02	36.58	b	8.53	589.48	sh	0.6
89	NW	12	53	4	598.02	32.92	c	13.11	584.91	-	1.5
90	NW	15	53	4	601.98	30.48	c	9.14	592.84	tl	1.5
91	SW	18	53	4	617.22	54.86	b	24.38	592.84	sh	1.5
92	SE	19	53	4	632.46	71.93	c	48.77	583.69	sd/gr	1.1
93	SE	21	53	4	601.98	95.71	c	24.08	577.90	cl	1.8
94	SE	21	53	4	601.98	99.36	c	25.30	576.68	sd/gr	3.8
95	SW	22	53	4	601.98	76.20	a	25.91	576.07	sh	-
96	SE	26	53	4	594.36	49.99	c	21.64	572.72	sd/gr	1.1
97	SW	26	53	4	594.36	40.84	c	21.21	573.02	sd/gr	0.8
98	SW	27	53	4	594.36	41.15	c	27.43	566.93	gr	-
99	NW	28	53	4	601.98	53.34	c	24.38	577.60	sd	2.2
100	SW	30	53	4	632.46	47.85	c	35.36	597.10	gr	0.5
101	NE	31	53	4	609.60	28.04	b	2.44	607.16	gr	0.3
102	SW	36	53	4	586.74	34.44	c	12.80	573.94	sd	3.0
103	SE	3	53	5	609.60	39.01	c	14.63	594.97	b/r	1.5
104	NW	4	53	5	609.60	31.09	b	9.14	600.46	sd/gr	0.8
105	NW	5	53	5	624.84	29.57	c	7.62	617.22	gr	3.0
106	NW	6	53	5	624.84	44.20	b	14.94	609.90	ss	1.1
107	SW	7	53	5	617.22	51.21	b	14.33	602.89	sh	0.5
108	NE	7	53	5	617.22	53.95	b	8.44	608.69	sh	0.9

NO.	LSD	SEC	TP	R.	EL.(m)	w.d.(m)	Type	w.l. (m)	elev (m)	Litho	Y. (l/s)
109	SE	8	53	5	601.98	17.68	c	9.45	592.53	ss	0.2
110	SE	8	53	5	601.98	17.37	c	6.71	595.27	sd	0.3
111	SW	9	53	5	601.98	20.73	c	15.85	586.13	sd/gr	0.4
112	NE	10	53	5	617.22	53.95	b	7.04	610.21	sh	0.5
113	SW	16	53	5	632.46	30.18	b	4.57	627.89	ss	1.1
114	SW	17	53	5	627.89	19.51	b	11.58	616.31	ss	0.7
115	SW	17	53	5	627.89	16.76	b	9.72	618.13	ss	1.3
116	NE	18	53	5	632.46	32.00	b	16.64	615.70	sh	0.5
117	SE	19	53	5	640.08	33.53	b	21.95	618.13	ss	1.5
118	NE	25	53	5	655.32	60.96	b	26.52	628.80	ss	1.1
119	SW	27	53	5	617.22	9.75	c	3.66	613.56	sd	0.2
120	SE	31	53	5	647.70	49.07	c	11.58	636.12	sd	1.5
121	SE	33	53	5	624.84	11.58	a	2.44	622.40	cl	0.5
122	SW	34	53	5	624.84	60.96	b	13.11	611.73	-	2.2
123	NE	36	53	5	628.50	14.02	b	0.61	627.89	cl	0.2
124	NE	1	53	6	617.22	26.52	b	0.00	617.22	sh	0.8
125	SW	6	53	6	624.84	47.85	b	7.28	617.52	sh	0.6
126	SW	6	53	6	624.84	12.80	c	7.16	617.68	ss	0.2
127	NE	12	53	6	624.84	36.58	b	15.54	609.30	sh	0.2
128	SW	14	53	6	624.84	23.16	c	7.32	617.52	gr	1.1
129	SW	16	53	6	617.22	7.01	b	2.13	615.09	ss	0.3
130	NE	16	53	6	617.22	60.05	b	24.26	592.84	ss	0.4
131	SW	17	53	6	632.46	16.76	b	5.18	627.28	ss	0.8
132	SE	25	53	6	647.70	54.86	a	12.19	635.51	sh	0.5
133	SE	26	53	6	632.46	41.15	b	9.75	622.71	b/r	0.6
134	SW	28	53	6	632.46	26.21	c	22.25	610.21	gr	1.1
135	SE	32	53	6	632.46	22.25	a	16.46	616.00	sd	0.3
136	NW	32	53	6	640.08	23.47	b	3.66	636.42	ss	1.9
137	NE	36	53	6	624.84	16.46	c	5.49	619.35	sh	0.8
138	SE	1	53	7	624.84	15.24	b	7.32	617.52	sh	0.6
139	SW	3	53	7	624.84	25.60	b	3.05	621.79	sh	1.9
140	SE	18	53	7	662.94	54.25	c	16.15	646.79	sd	0.5
141	SW	19	53	7	662.94	40.84	c	24.08	638.86	sd	0.8
142	SE	27	53	7	609.60	36.58	b	17.01	592.53	sh	0.5
143	SE	27	53	7	609.60	39.62	b	15.61	594.06	sh	0.1
144	SW	27	53	7	617.22	11.89	b	7.32	609.90	cl	0.2
145	SE	32	53	7	601.98	38.40	a	12.19	589.79	cl	0.4
146	NW	1	54	3	571.50	73.46	a	42.67	528.83	sh	0.2
147	SE	2	54	3	579.12	11.89	a	5.49	573.63	sd	0.2
148	NW	10	54	3	563.88	9.75	a	5.49	558.39	cl	0.2
149	NW	11	54	3	518.16	8.84	a	5.18	512.98	sd	3.0
150	SW	14	54	3	525.78	9.14		4.88	520.90	sh	0.2
151	NE	15	54	3	518.16	12.34	a	4.88	513.28	cl	0.2
152	SW	17	54	3	579.12	63.40	c	51.82	527.30	gr	2.2
153	SE	19	54	3	579.12	19.51	a	3.05	576.07	cl	0.1
154	SE	19	54	3	579.12	44.81	c	9.14	569.98	gr	1.5
155	SW	21	54	3	563.88	12.19	a	6.71	557.17	cl	-
156	SE	22	54	3	541.02	41.45	a	4.57	536.45	sh	0.5
157	NW	36	54	3	563.88	10.97	a	5.18	558.70	gr	3.0
158	NW	1	54	4	571.50	20.73	c	6.10	565.40	co	1.5
159	SW	1	54	4	571.50	57.00	c	15.24	556.26	sd	0.6
160	SE	3	54	4	590.40	31.09	c	19.81	570.59	gr	0.9
161	NW	3	54	4	598.02	42.67	c	23.16	574.85	co	0.7
162	NE	4	54	4	598.02	30.48	c	23.47	574.55	sd/gr	0.7

NO.	LSD	SEC	TP	R.	EL.(m)	w.d.(m)	Type	w.l. (m)	elev (m)	Litho	Y. (l/s)
163	NE	6	54	4	605.64	20.73	a	16.15	589.48	cl	-
164	SE	9	54	4	601.98	60.96	c	38.71	563.27	sh	0.8
165	NE	20	54	4	601.98	49.38	c	34.96	566.93	gr	0.8
166	SW	21	54	4	594.36	51.82	c	27.43	566.93	sd	0.6
167	NE	21	54	4	601.98	46.94	c	30.48	571.50	sd/gr	1.5
168	SW	23	54	4	575.16	56.39	c	39.01	536.14	sd	1.1
169	NE	31	54	4	609.60	79.25	b	40.23	569.37	sh	0.2
170	SE	33	54	4	609.60	51.51	c	41.00	568.45	sd/gr	-
171	SE	35	54	4	609.60	29.87	c	26.79	582.78	sh	0.4
172	SE	1	54	5	617.22	45.72	b	6.74	610.51	cl	0.9
173	SE	1	54	5	617.22	53.34	c	28.96	588.26	sd	0.6
174	SW	3	54	5	655.32	30.18	b	20.73	634.59	b/r	0.8
175	NW	4	54	5	647.70	48.77	a	18.29	629.41	sh	0.8
176	SW	8	54	5	624.84	32.31	c	12.19	612.65	sd	0.8
177	NE	12	54	5	601.98	27.13	b	9.14	592.84	cl	<0.1
178	NW	14	54	5	609.60	12.80	a	5.49	604.11	cl	0.2
179	SW	16	54	5	624.84	21.34	c	9.14	615.70	sd	0.2
180	NW	18	54	5	617.22	54.86	b	2.29	614.93	sh	1.0
181	NE	31	54	5	624.84	41.76	c	39.01	585.83	tl	0.1
182	SE	32	54	5	624.84	66.45	c	41.45	583.39	sh	2.2
183	NW	32	54	5	632.46	51.82	c	45.42	587.04	tl	0.5
184	SW	35	54	5	617.22	47.85	c	32.92	584.30	sd	0.8
185	SE	12	54	6	640.08	21.34	b	4.27	635.81	-	2.2
186	SE	14	54	6	640.08	13.72	c	4.88	635.20	-	0.2
187	NW	25	54	6	632.46	49.38	c	43.89	588.57	sd/gr	0.8
188	SW	26	54	6	647.70	36.58	b	17.07	630.63	ss	0.8
189	NE	26	54	6	624.84	36.58	c	29.26	595.58	cl	0.6
190	NW	3	54	7	632.46	22.86	a	11.28	621.18	sh	0.2
191	NE	5	54	7	617.22	26.82	c	9.75	607.47	tl	1.9
192	SE	8	54	7	609.60	37.49	c	19.20	590.40	sh	1.1
193	NE	9	54	7	632.46	22.86	b	12.19	620.27	b/r	0.5
194	SE	14	54	7	640.08	13.72	c	4.88	635.20	sd	0.2
195	NE	16	54	7	647.70	24.38	b	3.66	644.04	ss	0.9
196	NW	27	54	7	624.84	12.19	b	3.66	621.18	sh	0.6
197	NW	30	54	7	601.98	16.15	b	10.67	591.31	ss	0.2
198	NW	32	54	7	617.22	29.26	b	10.36	606.86	sd	0.5
199	NE	36	54	7	647.70	39.62	c	3.96	643.74	sd	0.6
200	NW	5	55	3	525.78	12.80	b	5.18	520.60	cl	0.2
201	SE	7	55	3	521.82	26.52	b	21.34	500.48	cl	0.1
202	SE	10	55	3	571.50	26.21	a	20.73	550.77	cl	0.4
203	SE	16	55	3	556.26	14.94	a	7.01	549.25	cl	0.3
204	SW	28	55	3	579.12	67.36	c	41.15	537.97	sd/gr	0.5
205	NE	29	55	3	594.36	14.94	a	6.10	588.26	sd	0.4
206	NW	31	55	3	579.12	18.29	c	10.36	568.76	sd	0.8
607	SW	1	55	4	598.02	26.82	c	18.59	579.42	sd	0.5
208	NW	4	55	4	617.22	11.73	b	6.71	610.51	cl	0.1
209	SW	5	55	4	617.22	57.91	c	44.20	573.02	sd	0.9
210	NW	6	55	4	617.22	68.58	c	59.13	558.09	sd	0.8
211	8	9	55	4	609.60	63.09	c	40.23	569.37	sd/gr	1.2
212	SW	10	55	4	606.55	41.76	c	7.92	598.63	cl	0.8
213	NW	14	55	4	541.02	20.12	c	12.50	528.52	sd	0.6
214	NW	15	55	4	586.74	14.63	b	11.89	574.85	sd	0.1
215	NE	17	55	4	609.60	44.20	c	31.70	577.90	cl	1.9
216	9	17	55	4	617.22	42.98	c	33.83	583.39	sd	0.2

NO.	LSD	SEC	TP	R.	EL.(m)	w.d.(m)	Type	w.l. (m)	elev (m)	Litho	Y. (l/s)
217	SE	18	55	4	609.60	51.51	c	36.61	573.02	sd/gr	0.4
218	SW	18	55	4	609.60	11.89	a	6.10	603.50	cl	0.2
219	SW	22	55	4	533.40	15.85	c	7.01	526.39	sd	1.1
220	SW	22	55	4	533.40	24.38	c	18.59	514.81	sd	0.6
221	NW	22	55	4	533.40	15.54	c	7.01	526.39	sd	0.8
222	SE	29	55	4	579.12	21.34	c	16.15	562.97	sd	0.3
223	NW	35	55	4	601.98	49.99	c	18.29	583.69	cl	0.8
224	NW	35	55	4	601.98	12.95	a	6.86	595.12	sd	0.2
225	SE	1	55	5	609.60	43.89	c	29.87	579.73	sd/gr	0.9
226	SE	6	55	5	624.84	45.42	c	33.22	591.62	sd/gr	0.3
227	SW	7	55	5	640.08	17.37	b	3.66	636.42	gr	0.3
228	NE	9	55	5	640.08	23.77	a	18.59	621.49	cl	0.2
229	SW	12	55	5	617.22	55.47	b	40.54	576.68	sd/gr	0.3
230	SE	13	55	5	624.84	71.02	c	46.02	578.82	sd	0.5
231	SW	15	55	5	628.50	6.40	a	3.05	625.45	gr	0.4
232	NW	16	55	5	632.46	17.98	a	8.23	624.23	cl	0.2
233	SW	18	55	5	640.08	21.34	c	7.62	632.46	sh	0.4
234	SW	28	55	5	601.98	67.06	b	24.38	577.60	sh	1.1
235	SE	1	55	6	643.74	53.34	c	28.96	614.78	sd	0.6
236	SW	1	55	6	647.70	102.72	c	72.24	575.46	gr	0.8
237	SE	2	55	6	647.70	98.45	c	69.49	578.21	sd	-
238	NW	5	55	6	632.46	37.49	c	10.97	621.49	cl	1.5
239	SW	6	55	6	632.46	54.86	b	5.18	627.28	cl	0.6
240	SW	7	55	6	624.84	58.83	c	9.75	615.09	gr	2.7
241	SW	10	55	6	640.08	39.93	c	12.19	627.89	gr	1.1
242	SW	16	55	6	662.94	42.67	b	22.25	640.69	ss	0.5
243	NE	16	55	6	685.80	65.53	c	36.58	649.22	ss	0.4
244	NW	20	55	6	662.94	38.71	c	26.82	636.12	gr	0.5
246	NW	26	55	6	647.70	38.71	c	26.82	620.88	-	-
247	NE	33	55	6	624.84	17.98	a	13.72	611.12	cl/sd	0.3
248	NW	35	55	6	662.94	36.58	c	23.16	639.78	gr	0.8
249	SE	2	55	7	632.46	17.37	a	6.10	611.12	cl	0.1
250	SE	2	55	7	632.46	22.25	a	12.80	619.66	ss	1.5
251	SW	5	55	7	617.22	21.34	b	6.10	611.12	ss	0.4
252	NE	6	55	7	632.46	7.62	b	3.05	629.41	cl	2.7
253	NW	9	55	7	617.22	21.95	c	13.41	603.81	sd	0.8
254	SE	13	55	7	624.84	13.72	a	5.18	619.66	cl	0.2
255	NW	14	55	7	632.46	28.04	b	16.46	616.00	sd	0.6
256	SE	15	55	7	613.26	19.81	b	10.06	603.20	ss	0.4
257	SE	21	55	7	651.36	44.50	c	37.76	613.56	gr	0.5
258	SW	21	55	7	647.70	41.15	b	9.14	638.56	sd	0.3
259	SW	22	55	7	647.70	48.77	a	38.71	608.99	sh	0.6
260	SW	25	55	7	617.22	50.29	c	18.29	598.93	cl	-
261	SW	27	55	7	655.32	57.91	c	53.34	601.98	gr	0.5
262	SW	31	55	7	598.02	19.35	a	10.67	587.35	sd	1.5
263	SW	4	56	3	594.36	58.52	c	21.64	572.72	gr	2.3
264	SW	5	56	3	594.36	59.74	c	33.83	560.53	tl	2.3
265	SE	8	56	3	594.36	54.56	c	40.72	553.52	gr	0.5
266	SW	16	56	3	586.74	38.71	c	16.15	570.59	sd/gr	0.6
267	SW	17	56	3	605.64	19.81	c	13.56	592.07	tl	0.5
268	1	18	56	3	609.60	48.31	c	5.49	604.11	tl	0.9
269	SW	19	56	3	613.26	60.05	c	16.76	596.49	sd	0.6
270	NW	19	56	3	613.26	71.02	c	52.18	560.83	gr	0.5
271	NE	19	56	3	613.26	62.48	c	40.78	572.41	sd/gr	0.5

NO.	LSD	SEC	TP	R.	EL.(m)	w.d.(m)	Type	w.l. (m)	elev (m)	Litho	Y. (l/s)
272	SW	20	56	3	617.22	41.15	c	29.81	587.35	gr	0.5
273	NW	21	56	3	609.60	35.36	c	24.38	585.22	gr	0.6
274	NW	22	56	3	609.60	51.21	c	23.77	585.83	gr	0.5
275	NW	25	56	3	579.12	39.62	c	36.58	573.02	sd/gr	0.2
276	NW	25	56	3	601.98	67.36	c	33.53	568.45	ss	0.6
277	SE	28	56	3	617.22	56.69	c	37.49	579.73	sd/gr	0.5
278	NW	28	56	3	613.26	46.94	c	34.75	578.51	sd/gr	0.9
279	SW	29	56	3	609.60	31.09	c	24.69	584.91	gr	0.6
280	9	31	56	3	609.60	32.61	c	23.16	586.44	gr	0.7
281	6	33	53	3	624.84	39.01	c	35.66	589.18	sd/gr	0.5
282	NW	35	56	3	594.36	86.87	c	59.44	534.92	ss	0.5
283	NE	3	56	4	617.22	23.47	c	12.80	604.42	sd	0.4
284	NW	4	56	4	582.78	9.60	a	6.55	576.22	gr	3.0
285	NW	4	56	4	582.78	10.06	c	5.79	576.99	sd	0.2
286	SE	10	56	4	609.60	24.69	c	10.67	598.93	cl/sd	0.8
287	SE	11	56	4	594.36	21.34	c	18.59	575.77	sd	0.2
288	SW	11	56	4	601.98	18.29	c	10.91	591.01	sd	0.1
289	SE	15	56	4	586.74	67.36	c	10.97	575.77	sd	0.4
290	NW	15	56	4	571.50	18.29	c	4.27	567.23	sh	0.5
291	NE	15	56	4	571.50	36.27	c	2.97	568.45	sh	0.6
292	NE	18	56	4	594.36	12.19	c	6.10	588.26	sd	0.4
293	SW	22	56	4	571.50	10.67	c	5.18	566.32	cl	0.1
294	SW	22	56	4	571.50	18.29	c	3.05	568.45	sh	0.4
295	NW	23	56	4	586.74	51.21	c	0.00	586.74	gr	0.4
296	NW	23	56	4	579.12	41.15	c	7.01	572.11	sd	0.3
297	SE	30	56	4	571.50	37.03	c	31.70	539.80	sd/gr	0.4
298	NW	30	56	4	605.64	50.90	c	21.34	584.30	sd/gr	0.6
299	SW	6	56	5	670.56	19.81	a	10.67	659.89	cl	0.2
300	NW	10	56	5	594.36	49.99	c	34.75	559.61	gr	0.2
301	NE	10	56	5	594.36	60.96	c	34.44	559.92	sd	0.1
302	SW	18	56	5	617.22	42.67	c	7.62	609.60	cl	-
303	NW	19	56	5	556.26	24.69	c	15.54	540.72	cl/sd	2.3
304	NE	19	56	5	548.64	40.84	c	18.59	530.05	sd/gr	0.8
305	SW	25	56	5	571.50	13.11	a	2.13	569.37	cl	0.2
306	SE	26	56	5	579.12	24.38	c	8.53	570.59	sd	0.3
307	SE	26	56	5	579.12	14.02	a	3.96	575.16	tl	1.7
308	NE	26	56	5	579.12	37.80	c	10.67	568.45	sd	1.5
309	NE	27	56	5	533.40	14.63	c	9.45	523.95	gr	0.6
310	SW	29	56	5	548.64	33.53	c	12.19	536.45	gr	0.4
311	SE	32	56	5	575.16	16.46	a	4.27	570.89	cl	0.2
312	NW	34	56	5	533.40	12.80	c	3.66	529.74	sd	0.8
313	SW	5	56	6	640.08	24.38	a	12.19	627.89	cl	0.2
314	SW	6	56	6	662.94	23.77	a	14.02	648.92	cl	0.1
315	NW	10	56	6	658.98	85.34	a	30.18	628.80	sd	0.3
316	1	12	56	6	655.32	13.41	a	6.10	649.22	sd/cl	0.2
317	NW	14	56	6	662.94	17.68	a	4.57	658.37	cl	0.2
318	SW	16	56	6	628.50	22.56	a	10.36	621.18	cl	0.4
319	NE	17	56	6	617.22	13.72	a	8.84	608.38	cl	0.2
320	NE	18	56	6	605.64	59.44	c	39.62	566.01	cl	0.4
321	NW	20	56	6	601.98	8.84	a	5.79	596.19	cl	1.0
322	SW	22	56	6	640.08	53.95	c	32.00	608.08	sd	0.6
323	SW	24	56	6	556.26	10.36	a	4.88	551.38	sd/cl	0.2
324	SW	25	56	6	579.12	9.45	a	4.57	574.55	sd	0.4
325	SW	30	56	6	541.02	33.53	c	21.34	519.68	sh	0.4

NO.	LSD	SEC	TP	R.	EL.(m)	w.d.(m)	Type	w.l. (m)	elev (m)	Litho	Y. (l/s)
326	NW	32	56	6	601.98	6.10	a	1.52	600.46	cl	0.4
327	SE	36	56	6	601.98	29.57	c	8.02	594.06	sd	1.1
328	NW	2	56	7	594.36	42.06	c	16.76	577.60	cl	0.8
329	NE	3	56	7	601.98	47.24	c	13.72	588.26	cl	-
330	SW	5	56	7	609.60	13.72	a	7.01	572.11	cl	2.3
331	NW	7	56	7	571.50	10.36	a	5.49	566.01	cl	0.2
332	SW	8	56	7	548.64	11.58	a	4.57	544.07	cl	0.2
333	SE	10	56	7	605.64	38.10	c	16.46	589.18	cl	-
334	NW	12	56	7	628.50	64.01	c	15.85	612.65	cl	0.4
335	9	12	56	7	617.22	51.21	c	38.40	578.82	gr	0.7
336	SW	13	56	7	613.26	14.63	a	4.88	608.38	cl	0.2
337	NW	19	56	7	601.98	89.00	a	15.85	586.13	cl/gr	0.2
338	NE	20	56	7	594.36	16.76	a	12.50	581.86	sh	0.3
339	SE	25	56	7	533.40	73.15	b	2.44	530.96	sh	0.2
340	NE	28	56	7	613.26	12.19	a	5.49	607.77	cl	1.5
341	SE	30	56	7	613.26	43.28	c	24.38	588.87	cl	0.5
342	NW	30	56	7	632.46	51.82	a	28.35	604.11	ss	0.3
343	NW	4	57	3	624.84	77.88	c	48.65	576.07	sd	0.3
344	NE	4	57	3	628.50	75.29	c	56.78	571.80	gr	0.5
345	SE	5	57	3	617.22	49.38	c	33.38	583.69	gr	0.7
346	1	6	57	3	609.60	31.24	c	19.99	589.48	sd/gr	0.7
347	SW	9	57	3	628.50	45.72	c	33.77	594.66	gr	0.5
348	13	16	57	3	620.88	59.44	c	44.10	576.68	tl	0.6
349	9	17	57	3	620.88	56.39	c	37.19	583.69	tl/sd	0.6
350	NE	19	57	3	613.26	54.25	c	30.48	582.78	cl	-
351	SW	28	57	3	609.60	28.35	c	20.06	589.48	sd/gr	0.6
352	NW	5	57	4	617.22	30.18	c	18.23	598.93	sd	0.5
353	SW	6	57	4	609.60	71.63	c	10.36	599.24	gr	0.6
354	NW	6	57	4	617.22	13.11	c	3.66	613.26	gr	0.2
355	NW	12	57	4	624.84	37.80	c	24.87	599.85	sd/gr	0.4
356	SE	16	57	4	640.08	62.18	c	31.24	608.69	sd/gr	0.5
357	NE	21	57	4	601.98	50.60	c	35.36	566.62	sd	0.5
358	NE	32	57	4	617.22	9.14	b	3.96	613.26	cl	0.6
359	NE	2	57	5	609.60	12.80	b	3.35	606.25	sd	0.4
360	4	10	57	5	563.88	39.01	c	9.14	554.74	cl	0.5
361	NE	15	57	5	586.74	7.62	b	1.68	585.06	cl	0.2
362	NE	18	57	5	594.36	21.34	c	6.10	588.26	sd	0.8
363	SE	19	57	5	609.60	10.36	b	4.57	605.03	cl/gr	<0.1
364	NE	20	57	5	594.36	6.40	c	1.52	592.84	sd	0.8
365	SW	22	57	5	632.46	15.54	b	12.50	619.96	sd	0.2
366	NW	23	57	5	640.08	14.33	a	11.28	628.80	cl	0.2
367	NW	24	57	5	643.74	25.30	c	5.18	638.56	gr	1.5
368	SW	26	57	5	643.74	8.23	b	3.05	640.69	sd	0.5
369	NW	26	57	5	651.36	17.37	a	8.84	642.52	cl	-
370	SW	32	57	5	647.70	39.01	c	9.14	554.74	sh	0.5
371	SE	33	57	5	640.08	30.30	c	4.24	635.81	sd/gr	0.9
372	NW	2	57	6	579.12	13.72	a	3.05	576.07	cl	0.4
373	SW	2	57	6	609.60	11.89	a	10.36	599.24	cl	<0.1
374	NW	3	57	6	601.98	10.36	a	3.05	598.93	cl	0.2
375	SW	4	57	6	594.36	11.58	a	3.05	591.31	cl	0.3
376	NW	4	57	6	586.74	13.11	c	3.66	583.08	gr	0.2
377	NW	5	57	6	594.36	14.33	a	11.28	583.08	cl	0.2
378	SW	6	57	6	594.36	48.77	b	6.71	586.13	cl	1.7
379	NW	7	57	6	647.70	11.58	a	3.05	644.65	cl	0.4

NO.	LSD	SEC	TP	R.	EL.(m)	w.d.(m)	Type	w.l. (m)	elev (m)	Litho	Y. (l/s)
380	NW	8	57	6	643.74	17.68	a	9.14	634.59	sd	0.4
381	SE	9	57	6	590.40	9.14	b	2.44	587.96	cl	0.3
382	SW	14	57	6	548.64	19.20	c	10.67	537.97	sd	0.2
383	SE	15	57	6	586.74	11.58	a	6.10	583.69	sd	0.4
384	NE	15	57	6	571.50	11.28	a	9.14	562.36	sd	0.2
385	SW	16	57	6	647.70	18.29	b	13.41	634.29	ss/sd	0.4
386	NW	18	57	6	658.98	21.64	b	14.63	644.35	sd	0.2
387	SE	25	57	6	609.60	21.34	c	0.00	609.60	sd	2.3
388	NE	25	57	6	632.46	43.89	c	12.19	620.27	gr	1.0
389	SW	28	57	6	563.88	21.34	a	16.76	547.12	cl	0.1
390	NW	30	57	6	624.84	41.76	b	8.23	616.61	sh	0.5
391	SW	30	57	6	624.84	67.06	b	13.72	611.12	sh	0.9
392	SW	32	57	6	609.60	14.63	a	10.97	598.63	cl	0.8
393	NE	36	57	6	670.56	60.66	a	6.71	663.85	cl	0.4
394	SE	2	57	7	601.98	20.73	b	12.19	589.79	cl	0.2
395	NW	2	57	7	624.84	21.34	c	9.14	615.70	sd	0.2
396	SE	3	57	7	613.26	18.90	a	6.40	606.86	sd	0.2
397	SE	4	57	7	594.36	29.87	c	3.05	591.31	cl	2.3
398	SW	4	57	7	601.98	21.03	c	4.15	597.71	sd	0.5
399	SE	5	57	7	620.88	41.45	c	13.72	607.16	ss	0.7
400	SE	9	57	7	636.12	12.80	b	3.05	633.07	cl	0.1
401	NE	12	57	7	647.70	39.32	b	7.83	639.78	ss	1.9
402	NE	16	57	7	662.94	31.09	c	12.80	650.14	sd/gr	3.8
403	NW	20	57	7	640.08	22.56	a	9.14	630.94	sd	0.8
404	NW	23	57	7	678.18	33.53	c	21.95	656.23	sd/gr	0.5
405	SE	24	57	7	662.94	62.79	b	17.83	644.96	sh	0.8
406	SW	24	57	7	662.94	23.47	c	14.33	648.61	sd	0.7
407	NE	26	57	7	674.22	43.28	c	22.25	651.97	gr	0.6
408	SW	32	57	7	681.84	11.89	b	6.71	675.13	sd	1.5
409	NW	32	57	7	685.80	27.43	c	18.90	666.90	tl	0.4
410	NW	2	58	3	640.08	13.56	b	1.52	638.56	cl	0.2
411	SW	2	58	3	640.08	9.45	a	4.57	635.51	cl	1.5
412	SW	10	58	5	640.08	7.01	b	2.74	637.34	sd	0.7
413	SW	7	58	6	586.74	29.26	c	9.42	577.29	sd/gr	0.7
414	SW	3	58	7	685.80	29.87	c	9.14	676.66	cl	

APPENDIX 2

List of field observations in the Lindbergh area

NO.	Location	Elev.(m)	Type of feature and characteristics
1	SE-26-53-7	613.26	willow ring- open water- local depression
2	SE-26-53-7	613.26	willow rings-open water-soft ground- relatively flat
3	SE-26-53-7	609.60	slough- vegetation zone- local depression
4	NE-26-53-7	617.22	moist depression-marsh type grasses- some water
5	SE-26-53-7	613.26	willows and poplars along fenceline
6	NE-26-53-7	605.64	salt precipitates- on edge of wood- salty taste-damp soil
7	NE-26-53-7	601.98	salt precipitates- vegetation zoning-hummocky damp ground-slough- broad depression
8	SE-26-53-7	613.26	willow ring- open water in centre- local depression
9	SE-26-53-7	617.22	small slough- local depression- rushes and sedges- surrounded by cultivated fields
10	SE-26-53-7	617.22	willow ring- open water- sedges &rushes
11	SW-26-53-7	598.02	large depression around creek-mois but solid ground-creek marshy-salt precip.-foxtails
12	SW-26-53-7	609.60	higher ground -dry-
13	SE-27-53-7	600.46	salt precipitates-on edge of slough- bottom of hill
14	SE-34-53-7	594.36	slough- local depression- marshy on edges
15	NW-35-53-7	599.54	salt precipitates-flat area below hill-north side of stream
16	SW-2-53-7	599.54	salt precipitates-small depression-foxtail barley & gumweed
17	SW-27-54-7	620.88	moist depression-sorrunded by marsh grasses
18	SE-33-54-7	601.98	salt precipitates-small depression in field
19	SE-33-54-7	594.36	salt precipitates- in road allowance beside stream- at bottom of hill
20	SE-3-54-7	598.02	salt precipitates-large rim around slough-prolific foxtail, gumweed &red samphire
21	SW-3-54-7	605.64	salt precipitates- small patch near slough- woody area
22	NW-3-54-7	609.60	salt precipitates- 2 small patches near slough
23	SE-2-54-7	605.64	damp soil- small depression- circular- no vegetation
24	NE-35-53-7	601.98	salt precipitates- at bottom of hill in field
25	SE-2-54-7	601.98	saltprecipitates- in trench-near stream- phreatophytes and halophytes
26	SE-3-54-7	601.98	salt precipitates- small patch in local depression
27	SE-3-54-7	605.64	willow ring- local depression-open water- cattails , rushes & sedges on edges
28	NE-3-54-7	605.64	salt precipitates-beside very swampy lower ground
29	SE-10-54-7	613.26	salt precipitates- linear trend in broad depression-vegetation zoning -halophytes-slough
29b	SW-11-54-7	613.26	salt precipitates- at bottom of hill near slough
30	NW-11-54-7	628.50	large slough- vegetation zoning-
31	SW-14-54-7	640.08	willow ring- open water

NO.	Location	Elev.(m)	Type of feature and characteristics
32	NW-14-54-7	643.74	slough- surrounded by cattails & willows- local depression
33	NW-14-54-7	643.74	willow ring- water- local depression
34	SW-24-54-7	640.08	outcrop of surficial sand (outwash?)
35	NW-24-54-7	647.70	outcrop- sandstone- possibly thrusted into surficial material
36	NE-26-54-7	643.74	slough- local depression-cattails and sedges
37	NE-26-54-7	640.08	lake-slight depression- some cattails
38	NE-27-54-7	643.74	moist depressions- in cultivated field- circular shape
39	SE-27-54-7	643.74	slough- minor depression- surrounded by grasses
40	SE-27-54-7	640.08	willow ring- in cultivated field- high water level- sedges and rushes
41	NE-22-54-7	643.74	slough- cattail ring- local depression
42	NW-15-54-7	620.88	sloughs- lush vegetation of sedges & cattails. possible discharge for immediate hills
43	NW-22-54-7	636.12	sloughs- ring of cattails and willows- local depression
44	NW-22-54-7	640.08	sand exposure in outcrop. patches of bedrock sst throughout
45	NE-22-54-7	640.08	marsh- open water in centre- mostly cattails & sedges
46	SE-28-53-7	620.88	willow ring- local depression- open water in centre- mushy soft ground- no cattails
47	SW-28-54-7	613.26	hummocky ground- at source of stream near road
48	SE-32-54-7	601.98	lake- cattails at each end- steep slopes otherwise
49	NE-32-53-7	594.36	marshy ground- at edge of lake- ring of cattails
50	NW-4-54-7	594.36	salt precipitates- phreatophytes & halophytes - adjacent to slough
51	NW-9-54-7	605.64	sloughs- lush ring of cattails
52	NW-3-54-7	605.64	slough- ring of cattails
53	NE-33-53-7	594.36	stream- phratophytes- low topography- damp ground (partly due to rain)
54	SW-5-54-7	624.84	slough- sedges and rushes- some cattails
55	SW-5-54-7	624.84	seepage- where stream originates- marshy ground- equisitum
56	NW-32-53-7	628.50	damp soil- circular shape - small depression- in field
57	NW-29-53-7	624.84	slough- very marshy- many sedges and rushes- local depression
58	SE-30-53-7	620.88	slough- local depression- ring of cattails and sedges- wooded hill adjacent
59	NW-30-53-7	621.79	dugout- water within 2-3 feet of surface
60	NW-31-53-7	621.79	willow ring- open water in centre- cattails and sedges
61	SW-6-54-7	621.79	willow ring- many cattails grow in it
62	NW-6-54-7	621.79	willow ring- huge ring of cattails- open water in centre
63	NW-9-54-7	605.64	salt precipitates- scarce vegetation- mostly foxtail barley

NO.	Location	Elev.(m)	Type of feature and characteristics
64	SW-16-54-7	605.64	salt precipitates- on edge of strem- stream marshy (phreatophytes)
65	NW-16-54-7	617.22	salt precipitates- salinization not as intense as other spots- adjacent to marshy ground
66	SE-20-54-7	613.26	damp soil- circular- small- some sedges
67	SW-28-54-7	621.79	willow ring- open water- marsh grasses
68	SE-29-54-7	620.88	stream -marshy
69	NW-19-54-7	586.74	stream- local low- marshy ground- many phreatophytes
70	SW-19-54-7	594.36	marsh- in wooded area
71		0.00	
72a	SW-16-54-7	605.64	soaphole- flat type- bubbling mud- ice core- salt precip. & halophytes in vicinity
72b	NE-17-54-7	613.26	2 springs along perennial creek (reported by farmer)
73	NW-20-53-7	624.84	salt precipitates- thick crust - white color
74	SE-15-54-7	647.70	thrust bedrock in surficial outcrop
218	NW-34-54-7	605.64	vegetation zoning around slough - phreatophyte and halophyte rings
219	NW-34-54-7	594.36	halophytes on each side of crek (foxtail barley and gumweed)
75	SW-18-55-6	630.02	willow ring-phreatophytes in centre- open water- local depression- no cattails
76	SW-18-55-6	647.70	topographic high- wild roses and clover
77	S-18-55-6	630.02	moist depression- large slough with wide ring of cattails
78	se-18-55-6	632.46	willows and poplars along road- damp soil
79	SW-17-55-6	630.02	sand exposure in pit- dry- foxtail barley and brown eyed susans
80	SW-17-55-6	630.02	willow ring- local depression- water in centre- cattail ring
81	SE-17-55-6	630.02	willow ring- open water- cattail ring- willows and poplars
82	SE-17-55-6	636.12	willow ring- phreatophyte cover- no water- dugout at north end
83	SW-14-55-6	651.[illegible]6	branch of Irish creek- thick vegetation (dense)
84	SE-14-55-6	640.08	main branch of Irish creek- dense vegetation
85	SW-18-55-5	640.08	small patch in field covered with marsh grasses- dry depression?
86	NE-7-55-5	636.12	moist depression- large slough- water but many phreatophytes
87	SW-5-55-5	630.94	dugout- water level 1-1.5 ft below land surface- near willow ring
88	SE-6-55-5	627.89	dugout- water level within 2 ft of land surface- not much topographic relief
89	SE-6-55-5	621.79	marsh- some standing water- ground very wet- phreatophytes- some willows
90	SE-6-55-5	627.89	moist depression- in small depression on hill
91	SW-6-55-5	636.12	slough- open water in centre- marsh grasses in ring- local depression
92	SW-6-55-5	632.46	marsh along branch of creek- phreatophytes- poplars and willows

NO.	Location	Elev.(m)	Type of feature and characteristics
93	NE-1-55-6	628.50	marsh along creek- many cattails , willows and poplars
94	NW-12-55-6	628.50	marsh along creek- valley floor marshy- slopes dry- polars and willows along sides
95	NE-11-55-6	628.50	flooded creek
96	SE-12-55-6	643.74	creek- valley floor marshy but no flowing water- ground wet
97	NW-12-55-6	655.32	topographic high from which phreatophyte zone can be observed around lake
98	SE-3-55-6	651.36	vegetation zoning around lake
99	SW-3-55-6	655.32	sand exposure (sandy soil) on edge of field
100	NW-3-55-6	628.50	willow ring-little open water- phreatophyte cover- topographic low
101	NE-4-55-6	643.74	willow ring- local depression- phreatophyte cover- little water
102	NE-9-55-6	649.22	slough- phreatophyte cover (sedges & rushes)- local depression
103	NE-9-55-6	651.36	linear depression- brownish vegetation- between hummocks
104	NW-8-55-6	628.50	willow ring- marsh grasses and cattails in centre- some water- local depression
105	SE-7-55-6	636.12	slough- covered with marsh grasses- very little water- young willows
106	NE-4-55-6	620.88	slough- cattail ring- local depression
107	SE-6-55-6	636.12	slough- open water- cattail ring- willows and poplars- local depression
108	SW-5-55-6	636.12	willow ring- open water- ring of cattails- topographic low
109	4-6-55-6	636.12	marsh- large marshy area- surroundings wooded- local depression- adjacent to slough
110	NW-31-54-6	643.74	salt precipitates- at bottom of hill- cracked soil- rusty surface- scarce vegetation
111	NW-31-54-6	640.08	salt precipitates- at bottom of hill- cracked soil- vegetation scarce- linear depression
112	SE-6-55-6	636.12	salt precipitates- at botton of hummock- cracked soil- vegetation scarce
113	NE-31-54-6	636.12	salt precipitates- at bottom of hill- also sandy patches in field
114	NE-31-54-6	643.74	dry slough at top of hill- gully to bottom of hill- numerous seepages and damp soil
115	SE-6-55-6	636.12	linear depression- clover and other grasses
116	SE-6-55-6	640.08	salt precipitates in local pepression adjacent to linear depression and clump of trees
117	NE-31-54-6	643.74	salt precipitates- soil cracked- sandy patches- in low between two hummocks
118	NE-31-54-6	643.74	bare soil at bottom of hill- cracked- possible salt precipitates washed off
119	SE-31-54-6	643.74	slough- wide cattail ring- phreatophytes- surrounded by hills
120	NE-32-54-6	640.08	large willow ring on each side of road- thick cattail ring- open water
121	NE-32-54-6	643.74	slough in local depression- marsh grasses and cattails- open water
122	NE-32-54-6	643.74	dry slough- covered with phreatophytes, foxtail barley- local depression
123	NW-33-54-6	643.74	linear depression- brownish vegetation
124	SW-4-55-6	636.12	willow ring- marsh grasses and cattails- some water

NO.	Location	Elev.(m)	Type of feature and characteristics
125	NW-33-54-6	640.08	dry slough- phreatophyte cover- linked to linear depression- salt precip. on edges
126	NW-33-54-6	640.08	slough covered with phreatophytessolid ground- some water-salt precip. adjacent
127	NE-33-54-6	643.13	dry slough covered with phreatophytes- sama characteristics as previous
128	NE-33-54-6	643.74	dry slough covered with phreatophytes
129	NE-33-54-6	643.74	marsh- phreatophytes- adjacent to woods- local depression
130	NW-34-54-6	640.08	dry slough- covered with phreatophytes- local depression (between hummocks)
131	SE-33-54-6	649.22	willow ring- open water- cattial and phreatophyte rings- cow parsnip- local low
132	SW-34-54-6	655.32	slough- open water- marsh grasses
133	SE-27-54-6	643.74	willow ring- covered with sedges and rushes- local low
134	SE-27-54-6	647.70	willow ring- high water level- no grasses
135	SW-26-54-6	643.74	willow ring- local depression- no cattails- high water level- ring of marsh grasses
136	NW-25-54-6	628.50	flat area beside slough- halophyte growth
137	NW-25-54-6	628.50	dry depression- halophytes?
138	NW-36-54-6	630.94	higher elevation - no features
139	NW-25-54-6	630.02	dry slough - phreatophytes and halophytes- small local depression
140	SW-36-54-6	640.08	salt precipitates- scarce vegetation
141	NE-25-54-6	643.74	dry slough- phreatohytes- local depression
142	NE-25-54-6	636.12	willow ring- cattail ring- high water level
143	NE-19-54-5	632.46	marshy ground at bottom of hill
144	SE-30-54-5	620.88	linear depression- covered with grasses- very wet- salt precipitates at bottom
145	NE-30-54-5	624.84	willow rings- open water- marsh grasses- local depression
146	NW-9-53-4	636.12	linear depression leading to dugout- dugout spring fed:concave cavity, slumping, very wet
147	NW-9-53-4	647.70	gumbo? scarce vegetation- clayey soil (black)-gound water saturated- local depression
148	SW-9-53-4	658.98	willow ring- open water- marsh grasses on edge
149	NW-4-53-4	643.74	dugout- water level 5 ft from surface- linear depression leads to it- lowest elev. in field
150	SW-4-53-4	630.02	dugout at bottom of hill- slope of hill dry, with wolfwillow, wild roses, etc.
151	SW-4-53-4	632.46	linear depressions, between hummocks in field
152	NE-33-52-4	617.22	bouldery slope with wolfwillow, wild roses, prairie sage, common yarrow, etc.
153	SE-4-53-4	630.02	marsh- willows and grasses- open water- adjacent to hill
154	SW-3-53-4	630.94	a dry sloughs in cultivated field- phreatophytes but no water- area generally flat
155	SW-3-53-4	632.46	willow ring- grass covered- wolfwillow in centre- some water at north end
156	NE-4-53-4	632.46	linear depression- leads to dry slough in field- vegetation cover

NO.	Location	Elev.(m)	Type of feature and characteristics
157	NE-53-4	632.46	damp soil- circular shape- in field
158	SW-9-53-4	617.22	salt precipitates- lowest elevation in field- mudcracks- no vegetation- wet soil
159	NW-10-53-4	609.60	willow ring- high water level
160	SW-15-53-4	601.98	bare soil: mudcracks, no growth, flat area. Possibly washed out salt precipitates
161	NE-10-53-4	600.46	Dugout- water level within 3 ft of surface- cattails on side- marsh grasses
162	NW-11-53-4	600.46	2 dry sloughs in field. covered with grasses
163	SW-10-53-4	600.46	willow ring- lush vegetation
164	NE-35-52-4	600.46	slough- <1 foot of water- marshy all around
165	SE-2-53-4	600.46	faint patches of salt precipitates (greyish tinge on soil surface)
166	SW-1-53-4	600.46	salt precipitates - linear patch in trench-like depression
167	SE-2-53-4	600.46	patch in field with retarded growth- mudcracks- rust stains- greyish tinge to soil
168	SE-2-53-4	598.93	moist depression- wet, semi-circular patch in field- water saturated- mudcracks
169	NE-2-53-4	598.93	slough- vegetation zoning of phreatophytes and halophytes
170	SE-11-53-4	598.93	willow ring- elongated in shape- open water
171	NE-11-53-4	598.93	large willow ring- many willows and poplars- open water
172	NE-11-53-4	600.46	slough with young willows on edges- grass covered
173	NW-11-53-4	600.46	large willow ring- dry - many willows and poplars
174	NW-12-53-4	598.93	dugout- water level 0.5 ft below land surface- some cattails on edges
175	NE-12-53-4	597.41	thickets of willows and halophytic vegetation:foxtail barley, cow parnip, rushes, sedges,etc
176	NE-12-53-4	597.41	moist depressions in field-circular- young grasses- salt precipitation
177	NW-6-53-3	595.88	light salt precipitation on edge of field (soil surface greyish)
178	SE-1-53-4	595.88	willow ring- open water
179	NW-36-52-4	600.46	salt precipitates (encrusted) in ditches
180	NE-35-52-4	600.46	large slough- marsh grasses, cow parnip. a lot of water
181	NW-36-52-4	600.46	dugout in marshy area- marshy area leads to slough
182	NW-36-52-4	601.98	halophytic vegetation on side of slough- not cultivated
183	SW-36-52-4	609.60	willow ring
184	SE-35-53-4	613.26	bare patch in field: mudcracks, damp soil under crust, chamomille on edges
185	SW-30-52-3	605.64	linear depression in field- graas covered
186	NW-30-52-3	597.41	willow ring- high water level, sedges and rushes throughout
187	NE-25-52-4	597.41	willow ring- covered with marsh grasses- solid ground- no water
188	SW-31-52-3	586.74	springs along bank of Vermilion River valley- in coulees- 13 on property

NO.	Location	Elev.(m)	Type of feature and characteristics
189	SW-31-52-3	559.92	springs: rusty, 3-5 litre/min- area marshy- willow ring with quickground
190	NE-24-52-4	613.26	linear depression- covered with tall grasses
191	NW-24-52-4	630.02	large moist depression- semi-circular, standing water in centre- equisitum
192	SW-14-52-4	571.50	observed Vermilion river valley from here
193	NE-11-52-4	594.36	new springs:gullies, iron stains, salt precip., seepages- <1 l/min- discharge from sand
194	SW-11-52-4	609.60	salt precipitates in canola field- damp soil, cracked- adjacent to willow ring w/ phreato.
195	NE-3-52-4	609.60	large slough- cattail ring- suurounded by hills
196	SE-15-52-4	571.50	salt precipitates, phreatophytes & halophytes in river valley floor, near river
197	SE-21-52-4	632.46	dugout- spring fed: rushes, foxtail barley, equisitum, sedges, etc. - marshy, wooded
198	SE-16-52-4	571.50	springs along creek- don't freeze in winter- dammed by beavers
199	NW-15-52-4	586.74	spring in coulee:< 1l/min- trees, phreatophytes, culvert (w.l. 2-3 ft belo w surface)
200	NW-27-52-4	624.84	spring- beside stream- marshy- concave depression (< 1 l/min)- foxtail barley
201	SW-34-52-4	613.26	dugout- water level 3-4 ft below land surface
202	NE-33-52-4	630.02	salt precipitates in corner of field- no vegetation
203	NE-32-52-4	624.84	cutbank in road- no springs or seepages
204	SE-32-52-4	617.22	large slough- vegetation zoning of phreatophytes & halophytes- solid , wet ground-water
205	SW-33-52-4	624.84	prolific growth of foxtail barley- patch of willows- very hummocky ground
206	SW-33-52-4	624.84	small slough- 1 ft of water- rushes, sedges and cow parsnip-foxtail barley on side
207	NW-28-52-4	613.26	small slough- nearly dry- many sedges- some cow parsnip and willows
208	SW-28-52-4	620.88	slough- sedges on edges- low flat area- surrounded by hills- foxtail barley
209	SW-28-52-4	594.36	creek- marshy- foxtail barley- salt precipitation- no springs
210	NW-21-52-4	613.26	solid ground- no water:sedges, rushes, willows & poplars- some cow parsnip
211	SW-28-52-4	601.98	linear depression (wooded) leading to slough- no spring observed
212	NE-20-52-4	609.60	large sloug- open water- large ring of phreatophytes
213	NW-9-52-4	617.22	dry willow ring- same characteristics as stop 210
214	NE-9-52-4	609.60	small slough- flooding due to new road

APPENDIX 3

Details of piezometer installations

Piezometer site SW-4-54-7W4

TH-299

Piezometer No. 300

Depth 5.8 m

pipe length 6.44 m

stickup 0.64 m

screen length 0.56 m

pipe width 0.05 m

Piezometer No.301

Depth 3.41 m

pipe length 4.13 m

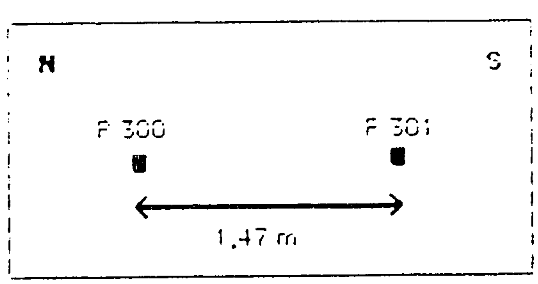
stickup 0.72 m

slotted interval 1.45 m

pipe width 0.05 m

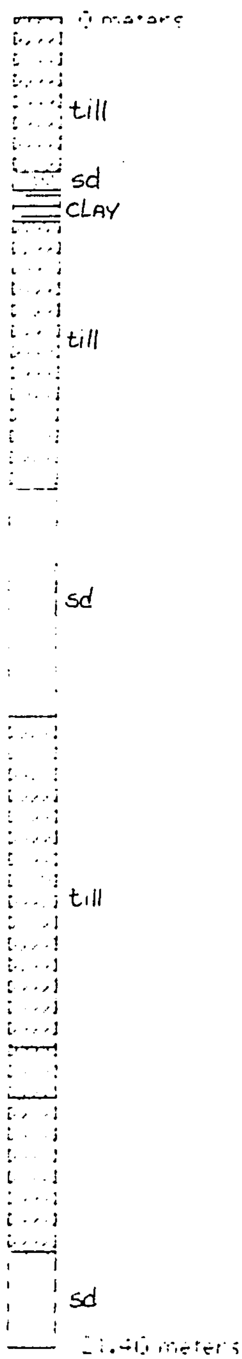
Distance between piezometers 0.47 m

Piezometer site SW-4-54-7W4



Piezometer site 9-26-54-7W4

P 302



Piezometer No 302

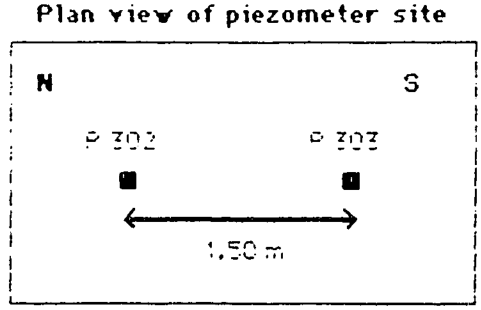
Depth 21.40 m
pipe length 21.55 m
stickup 0.74 m
screen length 0.59 m
pipe width 0.05 m

Piezometer No 303

Depth 16.48 m
pipe length 16.71 m
stickup 0.78 m
screen length 0.55 m
pipe width 0.05 m

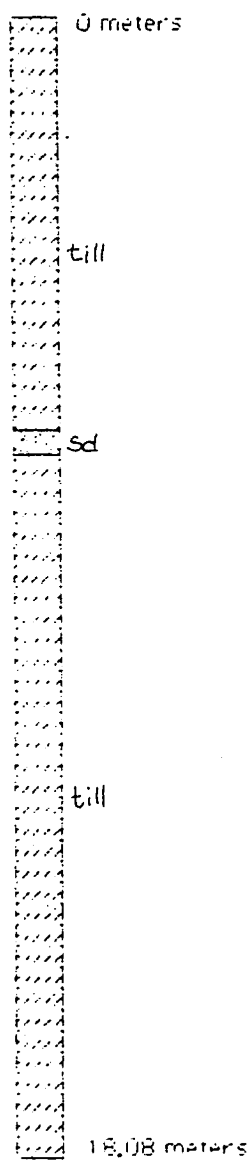
Distance between piezometers 1.50 m

Plan view of piezometer site



Piezometer site 13-9-55-6W4

P 304



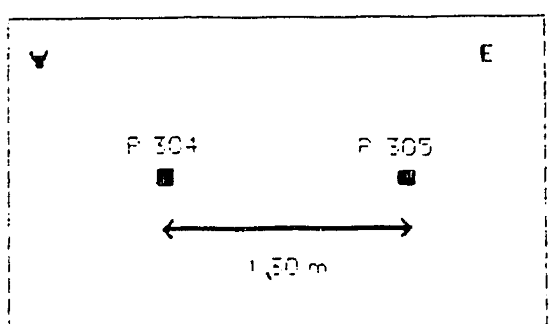
Piezometer No 304

Depth: 18.08 m
pipe length: 18.19 m
stickup: 0.66 m
screen length: 0.55 m
pipe width: 0.05m

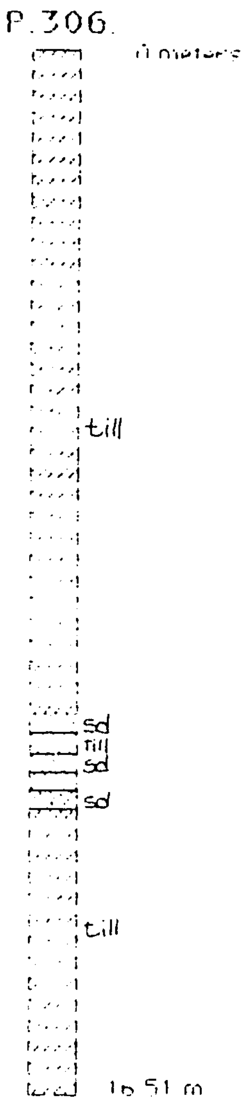
Piezometer No 305

Depth: 10.60 m
pipe length: 10.66 m
stickup: 0.62 m
screen length: 0.56 m
pipe width: 0.05m

Plan View of piezometer site



Piezometer site 1-4-55-6W4

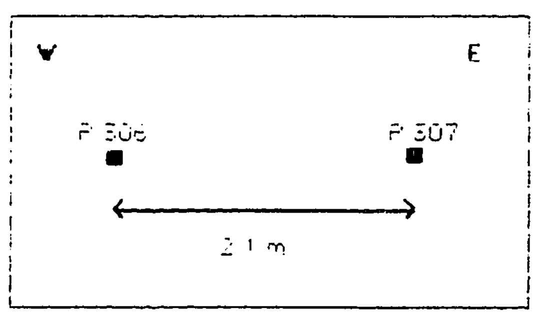


Piezometer No.306

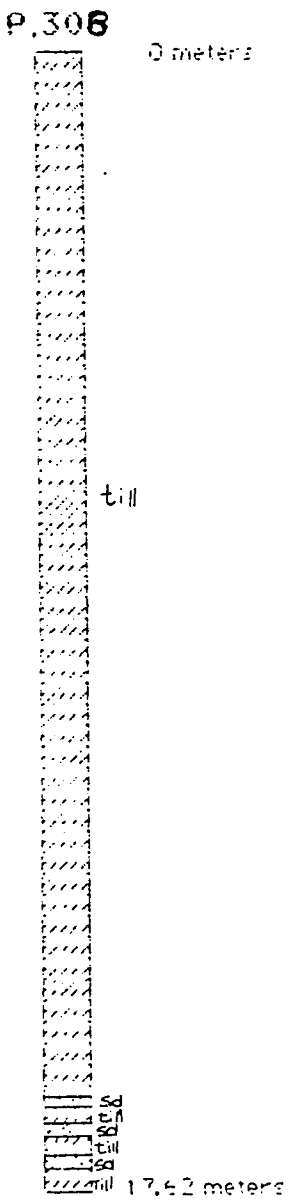
Depth 16.51 m
pipe length 16.70 m
stickup 0.73 m
screen length 0.54 m
pipe width 0.05 m

Piezometer No. 307

Depth 11.44 m
pipe length 12.07 m
stickup 0.68 m
screen length 0.55 m



Piezometer site 1-4-53-4W4



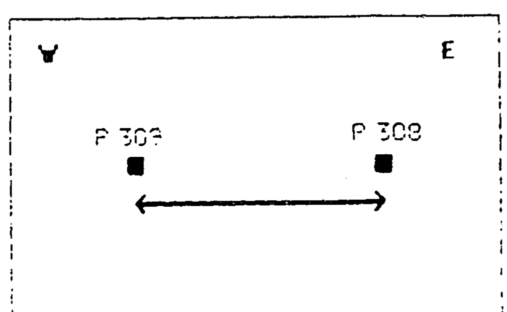
Piezometer No.308

Depth 17.62 m
pipe length 17.82 m
stickup 0.77 m
screen length 0.57 m
pipe width 0.05 m

Piezometer No. 309

Depth 8.74 m
pipe length 9.36 m
stickup 0.62 m
screen length 0.54 m
pipe width 0.05 m

Plan view of piezometer site



APPENDIX 4

Summary of chemical analyses results

Part 1- results for water samples submitted for chemical analysis (mg/l)

Part 2- results for water analyses obtained from Alberta Environment (mg/l)

Part 3- summary of major ion ratios (as percentage of total cations and total anions)

PART 1

No.	LSD	SEC	TWP	Rg.	Depth	Ca	Mg	Na	K	HCO3	CO3	SO4	Cl	Fe	F	TDS	pH	ALK.t.	Hard.t.
S-3	SW	32	53	7	16.8	39	21	315	4	611	0	374	3	0.03	0.13	1060	8.3	501	185
S-4	SE	36	53	8	7.3	187	80	182	15	647	-	629	5	0.04	0.16	1430	7.9	530	795
S-10	NE	17	54	7	19.9	8	4	455	3	654	4	446	22	0.05	0.23	1270	8.4	542	35
S-11	NW	27	54	7	11.2	77	35	37	5	390	-	94	0.9	0.07	0.16	447	8.1	320	335
S-20a	NW	32	54	5	12.5	248	88	21	4	582	-	77	105	0.03	0.22	1200	7.8	478	980
S-20b	NW	32	54	5	50.3	142	54	110	4	595	-	341	9	0	0	954	8.1	488	575
S-25	NE	2	55	6	14.1	492	297	306	9	586	-	2040	194	0.05	0.48	3970	7.7	480	2450
S-30	NW	10	55	6	24	153	95	71	4	686	-	326	16	0.02	0.48	1030	7.9	562	775
S-35	SE	5	55	6		72	34	253	4	694	-	245	50	0.45	0.27	1000	8.1	568	320
S-36	SE	5	55	6	12.2	85	27	7	3	345	-	22	8	0.16	0.19	351	7.2	283	323
S-42	NE	12	55	6	30.5	300	115	228	9	797	-	960	40	0.87	0.19	2050	7.9	653	1220
S-45	SE	2	53	4	28.8	129	40	115	3	758	-	17	64	0.35	0.11	741	7.9	622	485
S-47	SE	24	52	4	18.8	220	92	41	17	454	-	168	61	0.03	0.17	1371	7.5	372	928
S-51	NW	4	52	4	30.5	80	114	87	5	312	-	624	4	2.08	<0.1	1072	8.1	356	670
S-53	SW	31	52	3	26.7	112	49	101	4	838	-	10	6	1.12	0.15	708	7.9	687	480
2410E	SW	28	53	4	13	58	21	23	4	305	5	22	0.9	0.04	0.24	283	8.3	258	230
2408E	NW	7	55	6	27.5	101	44	145	5	549	-	269	7	1.18	0.22	845	8	450	433

PART 2

No.	Lsd	Sec	Twp	Rg	TDS	Ca	Mg	Na	K	HCO3	CO3	SO4	Cl
1	SE	1	52	3	698	2	2	272	0.7	539	0	118	38
2	NE	3	52	3	1181	52	20	364	3.9	664	0	392	22
3	SE	6	52	3	1232	168	53	193	6.6	636	0	440	60
4	NE	14	52	3	1046	3	1.3	402	1	716	0	228	20
5	NW	19	52	3	1037	46	37	290	4	555	0	229	152
6	NW	19	52	3	1235	88	37	315	4.4	725	0	276	158
7	NE	21	52	3	566	52	26	141	2.3	631	0	10	21
8	NE	22	52	3	1255	213	72	133	5.5	765	0	386	64
9	NE	23	52	3	1230	10	1	446	1.6	826	7	354	2
10	NW	24	52	3	1250	79	29	310	5	614	0	500	24
11	SE	26	52	3	840	50	21	162	4.6	456	0	142	3
12	SE	30	52	3	913	1	1	357	1.5	710	20	158	25
13	NW	.32	52	3	685	143	46	34	5.5	581	0	145	4
14	SE	35	52	3	774	158	48	27	3.8	374	13	330	9
15	16	10	52	4	949	100	55	145	4.6	541	0	351	15
16	SW	15	52	4	441	63	26	61	3.4	334	0	80	15
17	SW	16	52	4	1432	250	105	58	7.1	630	0	700	2
18	SE	1	52	5	890	139	47	128	6.5	648	0	94	152
19	SE	6	52	5	664	25	49	165	3.7	642	0	85	9
20	NW	7	52	5	743	145	69	32	4	582	0	141	23
21	SW	8	52	5	467	78	41	35	16.8	454	0	50	22
22	NW	15	52	5	743	56	59	161	4.1	691	0	89	28
23	NE	19	52	5	700	3	1	270	0.5	571	0	143	2
24	SW	22	52	5	1221	174	67	180	4.2	764	0	388	32
25	NE	25	52	5	1018	4	1	395	1.5	689	16	134	128
26	SW	32	52	5	845	149	58	65	4.9	593	0	275	1
27	E	34	52	5	830	53	29	212	4	614	0	220	6
28	NE	2	52	6	847	45	27	243	5.1	551	5	225	30
29	NE	7	52	6	2021	51	32	630	6	819	0	854	38
30	NW	8	52	6	1180	1	1	435	2.1	788	0	350	3
31	NE	19	52	6	1831	15	8	654	3.2	1030	0	635	5
32	NE	19	52	6	1731	13	4	620	2.8	921	33	600	5
33	SE	21	52	6	2037	323	124	152	5.3	703	0	1080	5
34	SE	34	52	6	1101	1	1	410	1.7	754	0	313	3
35	SE	2	52	7	861	70	33	195	5.5	621	0	250	2
36	SW	4	52	7	905	19	2	323	2.5	582	18	245	6
37	SE	16	52	7	374	65	30	44	3.7	437	0	10	6
38	SE	16	52	7	368	14	1	139	1.9	384	0	21	1
39	NW	17	52	7	395	38	37	61	4.3	407	0	49	1
40	SW	22	52	7	650	105	25	100	4.8	521	0	148	6
41	SE	25	52	7	1385	13	7	491	2.9	749	7	491	5
42	NW	30	52	7	591	107	63	27	1.4	682	0	30	7
43	NW	34	52	7	805	3	1	310	2	547	27	190	3
44	NW	34	52	7	1115	178	76	83	7.6	445	0	462	28
45	SW	4	53	3	250	52	20	10	4.2	254	7	19	2
46	NE	6	53	3	1416	74	32	379	6.8	625	0	581	36
47	NW	14	53	3	5947	335	340	1040	19.2	679	0	3600	51
48	SE	24	53	3	511	120	34	35	2.4	594	0	26	1

No.	Lsd	Sec	Twp	Rg	TDS	Ca	Mg	Na	K	HCO3	CO3	SO4	Cl
49	NE	24	53	3	328	59	26	23	2.6	289	7	57	2
50	NW	8	53	4	1657	209	93	230	7.4	761	0	716	25
51	NE	10	53	4	2607	364	192	191	6.9	604	0	1512	40
52	NW	15	53	4	640	89	33	118	3	757	0	10	14
53	NE	19	53	4	2217	40	21	788	4.5	343	0	11	1184
54	NE	21	53	4	1628	2	1	583	1.6	619	0	712	23
55	SW	26	53	4	692	17	20	237	4	599	32	46	41
56	SW	27	53	4	1019	68	50	225	5.1	602	0	359	5
57	NW	30	54	4	1899	220	140	154	9.4	462	0	1141	5
58	SE	33	53	4	625	101	39	76	3.6	525	13	123	12
59	SE	33	53	4	600	132	40	30	5.3	536	0	120	6
60	SE	3	53	5	1119	121	45	245	4.2	911	0	250	7
61	NE	7	53	5	811	19	8	292	2.8	636	0	140	37
62	SW	8	53	5	859	3	2	327	1.2	627	0	206	12
63	S	9	53	5	339	56	21	50	3.1	370	0	25	1
64	SW	9	53	5	330	54	20	39	3.3	351	5	35	2
65	NE	10	53	5	904	64	31	221	5	542	0	300	16
66	NE	11	53	5	332	71	28	15	2.8	341	0	35	3
67	SW	16	53	5	614	106	42	64	5.7	539	0	130	1
68	SE	18	53	5	774	133	57	60	6.7	533	0	254	2
69	NE	25	53	5	567	60	28	110	3.5	451	0	120	22
70		27	53	5	1415	118	135	191	7.6	1078	0	410	23
71	SW	29	53	5	742	90	62	73	5.6	388	0	319	2
72	NW	5	53	6	1854	87	35	490	5.2	637	0	920	2
73	SE	6	53	6	800	45	1	249	1.7	431	0	257	30
74	SE	9	53	6	1364	220	79	117	6.7	486	0	678	16
75	16	16	53	6	1028	143	56	155	6.3	593	0	317	20
76	SE	19	53	6	690	78	59	85	3.7	585	0	110	14
77	SW	20	53	6	360	66	23	33	4.4	255	0	102	3
78													
79	SE	26	53	6	970	309	25	12	8.6	756	0	107	131
80	SE	26	53	6	926	223	75	20	12	861	0	51	117
81	SE	30	53	6	983	163	61	104	5.3	634	0	331	7
82	SE	33	53	6	1363	249	109	41	6.6	606	0	602	17
83	NE	34	53	6	774	122	47	96	4.3	610	0	200	3
84	SE	1	53	7	714	55	33	147	4.6	437	0	232	1
85	SW	3	53	7	749	39	16	223	4.1	529	12	188	5
86	SW	12	53	7	1216	130	52	135	5.3	649	0	216	34
87	NE	25	53	7	1074	133	71	158	6.8	628	0	385	7
88	SE	27	53	7	514	65	31	87	6.1	443	0	107	1
89	SW	34	53	7	972	45	19	292	4.4	609	0	298	9
90	SE	2	54	3	569	89	35	75	4.7	526	0	90	16
91	NW	6	54	3	468	91	49	8	2.3	382	0	85	32
92	NW	11	54	3	1039	230	59	31	6.1	470	0	475	6
93	NE	14	54	3	1163	137	118	129	4.3	910	0	225	57
94	SE	17	54	3	419	76	45	13	4.1	323	0	106	3
95	SW	17	54	3	851	154	63	46	12.7	647	0	88	44
96	SW	18	54	3	930	153	59	100	5.2	658	0	284	6

No.	Lsd	Sec	Twp	Rg	TDS	Ca	Mg	Na	K	HCO3	CO3	SO4	Cl
97	NE	19	54	3	547	85	34	66	4.1	494	0	70	19
98	NW	20	54	3	869	80	50	149	5.6	466	0	291	15
99	SW	21	54	3	316	77	26	9	2.8	349	0	26	3
100	NW	29	54	3	360	81	34	9	3.4	424	0	15	1
101	NE	31	54	3	417	65	31	28	30	408	0	51	10
102	SW	34	54	3	258	62	21	6	2.8	280	0	9	5
103	SW	2	54	4	1539	168	47	300	4.8	615	0	680	31
104	SW	2	54	4	1188	1	5	427	7.4	590	0	428	23
105	NW	7	54	4	427	80	30	34	22	495	0	13	6
106	SE	19	54	4	682	116	38	85	3.8	586	0	144	7
107	SW	27	54	4	712	2	1	277	0.6	505	0	179	4
108	NE	32	54	4	756	76	37	142	3.5	559	0	207	14
109	SW	6	54	5	1433	136	150	107	9.1	591	0	735	4
110	SW	6	54	5	1299	180	103	126	8.8	919	0	426	3
111	NE	6	54	5	528	65	71	28	8	362	0	152	125
112	SE	7	54	5	1870	359	160	96	5.8	599	0	4	849
113	SE	7	54	5	1826	312	175	108	6.3	581	0	40	855
114	NE	12	54	5	684	359	160	96	5.8	599	0	40	849
115	16	31	54	5	6903	117	40	135	4.8	486	0	348	6
116	SW	11	54	[illegible]	1471	240	165	85	9.6	1353	0	141	122
117	NE	20	54	[illegible]	769	144	62.4	7.5	512	0	210	28	
118	NE	21	54	6	1444	108	200	107	5.4	871	0	250	80
119	SW	22	54	6	1021	145	88	106	9.8	927	0	209	6
120	NW	25	54	6	2534	462	109	178	9.6	540	0	1490	6
121	SE	27	54	6	542	71	58	3.2	564	11	38	11	
122	SE	27	54	6	1379	205	110	96	4.5	681	0	450	41
123	NE	31	54	6	1122	128	75	122	4.8	423	0	576	7
124	NE	9	54	7	1139	6	2	447	2.6	753	19	270	22
125	NE	9	54	7	974	23	8	330	2.1	553	0	296	37
126	NW	10	54	7	1041	30	2	368	1.9	696	6	277	8
127	SW	12	54	7	1938	159	93	336	17.1	566	0	1028	15
128	SW	15	54	7	1904	145	147	306	11.7	688	0	794	125
129	SW	15	54	7	5189	485	310	794	12	946	0	2700	252
130	NW	15	54	7	499	78	33	65	4.6	448	0	95	2
131	SE	16	54	7	1297	39	20	425	5.7	763	0	400	30
132	NE	16	54	7	1018	8	4	374	3.2	750	0	232	10
133	NE	17	54	7	1317	11	3	464	2.6	684	5	469	26
134	NW	20	54	7	865	148	62	68	6	545	0	280	1
135	SW	23	54	7	579	108	47	30	3.8	444	0	110	29
136	NW	32	54	7	497	59	20	109	4.5	541	0	38	1
137	NE	35	54	7	546	99	40	47	5.3	440	0	139	1
138	SE	7	55	3	836	132	55	73	4.7	548	0	293	7
139	NE	16	55	3	287	55	21	11	15.5	274	0	23	12
140	SW	5	55	4	769	1	1	300	2	547	0	185	11
141	SE	7	55	4	723	2	1	269	1.3	505	0	197	4
142	7	18	55	4	240	30	21.4	28	4.2	212	0	38.3	2
143	NW	22	55	4	846	115	85	75	6.7	661	0	138	78
144	NW	22	55	4	800	124	80	49	8.4	645	0	187	20

No.	Lsd	Sec	Twp	Rg	TDS	Ca	Mg	Na	K	HCO3	CO3	SO4	Cl
145	NE	24	55	4	428	87	35	18	2.7	455	0	44	3
146	NE	29	55	4	488	75	49	41	3.2	456	12	35	21
147	NE	11	55	5	2039	13	14	685	3.6	894	82	792	9
148	7	21	55	5	607	100	43	70	6.7	342	0	235	8
149	NW	34	55	5	203	42	11	11	4	167	0	25	6
150	SW	1	55	6	1096	24	20	352	3.6	630	5	222	162
151	NW	5	55	6	1024	165	52	133	4.1	665	0	338	3
152	SW	13	55	6	1178	215	85	64	4.9	602	0	490	17
153	NE	20	55	6	374	87	23	24	3	374	0	44	3
154	SW	21	55	6	2003	340	115	157	4.3	742	0	1010	7
155	SW	22	55	6	605	121	41	42	5.4	542	0	125	4
156	SW	25	55	6	400	110	24	14	2.5	485	0	10	1
157	NW	29	55	6	1739	87	35	485	5	839	0	650	64
158	NE	29	55	6	324	78	29	6	3.9	399	0	9	1
159	8	30	55	6	927	166	52	110	4.7	594	0	360	12
160	NW	30	55	6	1296	61	31	385	4.7	681	0	440	37
161	NE	32	55	6	633	96	59	47	4.3	491	0	168	4
162	NE	32	55	6	798	143	59	53	4	523	0	264	13
163	15	33	55	6	755	145	47	51	4.9	542	0	154	27
164	NW	2	55	7	481	2	1	185	1	441	0	70	2
165	SE	8	55	7	452	53	22	91	4.1	445	0	62	1
166	NE	14	55	7	1042	10	1	398	1.6	716	0	277	2
167	NW	19	55	7	721	139	75	26	14.2	704	0	86	29
168	SE	21	55	7	751	134	59	57	4.8	646	0	168	4
169	SW	31	55	7	2072	282	116	243	7.3	776	0	1025	11
170	SW	6	56	3	408	71	33	33	3.4	460	0	40	2
171	SE	4	56	4	1106	133	90	107	9	436	0	443	77
172	NW	9	56	4	177	37	10	15	0.2	206	0	8	2
173	SE	15	56	4	165	39	9	9	3.1	148	0	10	10
174	NE	15	56	4	1735	115	52	437	6.3	620	0	307	512
175	SW	22	56	4	399	75	36	28	3.2	443	0	30	9
176	NW	23	56	4	1526	52	37	473	6.3	728	0	394	204
177	SW	30	56	4	700	100	34	117	4.9	491	0	189	7
178	NE	4	56	5	1974	52	30	620	10.9	501	0	762	225
179	NW	10	56	5	3659	488	300	208	12.1	706	0	2300	3
180	NW	10	56	5	1874	45	21	630	4.1	643	0	457	400
181	NW	20	56	5	279	64	19	12	1.9	289	0	30	7
182	NE	36	56	5	2090	332	112	180	6.8	674	0	1119	5
183	SE	27	56	5	824	117	49	130	10	720	0	150	14
184	NE	29	56	5	461	36	13	125	3.5	445	0	57	7
185	SW	34	56	5	1245	245	68	80	6.8	418	0	395	245
186	NW	3	56	6	745	94	31	99	11.8	456	0	185	19
187	SW	5	56	6	797	181	57	30	4	628	0	213	3
188	SE	13	56	6	1303	106	48	262	4.7	503	0	590	45
189	NE	18	56	6	1730	85	34	510	4.7	828	0	825	64
190	SW	30	56	6	473	105	38	18	3.4	453	0	83	2
191	NE	36	56	6	473	79	42	29	9.6	411	0	29	65
192	NW	2	56	7	480	90	29	45	3	381	0	122	3

No.	Lsd	Sec	Twp	Rg	TDS	Ca	Mg	Na	K	HCO3	CO3	SO4	Cl
193	SW	5	56	7	632	125	56	31	4	599	0	77	7
194	SE	12	56	7	1516	69	52	396	5.7	638	0	596	84
195	NW	16	56	7	416	68	26	53	5.8	439	0	43	4
196	NE	20	56	7	307	67	24	15	4	357	0	20	1
197	SW	32	56	7	412	48	42	47	2.2	378	0	74	8
198	SW	6	57	4	1791	320	101	163	6.7	868	0	770	3
199	NE	19	57	4	360	80	36	7	7.1	423	0	10	6
200	NE	19	57	4	315	67	31	7	7.4	402	0	10	2
201	SW	3	57	5		45	9	8	1.7	210	0	7	3
202	NE	6	57	5	186	50	13	5	1	225	0	6	1
203	SE	19	57	5	551	119	53	17	9.5	561	0	38	13
204	NE	20	57	5	457	117	38	18	2.9	520	0	29	6
205	NW	23	57	5	466	103	45	8	3.4	492	0	8	31
206	NW	26	57	5	478	121	33	24	4.6	556	0	20	1
207	SE	27	57	5	401	61	54	11	4.8	519	0	10	1
208	NW	34	57	5	353	89	29	6	3.3	408	13	10	1
209	NE	5	57	6	1420	212	129	115	8.6	764	0	380	182
210	SE	9	57	6	1081	117	51	182	6	515	0	450	20
211	NW	18	57	6	336	81	29	11	4.7	391	0	12	4
212	SW	28	57	6	393	80	30	25	6	490	0	9	1
213	NW	30	57	6	423	39	44	62	4.4	466	0	39	1
214	NE	30	57	6	299	76	25	5	3	338	6	13	1
215	NW	2	57	7	315	53	26	13	4.5	176	0	123	7
216	SE	5	57	7	1292	11	2	450	2.1	522	0	526	37
217	NW	25	57	7	507	100	45	22	3.6	372	0	64	82
218	SE	24	57	7	364	58	26	47	3.6	417	0	23	1

PART 3

NO.	%Na	%Ca	%Mg	%Cl	%SO4	%HCO3	Type
1	97.82	0.82	1.36	8.67	19.87	71.46	4
2	78.98	12.86	8.15	3.16	41.50	55.34	3
3	40.20	39.35	20.46	7.95	43.05	48.99	1
4	98.56	0.84	0.60	3.31	27.85	68.84	4
5	70.43	12.71	16.85	23.62	26.27	50.11	3
6	65.01	20.66	14.32	20.18	26.02	53.80	3
7	56.68	23.75	19.57	0.53	1.96	97.51	2
8	26.37	47.29	26.35	8.07	35.91	56.02	1
9	97.10	2.49	0.41	0.27	34.77	64.97	4
10	68.27	19.77	11.96	3.20	49.22	47.58	3
11	62.92	21.91	15.17	0.80	28.12	71.08	4
12	99.16	0.32	0.52	4.33	20.18	75.49	4
13	12.92	56.91	30.17	0.89	23.86	75.25	2
14	9.70	60.17	30.13	1.85	50.20	47.95	1
15	40.31	31.31	28.38	2.55	43.03	53.42	1
16	34.16	39.19	26.66	5.59	22.02	72.38	2
17	11.36	52.38	36.26	0.23	58.40	41.38	1
18	34.68	41.95	23.38	25.42	11.60	62.97	2
19	57.95	9.94	32.11	2.02	14.11	83.87	2
20	10.37	50.23	39.40	4.94	22.37	72.69	2
21	21.18	42.23	36.59	6.82	11.44	81.75	2
22	48.17	18.94	32.89	5.65	13.27	81.08	2
23	98.07	1.25	0.69	0.46	24.02	75.52	4
24	35.87	39.23	24.90	4.20	37.57	58.23	1
25	98.39	1.14	0.47	19.81	15.31	64.88	4
26	19.48	49.05	31.47	0.18	37.00	62.81	2
27	64.96	18.42	16.62	1.14	30.92	67.94	4
28	70.55	14.81	14.64	5.75	31.81	62.45	4
29	84.19	7.77	8.04	3.32	55.09	41.59	3
30	99.31	0.26	0.43	0.42	35.92	63.66	4
31	95.30	2.50	2.20	0.47	43.71	55.82	3
32	96.51	2.32	1.17	0.49	43.33	56.18	3
33	20.41	48.75	30.85	0.41	65.85	33.74	1
34	99.27	0.28	0.46	0.45	34.37	65.18	4
35	58.15	23.55	18.30	0.37	33.71	65.92	2
36	92.69	6.23	1.08	1.10	33.10	65.80	4
37	26.02	42.02	31.96	2.24	2.76	94.99	2
38	88.64	10.16	1.20	0.42	6.47	93.11	4
39	35.88	24.62	39.51	0.37	13.22	86.42	2
40	38.01	44.52	17.47	1.44	26.14	72.43	2
41	94.60	2.86	2.54	0.62	44.69	54.69	3
42	10.32	45.51	44.17	1.65	5.20	93.15	2
43	98.32	1.09	0.60	0.61	28.45	70.94	4
44	20.09	46.90	33.01	4.46	54.34	41.20	1
45	11.34	54.36	34.40	1.16	8.16	90.68	2
46	72.48	16.07	11.45	4.35	51.72	43.86	3
47	50.58	18.49	30.93	1.64	85.64	12.72	1
48	15.28	57.75	26.97	0.27	5.25	94.47	2

NO.	%Na	%Ca	%Mg	%Cl	%SO4	%HCO3	Type
49	17.35	47.87	34.77	0.91	19.10	79.99	2
50	36.06	36.89	27.06	2.51	53.15	44.34	1
51	19.99	42.80	37.21	2.65	74.06	23.29	1
52	42.13	35.92	21.95	3.04	1.60	95.36	2
53	90.23	5.24	4.53	85.09	0.58	14.32	3
54	99.29	0.39	0.32	2.53	57.86	39.60	3
55	80.68	6.57	12.75	8.90	7.37	83.73	4
56	56.92	19.47	23.60	0.81	42.75	56.44	1
57	23.58	37.30	39.12	0.45	75.49	24.06	1
58	29.18	43.28	27.54	2.84	21.45	75.71	2
59	12.73	58.20	29.07	1.48	21.81	76.71	2
60	52.50	29.45	18.05	0.97	25.60	73.43	2
61	88.83	6.59	4.58	7.26	20.27	72.48	4
62	97.84	1.03	1.13	2.27	28.78	68.95	4
63	33.27	41.24	25.49	0.43	7.87	91.70	2
64	29.10	44.03	26.88	0.84	10.87	88.29	2
65	62.91	20.62	16.47	2.90	40.09	57.02	3
66	11.02	53.93	35.05	1.32	11.38	87.30	2
67	25.10	45.31	29.59	0.24	23.40	76.36	2
68	19.72	47.05	33.24	0.40	37.56	62.04	2
69	47.92	29.44	22.64	5.90	23.77	70.33	2
70	33.35	23.10	43.55	2.42	31.79	65.80	2
71	25.71	34.79	39.50	0.43	50.86	48.70	1
72	74.81	15.14	10.04	0.19	64.60	34.21	3
73	82.37	17.01	0.62	6.38	40.35	53.27	3
74	23.14	48.28	28.58	2.00	62.65	35.35	1
75	37.03	38.27	24.70	3.34	39.09	57.57	1
76	30.25	31.05	38.71	3.22	19.66	78.12	2
77	22.99	48.91	28.10	1.32	33.25	65.43	2
79	4.07	84.64	11.29	20.18	12.16	67.66	2
80	6.37	60.24	33.39	17.87	5.75	76.39	2
81	26.16	45.67	28.17	1.13	39.42	59.45	1
82	8.36	53.23	38.41	2.09	54.62	43.29	1
83	30.10	42.75	27.15	0.59	29.23	70.18	2
84	54.40	22.93	22.67	0.23	40.18	59.58	1
85	75.04	14.89	10.07	1.07	29.82	69.10	4
86	35.82	38.68	25.50	5.96	27.94	66.10	2
87	36.09	33.99	29.91	1.07	43.31	55.62	1
88	40.48	33.32	26.20	0.30	23.41	76.29	2
89	77.09	13.51	9.40	1.54	37.74	60.72	4
90	31.61	41.50	26.90	4.12	17.12	78.76	2
91	4.53	50.58	44.89	10.10	19.81	70.09	2
92	8.44	64.35	27.21	0.95	55.68	43.37	1
94	8.21	46.45	45.34	1.12	29.09	69.79	2
95	15.31	50.58	34.11	9.07	13.40	77.53	2
96	26.42	44.99	28.60	1.00	35.06	63.94	2
97	29.72	42.36	27.93	5.31	14.44	80.24	2
98	44.98	27.10	27.92	3.00	42.91	54.09	1

NO.	%Na	%Ca	%Mg	%Cl	%SO4	%HCO3	Type
99	7.19	59.63	33.19	1.33	8.53	90.14	2
100	6.54	55.24	38.22	0.39	4.28	95.33	2
101	25.52	41.70	32.78	3.51	13.22	83.27	2
102	6.45	60.03	33.52	2.87	3.81	93.32	2
103	51.82	32.98	15.21	3.48	56.38	40.14	1
104	97.60	0.26	2.14	3.37	46.34	50.29	3
105	24.02	46.96	29.03	1.98	3.16	94.86	2
106	29.86	45.55	24.59	1.54	23.42	75.03	2
107	98.51	0.81	0.67	0.93	30.76	68.31	4
108	47.83	28.94	23.23	2.85	31.08	66.07	2
109	20.35	28.36	51.38	0.45	60.96	38.59	1
110	24.64	38.78	36.58	0.35	36.93	62.72	2
111	13.54	30.87	55.59	7.19	32.28	60.52	2
112	12.22	50.61	37.18	70.75	0.25	29.00	1
113	13.95	44.71	41.34	69.96	2.42	27.62	1
114	12.22	50.61	37.18	69.22	2.41	28.37	
115	39.64	38.60	21.75	1.10	47.11	51.79	1
116	13.37	40.61	46.02	12.05	10.28	77.67	2
117	14.37	50.08	35.54	5.83	32.26	61.91	2
119	25.14	37.42	37.43	0.86	22.07	77.07	2
120	19.97	57.62	22.41	0.42	77.47	22.10	1
121	23.86	32.45	43.69	2.90	7.39	89.72	2
122	18.21	43.40	38.39	5.33	43.20	51.47	1
123	30.19	35.51	34.30	1.03	62.71	36.26	1
124	97.68	1.50	0.82	3.23	29.25	67.52	4
125	88.86	7.08	4.06	6.42	37.88	55.71	3
126	90.62	8.45	0.93	1.28	32.77	65.95	4
127	49.13	25.90	24.97	1.36	68.81	29.83	1
128	41.32	21.97	36.71	11.25	52.76	35.99	1
129	41.22	28.63	30.16	9.02	71.31	19.67	1
130	30.83	40.75	28.42	0.60	21.09	78.31	2
131	83.84	8.76	7.40	3.90	37.41	57.68	3
132	95.74	2.34	1.93	1.62	27.75	70.63	4
133	96.22	2.61	1.17	3.35	44.64	52.01	3
134	19.95	47.35	32.70	0.19	39.41	60.39	2
135	13.16	50.57	36.27	7.88	22.05	70.07	2
136	51.42	31.17	17.42	0.29	8.17	91.54	2
137	20.94	47.45	31.60	0.28	28.56	71.16	2
138	22.88	45.72	31.40	1.29	39.92	58.78	1
139	16.36	51.33	32.31	6.38	9.02	84.60	2
140	99.00	0.38	0.62	2.36	29.34	68.30	4
141	98.47	0.84	0.69	0.90	32.84	66.26	4
142	28.92	32.67	38.41	1.30	18.42	80.27	2
143	21.24	35.50	43.25	13.83	18.06	68.11	2
144	15.52	40.94	43.54	3.75	25.91	70.34	2
145	10.56	53.78	35.66	1.00	10.83	88.17	2
146	19.25	38.83	41.82	6.44	7.93	85.63	2
147	94.32	2.05	3.63	0.74	48.31	50.94	3

NO.	%Na	%Ca	%Mg	%Cl	%SO4	%HCO3	Type
148	27.49	42.49	30.12	2.10	45.62	52.27	
149	16.22	58.52	25.26	4.94	15.19	79.87	2
150	84.42	6.56	9.02	23.22	23.48	53.30	3
151	32.01	44.75	23.24	0.47	39.05	60.48	2
152	14.01	52.01	33.89	2.33	49.65	48.02	1
153	15.24	59.04	25.72	1.19	12.85	85.97	2
154	20.80	50.85	28.35	0.59	62.98	36.43	1
155	17.28	53.08	29.65	0.97	22.44	76.59	2
156	8.27	67.47	24.26	0.34	2.54	97.11	2
157	74.62	15.26	10.12	6.21	46.52	47.27	3
158	5.43	58.63	35.93	0.42	2.77	96.81	2
159	28.08	47.43	24.49	1.93	42.66	55.41	1
160	75.10	13.55	11.35	4.89	42.88	52.24	3
161	18.26	40.60	41.13	0.97	30.00	69.03	2
162	16.73	49.57	33.71	2.54	38.08	59.38	2
163	17.43	53.82	28.75	5.93	24.95	69.12	2
164	97.79	1.21	1.00	0.65	16.67	82.68	4
165	47.71	31.05	21.04	0.33	14.99	84.68	2
166	96.76	2.78	0.46	0.32	32.84	66.83	4
167	10.23	47.51	42.25	5.78	12.66	81.56	2
168	18.40	47.28	34.32	0.79	24.63	74.57	2
169	31.30	40.94	27.76	0.90	62.09	37.01	1
170	19.57	45.54	34.89	0.67	9.88	89.45	2
171	25.81	35.07	39.12	11.72	49.74	38.54	1
172	19.77	55.50	24.73	1.57	4.63	93.80	2
173	14.91	61.64	23.45	9.67	7.14	83.19	2
174	65.68	19.66	14.65	46.60	20.62	32.78	3
175	16.24	46.76	37.00	3.12	7.67	89.21	2
176	78.62	9.84	11.54	22.23	31.68	46.08	3
177	40.11	38.38	21.51	1.62	32.31	66.07	2
178	84.33	8.03	7.64	20.86	52.15	26.99	3
179	16.03	41.71	42.26	0.14	80.42	19.43	1
180	87.38	7.13	5.49	36.01	30.36	33.63	3
181	10.71	59.95	29.34	3.55	11.24	85.21	2
182	23.69	49.04	27.27	0.41	67.56	32.03	1
183	37.46	37.00	25.54	2.58	20.39	77.04	2
184	65.86	21.40	12.74	2.28	13.68	84.05	4
185	17.02	56.94	26.05	31.44	37.40	31.16	1
186	38.89	39.59	21.52	4.52	32.47	63.01	2
187	9.30	59.71	30.99	0.57	29.94	69.49	2
188	55.49	25.49	19.02	5.82	56.35	37.82	1
189	76.01	14.45	9.53	5.55	52.76	41.69	3
190	9.42	56.74	33.84	0.61	18.76	80.62	2
191	16.93	44.28	38.80	19.99	6.58	73.43	2
192	22.83	50.40	26.77	0.95	28.64	70.41	2
193	11.80	50.73	37.46	1.70	13.80	84.50	2
194	69.23	13.72	17.05	9.39	49.17	41.44	3
195	30.73	42.49	26.78	1.38	10.91	87.71	2

NO.	%Na	%Ca	%Mg	%Cl	%SO4	%HCO3	Type
196	12.43	55.06	32.51	0.45	6.61	92.94	2
197	26.42	30.13	43.45	2.83	19.35	77.81	2
198	23.03	50.63	26.34	0.28	52.08	46.89	1
199	6.53	53.66	39.80	2.32	2.85	94.84	2
200	7.73	52.35	39.92	0.82	3.04	96.14	2
201	11.59	66.49	21.92	2.30	3.97	93.73	2
202	6.38	65.53	28.08	0.73	3.25	96.01	2
203	8.71	52.64	38.65	3.54	7.64	88.82	2
204	9.19	57.28	33.53	1.82	6.50	91.68	2
205	4.69	55.41	39.90	9.60	1.83	88.57	2
206	11.72	60.90	27.38	0.30	4.36	95.35	2
207	7.43	37.64	54.92	0.32	2.38	97.30	2
208	4.82	61.93	33.26	0.38	2.83	96.79	2
209	19.77	40.05	40.17	20.08	30.94	48.98	1
210	44.58	32.25	23.17	30.70	50.99	45.94	1
211	8.52	57.53	33.95	1.97	3.69	94.64	2
212	16.11	51.84	32.04	0.34	2.27	97.39	2
213	33.55	23.34	43.21	0.33	9.58	90.09	2
214	4.79	61.74	33.47	0.47	4.48	95.05	2
215	12.46	48.40	39.14	3.50	45.38	51.12	1
216	96.49	2.70	0.81	5.08	53.29	41.63	3
217	10.77	51.23	38.00	23.74	13.68	62.58	2
218	29.80	40.37	29.83	0.38	6.52	93.09	2