GEOLOGICAL SURVEY OF CANADA

DEPARTMENT OF MINES AND TECHNICAL SURVEYS



BULLETIN 139

# GROUNDWATER STUDIES IN THE ASSINIBOINE RIVER DRAINAGE BASIN

## Part I: The Evaluation of a Flow System in South-Central Saskatchewan

Peter Meyboom

1966

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# PREFACE

The scarcity of adequate surface water throughout much of the Prairie Provinces has resulted in a strong interest in groundwater ever since the discovery of the "Great North West", for the relation between man and water has determined the outcome of all prairie enterprises. Earlier groundwater studies in the three Prairie Provinces were mainly concerned with the immediate solution of particular water supply problems, but many water problems now involve much more than a search for adequate supplies. Knowledge of the local and regional groundwater regimen is required for the solution of problems dealing with irrigation of low-lying lands and reclamation of saline soils, or with waste disposal in streams or underground reservoirs.

The research program that has been initiated by the Geological Survey of Canada in the Assiniboine River drainage basin aims at qualitative and quantitative solutions of groundwater phenomena on the Canadian prairie. This report, which is the first of a series of publications dealing with particular facets of this investigation, is an attempt to relate a number of groundwater phenomena of a typical prairie drainage basin to a common groundwater flow-system.

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

OTTAWA, May 13, 1963

BULLETIN 139 — Grundwasserstudien im Stromgebiet des Assiniboine River.
Von Peter Meyboom

Der erste in einer Reihe von Berichten über Grundwasserverhältnisse der kanadischen Prärie. Beschreibt eine Anzahl von Grundwasserverhältnissen, die empirisch zu einem gemeinsamen Stromsystem in Beziehung gebracht werden können, das seinerseits als Modell für weitere quantitative Grundwasserstudien dienen kann.

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БЮЛЛЕТЕНЬ 139 — Исследования грунтовых вод бассейна дренажа реки Ассинибойн.
Пётр Мейбум

Этот бюллетень является первым в серии отчётов, описывающих грунтовые воды канадских прерий. Дано описание некоторых различимых проявлений грунтовых вод, которые могут быть отнесены к общей системе их циркуляции. В свою очередь, это может быть использовано в качестве образца для дальнейшего количественного изучения грунтовых вод.

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# GROUNDWATER STUDIES IN THE ASSINIBOINE RIVER DRAINAGE BASIN

## Part I—The Evaluation of a Flow System in South-Central Saskatchewan


### *Abstract*

Discernible groundwater phenomena of a typical prairie drainage basin have been related to a flow system in a particular geological model, called the Prairie Profile. The Prairie Profile consists of a central topographic high bounded at either side by an area of lower elevation. Geologically, the profile is made up of two layers of different permeability, the upper layer having the lower permeability. The ratio of permeabilities is such that groundwater flow is essentially vertical in the poorly permeable layer and essentially lateral in the underlying permeable layer. Through the profile is a steady flow of groundwater from the area of recharge to the area of discharge.

The distribution of recharge and discharge areas can be mapped in a classical geological fashion, that is, by means of a large number of individual outcrops. In this report a groundwater outcrop is defined as any area where groundwater emerges at the surface. Geobotanical and chemical investigations show that in a prairie region the following features may be classified as groundwater outcrops: willow rings in hummocky moraine; saline river valleys; playas; saline soils; springs and seepages. Mapping the flow system is a prerequisite to an intelligent evaluation of the groundwater balance of a drainage basin.



### *Résumé*

Le comportement observable des eaux souterraines d'un bassin de drainage particulier aux Prairies a été comparé à un système d'écoulement d'un modèle géologique défini appelé le Profil des Prairies. Le Profil des Prairies comporte une hauteur topographique centrale flanquée de chaque côté d'aires moins élevés. Du point de vue géologique, le profil est formé de deux couches de perméabilité différente, la couche supérieure étant la moins perméable. Le degré de perméabilité est tel que l'écoulement des eaux souterraines est essentiellement vertical dans la couche peu perméable et essentiellement latéral dans la couche sous-jacente perméable. A travers le profil, l'écoulement des eaux souterraines est régulier à partir de la région de recharge jusqu'à la région de décharge.

On peut cartographier selon la méthode géologique classique les régions de recharge et de décharge à l'aide d'un grand nombre d'affleurements individuels. Dans le présent rapport une résurgence d'eau souterraine se définit comme toute région où l'eau souterraine sourd. Des recherches géobotaniques et chimiques montrent que dans une région de prairie les accidents suivants peuvent être considérés comme le résultat de la résurgence d'eau souterraine: les cercles de bouleaux dans une moraine en bosse et en creux; les vallées salines de rivière; les lacs temporaires; les sols salins; les sources et les infiltrations. Il faut d'abord cartographier le réseau d'écoulement pour arriver à une bonne compréhension du bilan hydrique des eaux souterraines d'un bassin de drainage.

# INTRODUCTION

Various authors (Kudelin, 1958; de Jong, 1960; Schicht and Walton, 1961)[1] have pointed out that quantitative regional groundwater studies should be based on the water balance of an area rather than on the sum of a large number of pumping tests. The groundwater balance of a basin may be written as: Recharge=Discharge, in which groundwater discharge is the sum of evapotranspiration, baseflow, and "artesian basin supply" (Kudelin, 1958). These three discharge factors can be measured. Before a balance can be set up, however, it is necessary to know what significance can be attached to such measurements and how such measurements should be obtained.

During the preparation of a basin-wide groundwater survey of the Assiniboine River drainage basin, it became apparent that knowledge of the origin and mutual relations of the various items of the groundwater balance is wholly inadequate for quantitative purposes. The following points particularly required further attention:

1. the validity of the concept of congruent surface water divides and groundwater divides;
2. the relation between topography, geology, and areas with flowing wells;
3. the relation between hydraulic head and position within the flow system;
4. geological control of minimum riverflow;
5. the distribution and manifestation of areas of recharge and areas of discharge; and
6. the role of phreatophytes in the groundwater budget of a prairie drainage basin.

The study carried out in the headwater region of Qu'Appelle River and in Saskatchewan furnished an answer to some of the questions, and a number of discernible groundwater phenomena have been related empirically to a common flow system. This flow system can be used as a model for further quantitative studies.

[1] Names and/or dates in parentheses are those listed in *References.*

## Acknowledgments

The writer is grateful to Mr. J. Hudson of the Saskatchewan Research Council for his excellent lessons in the ecology and taxonomy of the saline plant communities of southern Saskatchewan; to Dr. E. A. Christiansen also of the Saskatchewan Research Council for the many discussions and field trips; and to Mr. J. Toth of the Alberta Research Council for helpful discussions.

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# OBSERVATIONS

The groundwater geology of the Western Canadian Plains has been studied intermittently since the beginning of the century. As can be expected in a semi-arid area, most of the work has been directed towards recording and establishing the extent of the readily available resources. Areas of flowing wells were studied intensively. Existing published data have a number of observations in common that enable one to obtain a fairly complete, although incoherent, picture of the hydrogeological environment of the Canadian prairie.

Groundwater in western Canada is obtained from surficial Pleistocene deposits and from the underlying bedrock. The surficial deposits consist mainly of glacial till—an unsorted mixture of clay, silt, sand, and boulders—and associated glacial lake clays and sandy outwash deposits. The thickness and extent of these sediments vary greatly. The underlying bedrock strata are of Tertiary or Cretaceous age. The Tertiary beds consist of a succession of fine sands, clay, lignitic coal seams, and thick quartzite conglomerates, whereas the Cretaceous deposits are predominantly marine shales interbedded with sandstone strata, clay beds, and coal seams, which have been deposited in a transitional or continental environment.

The materials that make up these sediments determine to some extent the nature of groundwater movement. As there are essentially two types of materials: those of low permeability, and those of relatively high permeability, groundwater movement in the geological environment of the Western Plains is determined by the spatial arrangement of these two flow media.

Three fundamentally different arrangements of the permeable and less permeable materials can be recognized:

1. Both types of materials form a stratified succession in which the thickness of the strata is not negligible in comparison with their linear dimensions.
2. The permeable materials are interbedded with the slightly permeable in a lenticular fashion, the latter forming the matrix of the body.
3. Strata with an abundance of permeable lenses are enclosed in poorly permeable strata.

The importance of these arrangements are discussed in the next chapter.

Economic quantities of groundwater are always obtained from the permeable materials, that is, small gravel lenses in till, extensive outwash deposits, fluvio-glacial stream-channel deposits, isolated sandstone lenses in bedrock formations, coal seams, or extensive sandstone strata in the bedrock. It is interesting to note that in all publications dealing with the occurrence of groundwater in western Canada, mention is made of large numbers of artesian wells, which are invariably defined as wells "in which the water rises above the top of the aquifer".

By using the static water level of these "artesian wells" it is customary to construct a piezometric surface, which according to Meinzer (1923, p. 38) is an "imaginary surface that everywhere coincides with the static level of water in the aquifer". A similarity between such a piezometric surface and the local topography has been observed in many parts of the prairie (Farvolden, 1961; Jones, 1962; Meyboom, 1961). In areas where this relation exists, the underground water divide can be considered to coincide with the surface watershed, as was pointed out by Schicht and Walton (1961). This situation appears to compare favourably with Hubbert's statement that "the stream tubes at the divide descend to a depth which in a uniformly permeable material has no assignable limit" (Hubbert, 1940, p. 930). Moreover, Toth (1962) has stated that if the vertical scale of Hubbert's flow diagram (1940, Fig. 45) were drawn on proper scale, the flow lines would be horizontal, thus substantiating the concept of lateral flow, which is an essential assumption in the mathematical treatment of many groundwater problems (Todd, 1959, Figs. 4. 1-8, 4. 21). Another consequence of the congruence of topography and piezometric surface is that maps of the piezometric surface show that all prairie rivers are effluent. This observation and the alleged preponderance of lateral flow have led to the conclusion that basin-wide groundwater studies can be conducted conveniently by means of baseflow analysis (Meyboom, 1961; Kunkle, 1962).

Many of the artesian wells referred to above flow freely, but (except for a few areas) their distribution appears to be irregular. A few attempts have been made to relate minor areas of artesian flow to particular geological formations (Wickenden, 1935, p. 194; Jones, 1960, p. 21), but evidence for extensive aquifers is difficult to find. On the other hand, the relation between groundwater and geology has been established successfully in some of the larger artesian areas, such as the Carnduff area, the Red River area and Lake Winnipeg (Johnston, 1934), and in southern Alberta (Meyboom, 1960). Of these, the Milk River sandstone in southern Alberta compared most favourably with the classical examples of artesian aquifers, such as the Dakota sandstone (Darton, 1918) in the United States.

The following observations—all related to water levels—also deserve attention. Three conditions can be recognized: (1) where the head of water decreases with increasing depth; (2) where the head of water increases with increasing depth; and (3) where there is no change in head with increasing depth. All three conditions may be found during the construction of one well.

Selwyn (1881) reported that while drilling along Souris River below Roche Percee in Saskatchewan, the static water level in the drill hole suddenly sank to within 38 feet from the bottom of the hole; it had been within 5½ feet from the top during the drilling of the first 70 feet. In describing the water resources of the city of Moose Jaw, Saskatchewan, Johnston and Wickenden (1930, p. 60) commented on a 3,302-foot well at the power house there. Above a depth of about

900 feet this well yielded no important flow of water; at 980 feet, a flow amounting to about 4,000 gallons per hour was obtained; and at greater depths somewhat larger flows occurred. Simpson (1929, p. 100) reported from one of the test wells for the city of Regina in the Qu'Appelle Valley that the water level decreased to 6 feet below surface at a depth of 80 feet; previously the static level had been 2 feet above ground at the original depth of 241 feet. Farvolden (1961, p. 16) mentioned an increase in head with depth in the Pembina Valley (Alberta), whereas a decrease in head with depth was described from topographically high areas near Calgary (Meyboom, 1961). Toth (1962) noticed this phenomenon in a small drainage basin in central Alberta, where wells in a "definite recharge area" show a decrease in head of about 0.5 foot per foot of depth. Wells in a "definite discharge area" showed virtually no change in head to a depth of about 120 feet, beyond which depth the decrease in head amounted to as much as 0.70 foot per foot (Toth, 1962, Fig. 5).

These phenomena, which are common and widespread, are discussed in the next sections.

## Description of the Headwater Region of Qu'Appelle River

### Physiography

The headwater region of Qu'Appelle River is located in south-central Saskatchewan (Fig. 1). The centre of this region (townships 17-31, within ranges 21W2 to 8W3) is of particular interest. The Saskatchewan-Assiniboine drainage divide, which runs from the Missouri Coteau via the Eyebrow and Vermilion Hills to the Allan Hills, is the backbone of the area.

The topography east of the divide is undulating to gently rolling, with an average elevation of 1,800 feet above mean sea-level. The Missouri Coteau is a prominent escarpment rising to 2,500 feet elevation; the hills that make up the divide north of the Coteau are from 2,000 to 2,500 feet above sea-level. The deep valley of South Saskatchewan River is the most prominent topographic feature west of the divide. The area contains two large permanent lakes, Last Mountain Lake and Buffalo Pound Lake, both occupying valleys of former meltwater channels (Christiansen, 1961). It also contains several smaller lakes and undrained depressions.

The main drainage pattern in the eastern part of the area is lobate, being made up of a number of parallel valleys that are occupied by permanent or intermittent creeks. Lanigan Creek and Lewis Creek are the most important of the creeks that flow into the northern part of Last Mountain Lake; Arm River flows into the southern end of Last Mountain Lake. Squaw Creek, rising in Allan Hills, and Ridge Creek, rising in Eyebrow Hills, join in Tp. 22, R. 1, W.3 and form the beginning of Qu'Appelle River. Moose Jaw Creek, which drains the eastern slopes of the Missouri Coteau, merges with Thunder Creek in Moose Jaw and flows into Qu'Appelle River in Tp. 19, R. 24, W. 2, north of the city. Last Mountain Lake has an outlet into Qu'Appelle River in Tp. 20, R. 21, W. 2, near Lumsden. Beaver

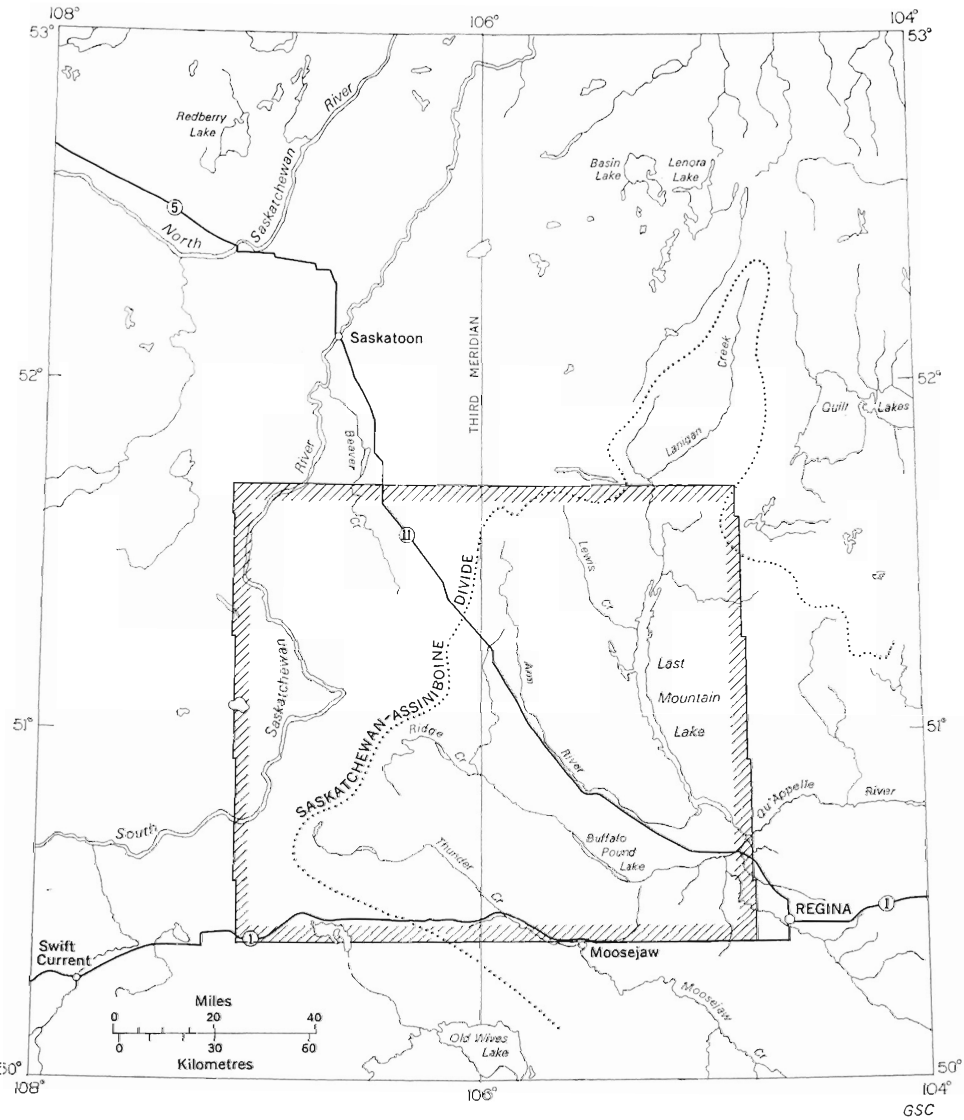


FIGURE 1. Index map showing area discussed, and headwater region of Qu'Appelle River.

Creek (or Brightwater Creek as it is called on the older maps) is the only permanent creek that flows into South Saskatchewan River.

## Pleistocene Geology

The glacial geology of the eastern part of the area has been studied by Christiansen (1961, 1962) and that of Elbow district by Scott (1962). The area is predominantly covered by till in the form of either ground moraine as in the lowlands, or hummocky moraine, which covers the uplands: both forms contain minor lenses of sand and gravel. Associated with the till are small patches of outwash sediments and ice-contact deposits (Christiansen, 1961). The area between Buffalo Pound Lake and Thunder Creek is covered by clay of Pleistocene Lake Regina. The various stream channels are bordered by minor sand and gravel deposits, many of which represent eroded till (op. cit.). The thickness of the surficial deposits ranges from a few feet on the bedrock highs to about 300 feet in the deeper bedrock valleys, the average being 100 feet.

From the bedrock topography as reconstructed by Christiansen (1961, Pl. I; 1962, Fig. 1), it is apparent that the present day drainage divide between the Assiniboine basin and the Saskatchewan basin is essentially the same as the one on the bedrock surface, which may be interpreted as the preglacial divide. At the east side of the divide there appears to be a well-developed dendritic drainage system, rising in the Missouri Coteau and converging into Last Mountain Lake (Christiansen, 1962, Fig. 1). The valleys of Qu'Appelle and Arm Rivers are virtually at right angles with the preglacial drainage.

## Stratigraphy of Bedrock Formations

West of the Saskatchewan-Assiniboine drainage divide, the bedrock is composed of dark shales and a few sandstone beds, which comprise the Upper Cretaceous Bearpaw Formation and overlie the sands, shales, and coal seams of the Belly River Formation (Fraser, *et al.*, 1935). On the highlands, the Bearpaw Formation is overlain successively by the Eastend, the Whitemud, and the Ravenscrag Formations. The two last mentioned are outside the area under discussion. The Vermilion Hills are capped by the Eastend Formation (Fig. 2)

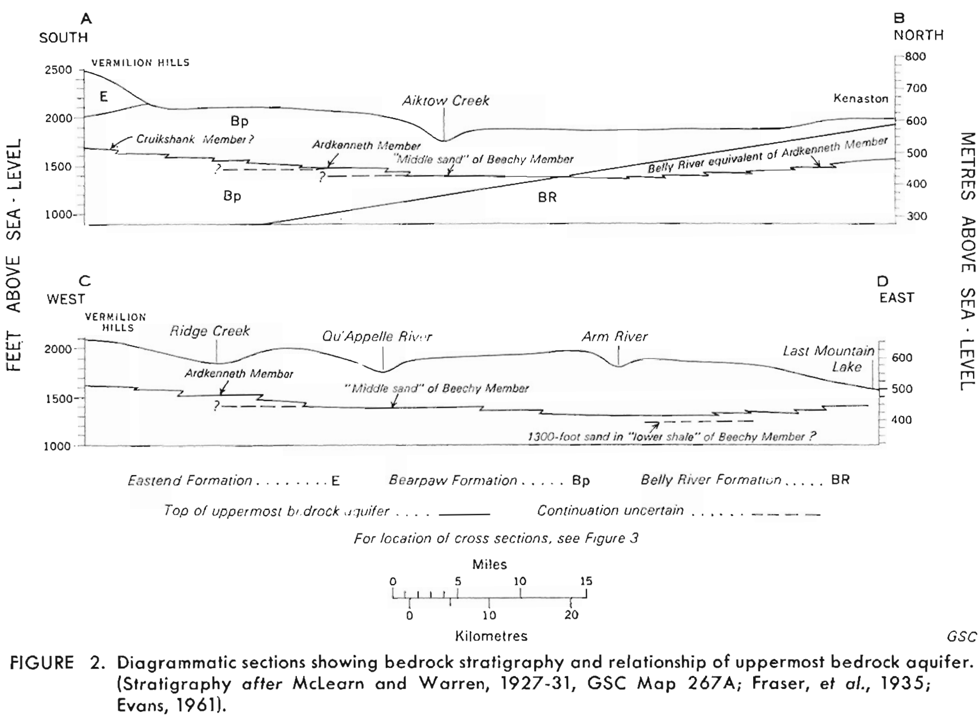


FIGURE 2. Diagrammatic sections showing bedrock stratigraphy and relationship of uppermost bedrock aquifer. (Stratigraphy *after* McLearn and Warren, 1927-31, GSC Map 267A; Fraser, *et al.*, 1935; Evans, 1961).

whereas the Bearpaw Formation underlies the drift in the Allan Hills. East of the divide, the drift is underlain directly by the Bearpaw and Belly River Formations, the stratigraphic equivalent of which is the Marine Shale Series (Fig. 3) to the east.

A more detailed description of the Eastend Formation and older Cretaceous formations follows in order to present a better understanding of the relative permeabilities of the various bedrock formations.

### *Eastend Formation*

By definition (Fraser, *et al.,* 1935), the Eastend Formation includes the fine sands and coarse silts that lie between the shales of Bearpaw Formation and the kaolinized sands of the Whitemud Formation. The upper part of the Eastend Formation consists of massive yellowish and yellowish green fine sands and coarse silts; the lower part is comprised of fine sands, silts, and grey shales in beds several feet thick. The basal beds are of marine origin and form a gradational contact with the underlying Bearpaw Formation.

### *Bearpaw Formation*

The detailed stratigraphy of the Bearpaw Formation in this area is well known from the studies of Evans (1961), L. L. Price (1961, pers. com.), and J. J. L. Tremblay (1962, pers. com.). The following generalized succession for the South Saskatchewan River valley was established by Evans (1961):

| Bearpaw Formation | Thickness (feet) | Lithology |
|---|---|---|
| Vermilion Member | 250 | shale, silty in parts, bentonitic bands |
| Cruikshank Member | 40 | sandstone, shaly in part |
| Snakebite Member | 250 | shale, grey, soft, bentonitic |
| Ardkenneth Member | 70 | fine-grained sandstone |
| Beechy Member | | |
| Upper shale | 120 | shale, dark grey, silty, oysters at base |
| Middle sandstone | 35 | well indurated, ironstone partings |
| Lower shale | 200 | dark grey, massive marine shale (contains 35′ sandstone bed in Tp. 20 R. 1 W3) |

Only the Snakebite, Ardkenneth, and Beechy Members are relevant to our present discussion.

L. L. Price (1961, pers. com.) gave the following detailed core description of the Ardkenneth and Beechy Members from a stratigraphic test hole near Beechy in

SW 1/4 sec. 27-21-9, W.3, elevation 2,135 feet, about 25 miles west of the Darmody area:

| Depth (feet) | Lithology | Thickness (feet) |
|---|---|---|
| | BEARPAW FORMATION | |
| 392–483 | *Ardkenneth Member*: sandstone, fine grained, loose at the top, shaly downward | 91 |
| 392–395 | loose sand | |
| 395–415 | core recovery 2′6″: sandstone, dark grey, poorly indurated to loose, very fine grained, angular quartz grains 65%, glauconite and other soft minerals 23%, dark chert and other rock fragments 12%, shell fragments. | |
| 415–435 | core recovery 8′: sandstone, dark greenish grey, largely shaly, poorly indurated to firm, recovered material is tight with intermittent slight porosity. | |
| 435–455 | core recovery 8′: 0–1′2″ sandstone, fine grained, glauconitic, loose, porous; 1′2″–6′6″ sandstone, argillaceous, firm abundant grains of white clay; 6′6″–8′ sandstone, very shaly, firm, tapered oval cast of sand from *Baculites* sp. belemnites or worm tube. | |
| 455–469 | core recovery 15′6″: 0–2′ sandstone, very fine grained, light grey, glauconitic, firm, porous, fragments of amber or fishbone, chlorite (?) grains; 2′–9′4″ sandstone, shaly, medium light grey, glauconitic, very fine grained, grading to sandy shale near base; 9′4″–12′ sandstone, argillaceous in part, more or less porous; 12′–15′6″ sandstone, argillaceous, medium light green, firm, tight, glauconitic, dark chert, abundant chlorite grains, biotite, interstitial clay, shell fragments. | |
| 469–483 | core recovery 16′3″: 0–6″ "sand"; 16′3″ sandstone, shaly, glauconitic, grading to fine sandy shale, firm, blocky. | |
| 483–652 | *Beechy Member* | |
| 483–552 | Upper shale: shale, silty, stringers of silt and sand 69 | |
| 552–612 | Middle sandstone 60 | |
| 552–572 | core recovery 9′6″: 0–2′3″ sandstone, greyish green, fine grained, glauconitic, loose, porous; 2′3″–9′6″ sandstone, shaly, greenish grey, firm, glauconitic. | |
| 572–592 | core recovery 15′: 0–7″ sandstone, shaly, firm, glauconitic, slightly harder than above; 7″–6′ sandstone, greyish green, fine grained, loose glauconitic, porous; 6′–7′6″ sandstone, shaly, grey-green, glauconitic, brown organic laminae at base of interval; 7′6″–8′4″ sandstone, argillaceous in places, greenish grey, glauconitic, poorly indurated porous in parts; 8′4″–9′6″ sandstone, shaly and firm in parts, soft in part, greenish grey, glauconitic; 9′6″–13′2″ sandstone, very shaly, grading to sandy shale at base, beds with abundant brown organic matter; 13′2″–15′, sandstone, argillaceous, greyish green, slightly indurated, glauconitic. | |
| 592–612 | core recovery 14′: 0–1′4″ sandstone, shaly, greenish grey, very fine grained, slightly indurated; 1′4″–13′6″ sandstone, or siltstone, very shaly intergrading and interlaminated with silty shale mudstone, medium grey, firm, dark grains of chert, glauconite, grains of white clay; 13′6″–13′8″ sandstone, loose, porous, very fine, glauconitic; 13′8″–14′ shale, fine sandy and soft, glauconitic. | |
| 612–652 | Lower shale: shale, medium grey, conchoidal fractures, rare glauconite 40 | 169 |

J. J. L. Tremblay (1961, pers. com.) recorded the following succession of strata in hydrogeological test holes in the South Saskatchewan River valley near Riverhurst, SW 1/4 sec. 5-23-7, W.3, elevation 1,930 feet:

| Depth (feet) | Lithology | | Thickness (feet) |
|---|---|---|---|
| 0–50 | sand of alluvial origin, contains silica-sand and is silty in places | | 50 |
| 50–70 | clayey till | | 20 |
| 70–164 | sandy till | | 94 |
| | BEARPAW FORMATION | | |
| 164–340 | *Snakebite Member*: shale, sandy at the top | | 176 |
| 340–439 | *Ardkenneth Member*: sandstone, shaly at the base loosely cemented | | 99 |
| 439–753 | *Beechy Member* | | |
| 439–505 | Upper shale, sandy shale | 66′ | |
| 505–545 | Middle sandstone (top at 1,425 feet above sea-level) | 40′ | |
| 545–753 | Lower shale, shale, somewhat sandy at the top | 208′ | 314 |
| | BELLY RIVER FORMATION | | |
| 753–808 | sandstone | | 55 |

The electrolog of one of Tremblay's test holes seems to indicate the presence of a silty sandstone between 618 and 640 feet, which may be the equivalent of the sand bed in the Lower shale of the Beechy Member that was mentioned by Evans (1961).

### *Belly River Formation*

Fraser, *et al.* (1935) reported that in central Saskatchewan the stratigraphic equivalent of the Belly River beds of southern Alberta consists of "non-marine and marine sandstones and shales and mostly or entirely marine shales in the eastern part of the area". Belly River beds were not recorded in the deep well in Moose Jaw (op. cit.) and the exact eastern boundary of the formation is not given by these authors. From information given in various Geological Survey Water Supply Papers, the shale boundary has been constructed as shown on Figure 3; this virtually coincides with the one given by Wickenden (1935, Fig. 1). In the deepest test hole that was described by J. J. L. Tremblay (1961, pers. com.), the Belly River Formation was encountered at a depth of 753 feet, or 1,177 feet above sea-level.

### *Marine Shale Series*

The non-marine deposits of the Belly River and Bearpaw Formations extend eastward and northeastward into marine shales, called the Marine Shales Series (*see* Fig. 3). On Figure 3 the writer has attempted to correlate the stratigraphic information contained in Geological Survey Water Supply Papers of the area with the stratigraphy established by Evans, Price, and Tremblay.

It appears from a number of scattered points on Figure 3 that the area west of Last Mountain Lake is underlain by a sandstone layer of unknown continuity and unknown thickness, the top of which is 1,300 feet above sea-level.

A comparison of electrologs of some water wells near Lawson in the Darmody area with those of Tremblay's test holes near Riverhurst shows that the main aquifer in the Darmody area can be correlated with the Ardkenneth Member. Other logs from the Darmody area show that the sandstone layer is overlain by 180 to 225 feet of shale, which would thus be the Snakebite Member:

| | NW 1/4 sec. 19–20–4, W.3 El. 2,100 | SW 1/4 sec. 13–19–5, W.3 El. 2,155 | NE 1/4 sec. 27–18–5, W.3 El. 2,255 |
|---|---|---|---|
| till | 0–270 | 0–252 | 0–58 |
| shale | 270–494 | 252–434 | 58–548 |
| sandstone | 494–532 | 434–464 | 548–562 |

None of the water wells in the Darmody area fully penetrates the Ardkenneth Member, the top of which occurs at successively higher elevations to the south until it reaches a maximum elevation of 1,700 feet (*see* Fig. 3). The question arises as to whether the sandstone beds occurring at this elevation in the southern part of the area mapped may still be part of the Ardkenneth Member, or whether they should be placed in the Cruikshank Member.

To the north, the top of the Ardkenneth Member occurs at increasingly lower elevations, and east and west of Craik (Tp. 24, R. 28, W.2) it may even merge with the deeper sandstone at 1,300 feet. Farther north, towards Hanley and Hawarden, the two sandstones seem to be separated again, leaving an upper sandstone succession whose top is between 1,500 and 1,600 feet above sea-level and a lower one at 1,300 feet. A similar feature is apparent to the east of Craik, where the elevation of the upper aquifer is 1,400 to 1,500 feet.

If it is assumed that the stratigraphy in the Darmody area is essentially the same as that near Riverhurst, the configuration shown on Figure 3 would indicate that the Ardkenneth Member is absent in the area north and east of Darmody. The main aquifer in that area would be the "middle sand" of the Beechy Member (at Riverhurst 1,425 feet above sea-level). The sandstone aquifer that is encountered at various locations at depths ranging from 1,260 to 1,320 feet above sea-level may thus be correlative with the sandstone bed in the lower shale of the Beechy Member. The sandstone topped at 1,500 feet elevation and which re-appears in the Brightwater Creek area would then be the stratigraphic equivalent of the Ardkenneth Member, keeping in mind that we are dealing with the Belly River Formation in that area (Map 267-A *in* Fraser, *et al.,* 1935). It seems logical therefore to accept Evans' conclusion that the sandstone intervals in this part of Saskatchewan are laterally continuous, but diachronous with the presumed time boundaries (Fig. 2).

In conclusion it may be said that the major bedrock aquifers in this area are the Ardkenneth Member and the "middle sandstone" of the Beechy Member, both within the Bearpaw Formation, and the stratigraphic equivalent of the Ardkenneth Member in the Belly River Formation.

The general stratigraphic succession of deeper formations (Fig. 4) has been determined from the logs of three wells, as they were reported in the Saskatchewan schedule of wells (1953, 1955): Eyebrow Crown No. 2 in LSD 5-30-23-1, W.3; Nash No. 1 in LSD 1-17-27-28, W.2; and Penzance Crown No. 1 in LSD 3-30-24-25, W.2. The Cretaceous stratigraphy is similar in all three wells. The basal part of the Upper Cretaceous contains 600 feet of shale of the Colorado Formation (Alberta shale), underlain by the Lower Cretaceous Blairmore Formation, which consists of 200 feet of interbedded sandstone, silt, clay, and coal. Salt water is reported from the Blairmore Formation in Nash No. 1 well.

The underlying Jurassic rocks consist of bentonitic shale, dolomites, evaporites, and red beds, which decrease in thickness from 500 feet in the eastern part of the area to 100 feet in the western part. In Eyebrow Crown No. 2 the Jurassic rocks are underlain by 600 feet of Mississippian limestones in contrast to the test holes to the east where the Jurassic is underlain by Devonian rocks, and an unconformable contact between the two has been inferred (Saskatchewan schedule of wells, 1952-1953; 1954-1955).

The uppermost Devonian beds in these wells are bentonitic shales of the Three Forks Formation overlying the Nisku dolomite in Eyebrow Crown No. 2 well and in Penzance Crown No. 1 well, or the Nisku Formation in Nash No. 1 well (*see* Fig. 4). The Nisku Formation is approximately 140 feet thick in Nash No. 1 well and overlies 600 feet of limestone of the Upper Devonian Duperow Formation. Salt water was reported to flow from the Nisku Formation in Penzance Crown No. 1 well. Formations deeper than 1,900 feet below sea-level were reported only from Eyebrow Crown No. 2 well, and are not discussed here.

## Structural Geology

The area under discussion lies in the western Canada sedimentary basin and the strata are part of a large homocline, dipping slightly westward (Fraser, *et al.*, 1935, p. 61). Kupsch (1958) has suggested that most of the pronounced geomorphological features in Saskatchewan have structural causes, of either tectonic or sedimentary origin. According to the tectomorphic map of Saskatchewan (op. cit.), the headwater region of Qu'Appelle River consists of the Regina Low Axis, bounded by the Missouri Coteau, Allan Hills, and Touchwood Hills, all of alleged structural origin. Kupsch interpreted this geomorphological configuration as a reflection of the deeply buried Palaeozoic erosional surface.

DeMille (1960) described a small dome (Elbow structure) on the western flank of the Saskatchewan-Assiniboine drainage divide. This structure is not

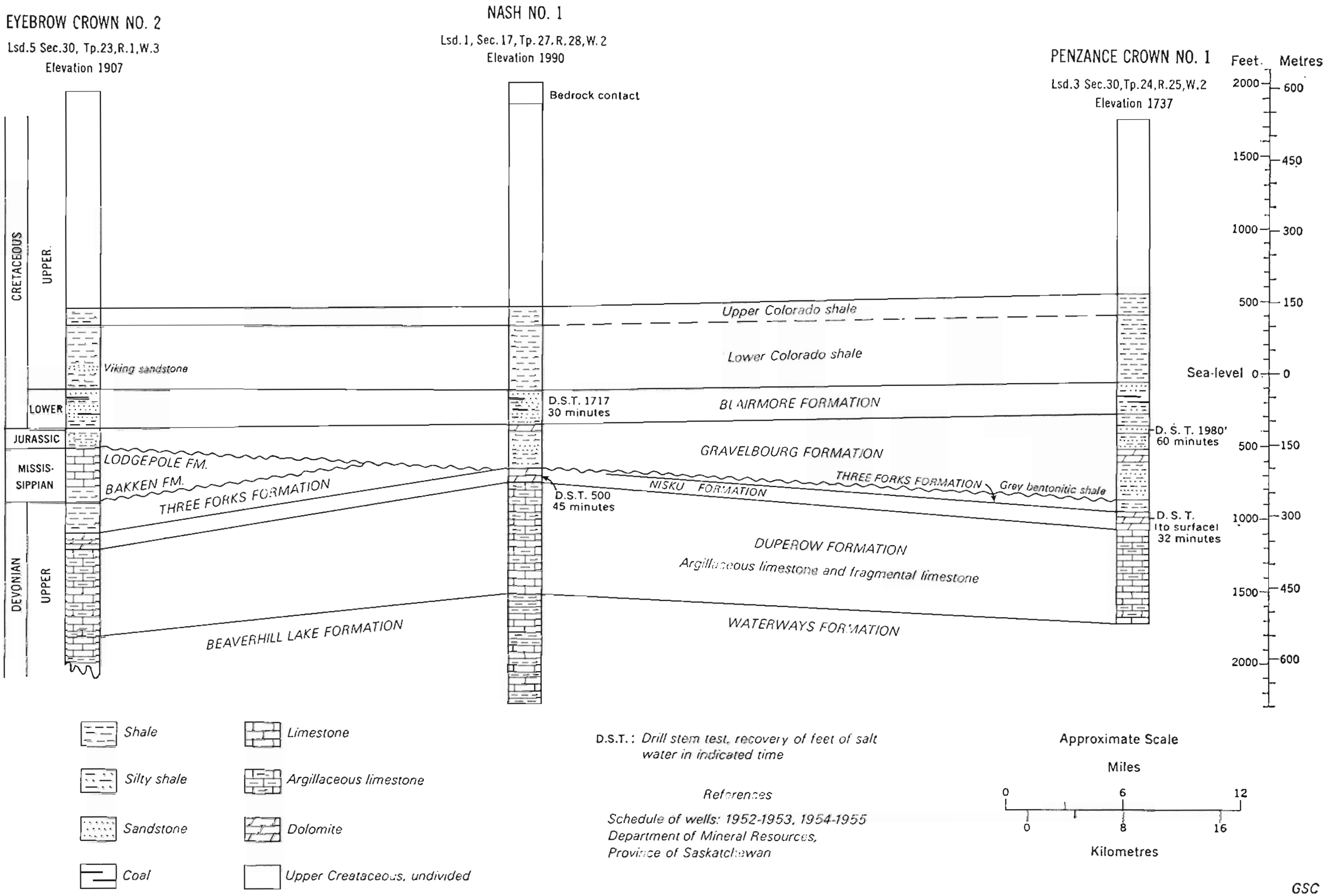


FIGURE 4. Graphic logs of wells showing relationship of Palaeozoic and Mesozoic formations, south-central Saskatchewan.

expressed on the surface, but DeMille obtained a clear configuration of it from a contour map on a shallow horizon in the Bearpaw Formation (DeMille, 1960, p. 159, Fig. 5). He interpreted this dome as a "crypto volcano", modified by the elevation of the Palaeozoic core.

## Hydrogeology of the Headwater Region of Qu'Appelle River

As the following paragraphs contain both a summary and a comparison of the hydrogeological characteristics of drift aquifers and bedrock aquifers, two criteria have been used: (1) the relation between well depth and static water level, and (2) the relative frequency of artesian wells. Experience has shown that a systematic comparison of these criteria gives important information as to the differences in nature of these flow media.

### Shallow Groundwater

Groundwater in the Pleistocene deposits is here referred to as shallow groundwater, and according to the Geological Survey of Canada Water Supply Papers of the 1936-well inventory, 5,299 wells in the area obtain water from this source (Table I). A characteristic, although somewhat pessimistic, description of the occurrence of Pleistocene aquifers has been given by Wickenden (1935), who stated:

> The finding of adequate supplies of water in the glacial drift presents a more difficult problem, on account of the haphazard distribution of this material and the irregular mode of occurrence of porous zones in it.

A summary of the descriptions of drift aquifers given in the various Water Supply Papers of the area reveals that permeable materials are distributed throughout the drift: (1) as scattered pockets of sand and gravel surrounded by till or clay; (2) as stream sediments in preglacial or interglacial river valleys buried by till; or (3) as outwash sediments underlying clay and till.

MacKay, *et al.* (1936) classified the wells that are finished in these deposits into the following types:

1. Flowing artesian wells, in which the water is under sufficient pressure to flow above the surface of the ground[1].
2. Non-flowing artesian wells, in which the water is under pressure but does not flow over the surface.
3. Non-artesian wells, in which the water does not rise above the water-table.

Of the 5,299 drift wells in the region, 65 per cent were non-artesian, nearly 35 per cent were non-flowing artesian, and 1.4 were flowing artesian wells (*see* Table I). The yield of the flowing wells never exceeded 10 gallons per minute (gpm), and the maximum static water level reported was 18 feet above surface.

[1] Where pressure is defined as "the pressure that causes the water to rise above the point at which it is struck".

## Table I

*Geological Survey of Canada Water-Well Inventory, 1936*

| Rural Municipality | Artesian | | Drift | Bedrock |
|---|---|---|---|---|
| | flowing | non-flowing | | |
| 280 | 18 (12 d) | 141 | 323 | 14 |
| 281 | — | 128 | 514 | 6 |
| 282 | — | 87 | 301 | 2 |
| 250 | 2 ( 2 d) | 165 | 393 | 9 |
| 251 | 23 | 75 | 326 | 60 |
| 252 | — | 116 | 260 | 21 |
| 220 | — | 109 | 427 | 4 |
| 221 | 15 | 152 | 351 | 84 |
| 222 | — | 100 | 310 | 19 |
| 223 | 1 | 129 | 315 | 21 |
| 190 | — | 109 | 721 | 9 |
| 191 | — | 50 | 178 | 1 |
| 193 | 21 | 219 | 390 | 32 |
| 194 | 5 | 151 | 490 | 44 |
| | 85 | 1,731 | 5,299 | 326 |

A water-table map constructed from the non-artesian wells less than 15 feet deep revealed a surface parallel to the topographic surface. A cartographic plot of the water levels in the non-flowing artesian wells between 50 and 100 feet deep produced a contour map that showed a somewhat subdued replica of the topographic surface. These observations compare favourably with those mentioned on page 4, and they substantiate the opinion that we are describing a groundwater environment that is typical for the Western Plains.

The relationship between static level and well depth in the drift wells (*see* Fig. 5) is characteristic in that most areas have a distinct negative correlation between the two. For instance, a random test in a so-called recharge area (Tp. 25, R. 2, W.3) indicates a decrease in head of 0.73′/ft. (Fig. 5). This value is of the same magnitude as reported by Meyboom (1961) and Toth (1962). Although the rivers are supposed to be areas of discharge, a random test in the "discharge area" of Qu'Appelle River (Tp. 20, R. 27, W.2) shows a decrease in head with depth of about 0.60′/ft. (Fig. 5). This seems contradictory to the observations to be expected from an examination of the flow diagrams of Hubbert (1940) or Toth (1962), according to both of which there should be an increase in head with depth in discharge areas. A random test in the discharge area of Last Mountain Lake (Tp. 23, R. 24, W.2) resulted in a bent line (Fig. 5), showing a decrease in head of 0.70′/ft. to a depth of 50 feet, and a significant change of slope to an increase in head with depth of 0.40′/ft. between 50 feet and 190 feet below surface.

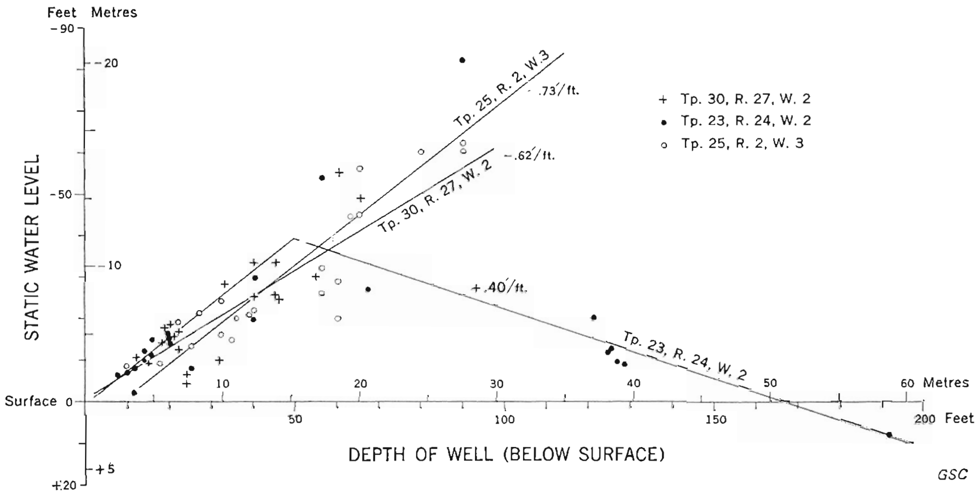


FIGURE 5. Relationship of well depth and static water level in drift aquifers.

Table II shows the relation between static water and well depth in areas with flowing wells in drift aquifers, as reported in the 1936 well inventory. Their hydrogeological setting is discussed below.

## Table II

*Flowing Artesian Wells in Drift Aquifers (1936)*

| Location | Municipality | Depth | Static level | Aquifer |
|---|---|---|---|---|
| 1. SW 10–28–23–W2 | 280 | 50 | 3 | gravel |
| 2. SE 16–28–23–W2 | 280 | 65 | 5 | gravel |
| 3. NE 34–28–23–W2 | 280 | 208 | 18 | sand |
| 4. SE 16–29–22–W2 | 280 | 122 | 2 | sand |
| 5. NE 30–29–22–W2 | 280 | 70 | 1 | gravel |
| 6. NW 2–29–23–W2 | 280 | 108 | 8 | gravel |
| 7. NW 6–29–23–W2 | 280 | 99 | 2 | gravel |
| 8. SE 14–29–23–W2 | 280 | 108 | 12 | gravel |
| 9. SE 18–29–23–W2 | 280 | 160 | 2 | gravel |
| 10. SW 24–29–24–W2 | 280 | 37 | 1 | sand |
| 11. NE 34–30–23–W2 | 280 | 150 | 3 | gravel |
| 12. SW 35–30–23–W2 | 280 | 150 | 4 | gravel |
| 13. NE 13–25–22–W2 | 250 | 72 | 7 | gravel |
| 14. SW 25–26–24–W2 | 250 | 90 | 2 | drift |

Wells 1 to 12 are in the wide depression north of Last Mountain Lake. According to Christiansen (1962), they tap the deposits in a bedrock channel, which accounts for the thickness of some of the gravels. Logs[1] of some recent water wells in this area show that the sand and gravel deposits are overlain by at least 55 feet of clay:

| NE 17–29–22, W.2 | Sec. 15–21–23, W.2 | NW 25–28–23, W.2 |
|---|---|---|
| 0–10 sandy top soil | 0–40 sandy brown clay | 0–20 saline soil |
| 10–55 blue clay | 40–70 blue clay | 20–21 sand, gravel |
| 55– sand | 70–78 gravel | 21–58 blue clay |
| | 78–80 brown sand | 58–64 sand |
| flowing 40 gpm | flowing | flowing |
| static level 1′ | static level 4′ | static level 6′ |

The relation between well depth and non-pumping water level in this area shows a decrease in head of 0.80′/ft. to a depth of 25 to 30 feet. Beyond that depth the head increases approximately 0.20′/ft. to at least 160 feet below surface.

Well 13, which is east of Last Mountain Lake at the foot of Last Mountain, is the only flowing well in an area with a general decrease in head with depth of 0.60′/ft. Well 14 was flowing 1½ gpm in an area where there is a decrease in head of 0.80′ per foot increase in depth. Thus, the only area that has a definite positive correlation between static level and depth of drift wells is that north of Last Mountain Lake.

## Deep Groundwater

For convenience, all groundwater that occurs in the bedrock is referred to as deep groundwater. GSC Water Supply Papers list 326 artesian bedrock wells in the area studied by the writer, 71 of which are flowing. It is apparent from the aquifer elevations reported in these Papers that the water is derived from a series of interconnected aquifers (Figs. 2 and 3) in the lower Bearpaw and upper Belly River Formations. A piezometric map of these aquifers for the entire area (Fig. 6) indicates that minor watersheds are no longer discernible, but the main watershed between the Saskatchewan and Assiniboine basins remains a significant feature. The same may be true for the Touchwood Hills drainage divide, but sufficient information is lacking in that area for want of a major aquifer.

The 2,000-foot piezometric contour closes at two places near Darmody (Tp. 21, R.4, W.3), the 1,900-foot contour is closed between Last Mountain Lake and Arm River (Tp. 26, R.27, W.2), and the 1,950-foot contour shows closure near Kenaston (Tp. 29, R.3, W.2) (*see* Fig. 6). Such "piezometric highs" are generally interpreted as indications for recharge ("groundwater creation", Hubbert, 1940, p. 912), but a similar feature was reported from the piezometric surface of the Milk River sandstone (Meyboom, 1960) where it was interpreted as a remnant of an

[1] Logs were made available through the courtesy of the Saskatchewan Department of Agriculture, Water Rights Division.

older piezometric surface left between two expanding cones of depression. The hydrogeological setting of the lower part of the Bearpaw Formation near Darmody seems comparable with that of the Milk River sandstone near Foremost (Alberta). Whether or not the same interpretation may be applied to the Darmody area is discussed later in this bulletin.

The relationship between well depth and non-pumping water level in bedrock wells is shown in Figure 7, taking conditions in tp. 25, ranges 24, 25, and 26 as an example. Wells in range 24 show no increase, whereas those in range 25 show a slight increase with depth of approximately 0.20′/ft. Range 26 is characterized by a small decrease in head with depth. Information available from other areas indicates that at any given place in the Darmody artesian area the water level in bedrock wells is virtually the same for the entire interval between 380 and 480 feet below surface. There is slight positive correlation between depth and static level in the Stalwart-Penzance artesian area (0.20′/ft.); the water levels reported from the Brightwater Creek area show no noticeable differences in head between depths of 369 and 569 feet.

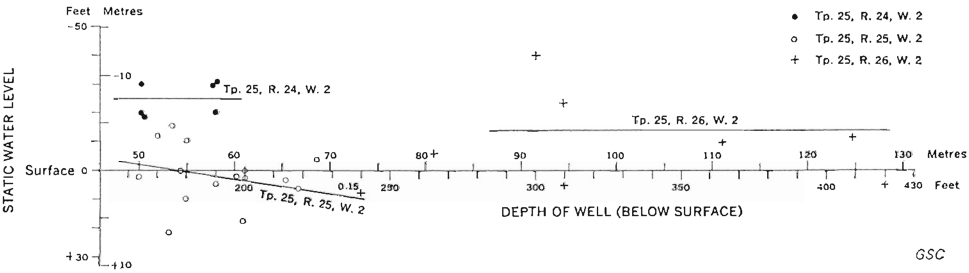


FIGURE 7. Relationship of well depth and static water level in bedrock aquifers.

The picture that emerges differs fundamentally from similar plots for shallow aquifers, nearly all of which showed a significant *decrease* in head with depth.

In the headwater region of Qu'Appelle River there are three major artesian areas associated with the deep bedrock aquifers: (1) Darmody artesian area (Maddox, 1931), (2) Penzance-Stalwart artesian area, and (3) Lanigan Creek artesian area, north of Last Mountain Lake. Although Brightwater Creek artesian area (Maddox, 1932) belongs geographically to the South Saskatchewan drainage basin it has also been included on Figure 6, for it is shown as an integral part of the groundwater system under discussion.

The distribution of flowing wells in these artesian areas seems difficult to explain. They are invariably near a stream or lake, and their distribution in relation to such depressions is either symmetrical or asymmetrical. In the symmetrical distribution the flowing wells are distributed evenly at either side of the depression (Brightwater Creek, north shore of Last Mountain Lake), whereas in the asymmetrical—although the aquifer is known to be continuous—the flowing wells are restricted to one side of the stream (Ridge Creek, west shore Last Mountain Lake).

To summarize, bedrock aquifers differ most strikingly from drift aquifers in that: (1) they are more continuous, (2) they provide a much greater number of flowing wells, (3) they have no change or a slight increase in head with depth, (4) their piezometric surface reflects the topographic surface to a much lesser extent than the water-table map or the equipotential map of the shallow "non-flowing artesian" wells, and (5) the distribution of artesian areas is either symmetrical or asymmetrical in relation to topographic depressions.

The mutual relations and the relative importance of these observations are discussed in the following section; these seemingly unrelated and contradicting phenomena are interpreted in terms of one flow system.

# DESCRIPTION OF THE FLOW SYSTEM

## Selection of Terminology

The following section presents definitions of the hydrologic terms that have been used throughout this report. To avoid misunderstandings that might result from ambiguity of some of the expressions the relation between these terms and the terminology of various text-books is shown in Table III.

The most important property of groundwater with regard to movement is its potential, which has been defined by Hubbert (1953, p. 1959) as:

> The amount of work that would be required to transport a unit mass of the fluid from some arbitrarily chosen standard position and state to the position and state considered.

Elaborating on this definition Hubbert stated:

> For the standard state we may take a closed chamber containing water at an elevation $z_o$ and pressure $p_o$, and the final state is that of the point of interest whose elevation is z and whose fluid pressure is p. The work done in transporting the unit mass of water from the initial system to the final one is composed of work against gravity to lift unit mass from elevation $z_o$ to z and work against pressure required to pump unit mass from chamber of pressure $p_o$ to one of pressure p. The sum of these two terms is the potential which is given by:
>
> $$\phi = g(z-z_o) + (p-p_o)v$$
>
> where g is the acceleration of gravity and v the specific volume of the fluid.

The fluid potential is generally expressed in terms of *total head* hereinafter designated simply as *head,* which is the sum of *pressure head* and *elevation*[1] (Fig. 8).

The pressure head of water at a given point is its hydrostatic pressure expressed as the height of a column of water that can be supported by that column. Pressure head is given as $\frac{p}{\rho g}$, where p is the pressure exerted by a column of water, $\rho$ is the fluid density, and g is the acceleration of gravity. The divider $\rho g$ is commonly written as $\gamma$, which is the specific weight of the fluid. Atmospheric pressure is taken as the datum plane for pressure head and it is convenient to

[1] Sometimes the energy contained by a fluid because of its elevation is referred to as *position head* (Reeve, 1957, p. 397), but the term is avoided here for reasons of ambiguity (Terzaghi and Peck, 1948, p. 41).

| ENGINEERING HYDRAULICS Rouse[1] 1950 (Fig. 8A) | GROUNDWATER HYDROLOGY Todd[2] 1959 (Fig. 8A) | SOIL MECHANICS Terzaghi and Peck[3] 1948 (Fig. 8B) | AGRICULTURE Luthin[4] 1957 Richards[5] 1955 | GROUNDWATER HYDROLOGY present study (Fig. 8C) |
|---|---|---|---|---|
| pressure head $P/\gamma$ | hydrostatic pressure level (refers to confined aquifers only) | piezometric head $U_w/\gamma_w$ | pressure head | pressure head $P/\gamma$ |
| | | | position head | elevation $Z$ |
| | | position head $\Delta H$ | | |
| piezometric head $h = P/\gamma + Z$ | | | hydraulic head | total head $h = P/\gamma + Z$ |
| velocity head $V^2/2g$ | velocity head $V^2/2g$ | | | |
| total head $H = V^2/2g + P/\gamma + Z$ | energy head $P/\gamma + V^2/2g + Z$ | | | |
| head loss $h_1 - h_2$ | head loss $h_l = (P_1/\gamma + Z_1) - (P_2/\gamma + Z_2)$ | hydraulic head $h$ | hydraulic head loss | head loss $h_l = h_1 - h_2$ |
| hydraulic gradient $I = h_l/L$ | | hydraulic gradient $h/l$ | hydraulic gradient | hydraulic gradient $i = h_l/L$ |
| hydraulic gradient (for small angles) $I = h/x$ | | | | |
| hydraulic grade line plot of $P/\gamma + Z$ | | | | |
| free surface | water-table (in the absence of impermeable strata) | water-table | phreatic surface | phreatic surface or water-table $P/\gamma = 0$ at 1 atm. |


References:
1. *Rouse, H., 1950, Engineering Hydraulics, John Wiley and Sons, 720p.*
2. *Todd, D. K.,1959, Groundwater Hydrology, John Wiley and Sons, 336p.*
3. *Terzaghi, K. and Peck, R. B., 1948, Soil Mechanics in Engineering Practice, John Wiley and Sons, 566p.*
4. *Luthin, L. H., 1957, Drainage of Agricultural lands. Am. Soc. Acronomy, Monograph VII, 620p.*
5. *Richards, L. A., 1955, in Yearbook of Agriculture, U.S. Dept. Agric. 723p.*


TABLE III. Relation between common terms used in different fields of hydrology.

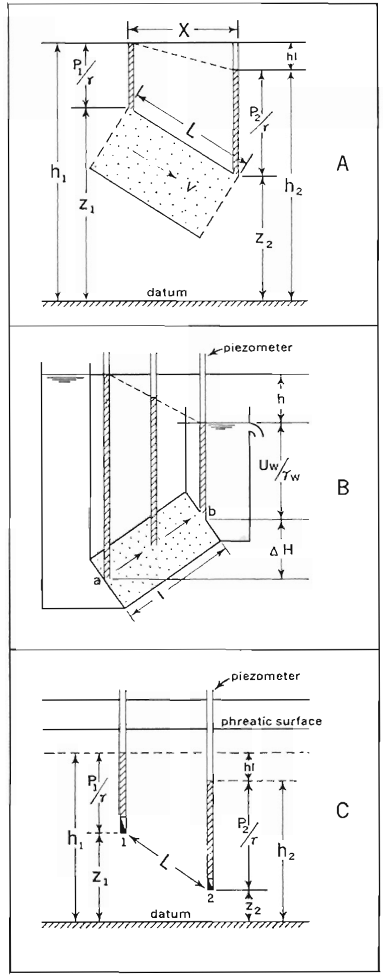

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FIGURE 8. Diagrams showing notations of some common terms in hydrology.

choose sea-level as the datum plane for elevation (z). Total head is thus given by the equation[1]:

$$h = \frac{p}{\gamma} + z$$

It thus follows from the expression of total head that the water level in a tightly cased well (or piezometer) expressed in feet above sea-level is a direct measure of the groundwater potential at the point within the flow system where the well or piezometer terminates (Fig. 8).

Three more terms given on Table III need to be mentioned:

(a) *headloss* which is the decrease in total head $h_l = h_1 - h_2$;

(b) *hydraulic gradient,* which is the change in head per unit distance $i = h_l/L$; and

(c) *phreatic surface,* which is the surface of atmospheric pressure in the flow system, commonly called the water-table:

$$\frac{p}{\gamma} = 0 \text{ at } 1 \text{ atm.}$$

## Patterns of Groundwater Flow in South-Central Saskatchewan

The water wells reported in the 1936 well inventory are, in general, of very simple construction, consisting of an open pipe that connects the aquifer with the surface. As these wells are neither screened nor gravel packed, they may be considered as simple manometer tubes extending into a water-saturated medium. The fluid potentials that exist within this medium are registered by the water levels in these wells, or, as Schlichter (1899, p. 354) has put it "a common well point driven to various depths would doubtless show a water-level corresponding closely to the pressure lines in the (flow) diagram".

It is therefore possible to utilize these levels in the construction of a diagram that shows the vertical potential distribution in the flow medium. To this end three cross-sections were constructed perpendicular to the topographic contours, and the original values of total head of all wells along these sections were entered at the proper elevation. Lines of equal head were then drawn, and the resulting flow diagrams in which the direction of flow is indicated by arrows are shown on Figure 9.

Figure 9 A-B is a plot of the groundwater flow in the region between South Saskatchewan River and Last Mountain Lake. Groundwater movement in this area is chiefly downward through the till and shale to the lower Bearpaw-Upper Belly River aquifer at a depth of about 500 feet. The downward movement is

[1]For groundwater studies the kinetic energy term (velocity head) may be neglected in determining the total head.

characterized by headloss of 0.70′/ft. In the Bearpaw-Belly River aquifer the direction of flow becomes more lateral (compare Ernst, 1962, Figs. 17 and 19). It can thus be seen that recharge to the deep unexposed aquifer is by water that is seeping downward from the overlying poorly permeable beds. This is the first indication that the closed contours that signify the piezometric highs of this aquifer indeed indicate recharge rather than a remnant of a previous piezometric surface. However, recharge is not restricted to the area within the 1,900-foot contour, for all of the terrain between the Saskatchewan-Assiniboine divide and Arm River contributes water to the deep aquifer.

Groundwater flow in the poorly permeable upper Bearpaw shales becomes radial in the vicinity of a drainage channel, such as Arm River, Squaw Creek, or even Qu'Appelle River. It is obvious from the flow patterns that the drainage influence of these streams does not reach beyond a few hundreds of feet at either side of the valley. The net effect is a small local discharge area, superimposed on the regional downward flow.

Groundwater movement near Last Mountain Lake is characterized by upward movement into the Stalwart-Liberty artesian basin, in a zone about 10 miles wide along the western shore of the lake. The increase in head in this area is about 0.15′/ft.

Section C-D (Fig. 9) gives a more complete picture of groundwater movement in the region. As shown in section A-B there is downward movement through the upper Bearpaw shales, accompanied by a headloss of 0.60 to 0.70′/ft. To the west groundwater moves laterally and upward from the upper Bearpaw aquifer into Saskatchewan River (Riverhurst artesian area). The Vermilion Hills cause a distinct groundwater divide to a depth of 1,000 feet, east of which there is a "groundwater stream" in the direction of Arm River. Upward leakage from this stream takes place near Ridge Creek (Darmody artesian basin) and probably near Thunder Creek. Evidence that the main eastward stream is not entirely interrupted by these leakages is shown by the vertical and lateral potential distributions in the aquifer. It is also evident from the chemical metamorphism of the water in the Bearpaw-Belly River aquifer. The water in the Vermilion Hills, for example, is chiefly bicarbonate water, containing up to 1,000 ppm (parts per million) total dissolved solids, whereas the water near Arm River is chloride water, which contains 6,000-7,000 ppm total solids. However, some of this chloride water may be derived from the east, as can be seen from the piezometric map (Fig. 6). This partial Chebotarev[1] sequence suggests that we are dealing with a continuous regional flow system, rather than a succession of disconnected local systems.

[1] Chebotarev (1955) stated that "while the least soluble salts are precipitated first and the most soluble salts last, at any given time and at any distance from the intake area the chemical compounds of higher solubility will be found in water in greater relative abundance". The sodium chloride tends therefore to be in solution as long as the extremely high salinity concentration of water is achieved (35-42%). Chebotarev found that groundwater tends to pass through the following stages of predominant anions: $HCO_3' \rightarrow HCO_3' + Cl' \rightarrow Cl' + HCO_3' \rightarrow Cl' + SO_4''$ (or: $SO_4'' + Cl'$)-$\rightarrow Cl'$. In a discussion of chemical methods as an aid to hydrogeology LeBreton (1962) remarked that experience had shown that this sequence for groundwater in Alberta tended to be: $HCO_3' \rightarrow HCO_3' + SO_4''$ (or $SO_4'' + HCO_3'$)$\rightarrow HCO_3' + Cl' \rightarrow Cl' + HCO_3' \rightarrow Cl'$.

Section E-F (Fig. 9) shows downward movement to a depth of 300 feet and from there lateral movement is inferred. Although control is scarce in this area, there is good evidence that Buffalo Pound Lake exerts little influence on the regional lateral flow. Towards the east, water moves upward from the lower Bearpaw aquifer into the Holdfast artesian basin along Last Mountain Lake.

The seemingly haphazard distribution of flowing wells can be explained by the direction of groundwater movement. For example, the principal direction of groundwater movement in the Bearpaw-Belly River aquifer in Darmody is to the northeast, perpendicular to the surface drainage. Upward leakage from the aquifer towards Ridge Creek is confined to that part of the aquifer that is "upstream" in relation to the topographic depression of the creek. The potentials in the overlying sediments increase upward northeast of Ridge Creek, prohibiting upward leakage "downstream" in the aquifer from Ridge Creek. If the divide northeast of Ridge Creek had been sufficiently high to influence the potential distribution in the deep aquifer (as is so, for instance, along South Saskatchewan River between the Coteau and Vermilion Hills) upward leakage from the deep aquifer would have taken place at either side of Ridge Creek.

The fact that flowing wells are not present everywhere along a uniformly topographic low such as Last Mountain Lake, suggests that the potential distribution due to topographic features is not the only factor that governs the arrangement of artesian areas. As artesian phenomena are essentially a particular case of the tangent refraction-law (Hubbert, 1940), it seems natural that the ratio of permeabilities plays a role also. The absence of flowing wells along the entire length of Last Mountain Lake, where no obvious changes in topography occur might thus be explained by the assumption that the more permeable parts of the bedrock—which would account for the smallest ratio of permeabilities and hence for the most pronounced refractions—are elongated stringers of considerable length (east-west) and limited width (north-south).

Flowing wells in drift aquifers can be explained similarly on the understanding that (with the exception of the area north of Last Mountain Lake) artesian drift aquifers are part of much smaller flow systems, owing to the more restricted occurrence of favourable Pleistocene deposits. The flowing drift wells near Qu'Appelle River are probably within the radius of influence of radial flow of a local discharge area.

These cross-sections permit six conclusions:

1. The sharp contrasts between the hydrological characteristics of shallow aquifers and bedrock aquifers, which were formulated in the summary of the previous chapter, are manifestations of three phases of groundwater flow in a continuous flow system, i.e., downward movement, lateral movement, and upward movement.
2. As no changes in water level warned of significant changes in groundwater storage between 1936 and 1962, it can be assumed safely that the groundwater flow depicted by the three cross-sections is in a steady state.

3. If artesian areas are restricted to one side of a topographic depression where the aquifer is known to be continuous it may indicate (1) that the driving force of the groundwater flow in the aquifer is governed by a potential distribution of a larger magnitude than could be brought about by the topography in the immediate vicinity of the depression; and (2) that the direction of groundwater movement in the aquifer is perpendicular to the direction of surface drainage.
4. If flowing wells are distributed symmetrically around the depression either the direction of groundwater flow may coincide with the direction of surface drainage (north shore of Last Mountain Lake, Brightwater Creek area) or the local topography is such that a symmetrical potential distribution can be established around the depression (South Saskatchewan River).
5. Closed contours on the piezometric surface of the deep bedrock aquifer do signify recharge to the aquifer. Similarly, the fact that some piezometric contours bend inward around surface streams does indicate discharge (upward leakage).
6. Detection of local discharge areas from areal plots of well depth versus static level should not be expected, for the area with actual increase of head with depth is often too small to be noticed statistically. The flow patterns suggest, however, that a significant change in slope of the headloss graph may be observed in areas adjacent to a local discharge area. (Compare Meyboom, 1962, Fig. 7.)

## The Prairie Profile

### Construction of a Model

If the stratigraphy of south-central Saskatchewan is viewed macroscopically, that is, hundreds of feet of sediment underlying hundreds of square miles, it offers a poorly permeable till and shale, overlying the more permeable interval of lower Bearpaw and upper Belly River Formations, which in turn are underlain by poorly permeable shale. The hydraulic conductivity of the combined till and shale section was formerly estimated at less than 1 gallon per square foot per day (1 gpd/sq. ft. = 0.08″/hr. = 0.05m/day) (Meyboom, 1962), but it has to be concluded from tritium counts[1] of water in the Darmody area that the hydraulic conductivity of the poorly permeable beds is less than 0.4 gpd/sq. ft. Pumping tests reported by local drillers indicate that the hydraulic conductivity of the more permeable beds is at least 20 gpd/sq. ft., which gives a permeability ratio of 1:50.

The distribution of pockets of sand and gravel in the till and of local sandstone lenses in the shale is so completely at random and the volumes of poorly permeable material are so large compared to the sizes of the gravel pockets and sand lenses, that the variations of flow velocity superimposed on the mean velocity are too small

[1] Tritium analyses were carried out by Dr. R. B. Brown of Atomic Energy of Canada Ltd.

to be noticed, and it is a good approximation that both till and shale will show isotropic properties with respect to water-flow. A similar reasoning applies to the more permeable interval of the lower Bearpaw and upper Belly River aquifer, and the picture that emerges is one of groundwater flow through a stratified medium, consisting of isotropic layers of different hydraulic conductivities, which are related at least as 1:50. The model of such a flow system is shown on Figure 10. Because of its applicability to conditions in western Canada, the model has been called the Prairie Profile (Meyboom, 1962).

By definition the Prairie Profile consists of a central topographic high bounded at either side by an area of lower elevation. Geologically, the profile is made up of two layers of different permeability, the upper layer having the lower permeability. Through the profile is a steady flow of groundwater from the area of recharge to the area of discharge. The ratio of the permeabilities is such that groundwater flow is predominantly downward in the poorly permeable layer and predominantly lateral in the permeable layer. Groundwater movement in both layers is upward underneath the topographic low areas, owing to the potential distribution in the profile, which is expressed by the differential equation of Laplace.

By definition, areas of recharge overlie those parts of the flow system that are characterized by a decrease in head with increasing depth[1]. It is essential to point out that the degree of decrease depends on the permeability of the flow medium and on the distance of the point measurement from the boundary between recharge area and discharge area (the "midline" of Toth, 1962). As was mentioned previously, the decrease in head in the Vermilion Hills ranges from 0.85′/ft. near the watershed to 0.20′/ft. towards Thunder Creek.

Nevertheless, when tapping a slightly more permeable zone in an area of predominantly downward flow, groundwater in the bore-hole may rise noticeably. This, however, is by no means a sign of "artesian conditions", but merely an indication that the static water level can establish itself there more rapidly than elsewhere in the section. Given sufficient time, virtually the same level would have been recorded if the entire section had been shale. If, on the other hand, this phenomenon is used as a criterion for artesian conditions (Todd, 1959, p. 229) and subsequently as the basis for the construction of a piezometric surface, the result would be a map showing close agreement between topography and "piezometric surface", for it would simply be a plot of the intersection of the topography with virtually horizontal equipotential planes.

A flowing well may occur in an area of overall downward flow, as is illustrated on Figure 11. Artesian or flowing wells will occur at any place where the potential at the bottom of the well exceeds that at the surface, and vertical wells terminated in the hatched part of Figure 11 will therefore flow. The flow will increase with depth as far as the boundary of the region of radial movement; beyond that, the

[1]Schlichter (1899, p. 354) already stated this condition in his theoretical model of a recharge area.

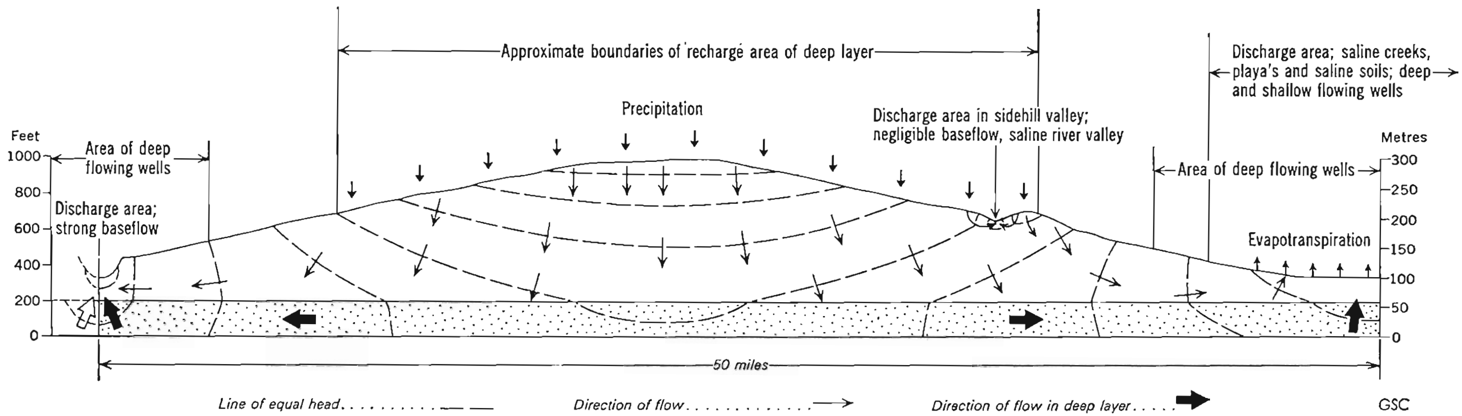


FIGURE 10. The Prairie Profile

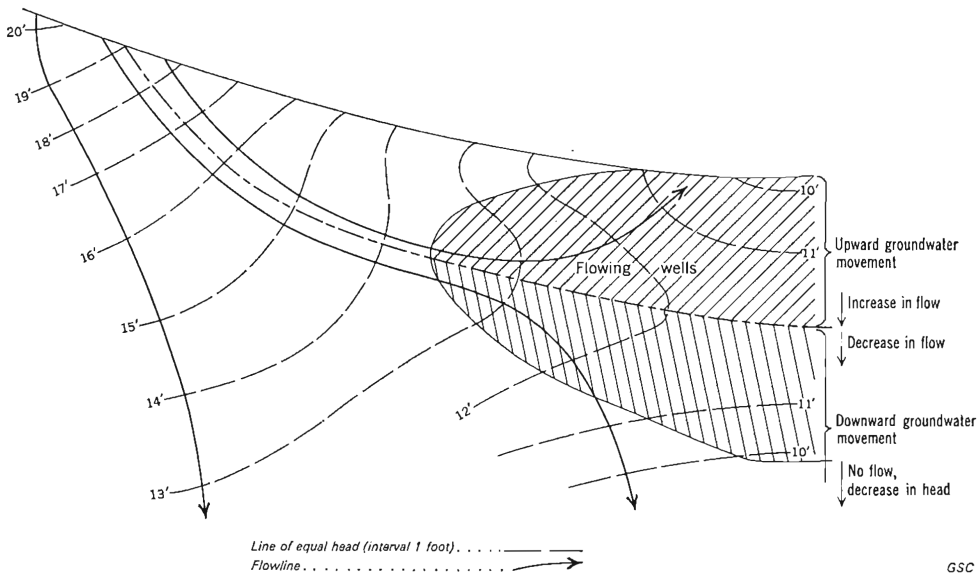


FIGURE 11. Diagrammatic explanation of case histories reported from the Souris River valley (Selwyn, 1881) and Qu'Appelle River valley (Simpson, 1929; city of Regina, 1961).

flow will diminish with depth and finally cease altogether. The level will then fall if deeper drilling is undertaken. The water well referred to by Simpson (1929) and the test well of the city of Regina[1] are field examples of this situation.

Thus, artesian wells are no infallible indications of any particular hydrogeological environment and it is suggested that the term "artesian" should be stripped of its wide connotations and that Webster's definition be adhered to, which states "artesian wells are made by a boring in the earth till water is reached which, from internal pressure, flows spontaneously like a fountain."

By definition, areas of discharge exhibit an increase in head with depth. Upward movement in aquifers of low permeability will take place within an area of radial flow underneath a drainage channel or because of the regional potential distribution at the discharge side of the Prairie Profile. For instance, in the headwater region of Qu'Appelle River the increase in head with depth ranges from 0.09'/ft. underneath Ridge Creek to 0.25'/ft. in the Bearpaw aquifer of the Stalwart artesian basin.

The boundary between recharge area and discharge area can be constructed conveniently by means of vertical cross-sections based on field measurements. The relation between well depth and static water level may then be employed as an additional means of identifying certain parts of the flow system.

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[1] The following information was kindly supplied by the Saskatchewan Department of Agriculture, Water Rights Division. The city of Regina had located a test well in NW ¼ sec. 27-20-20, W.2, in the Qu'Appelle Valley at Craven. At 152 feet the static level was 5 feet below surface; at 160 feet the well flowed. The flow decreased with increasing depth and the static level was again 5 feet below surface at a depth of 240 feet. The entire profile was a succession of sand and clay layers, ranging from 5 to 10 feet in thickness.

A constant head with depth will be observed in those parts of the flow system where the flow is chiefly lateral. It should be stressed that the condition of lateral flow is the sole prerequisite for the quantitative use of a piezometric map (Hubbert, 1940, p. 911; de Jong, 1960), and it is misleading to believe that the quantitative use of a piezometric surface is justified by the occurrence of so-called artesian conditions.

### Examples of the Prairie Profile

An interesting feature of the complete Prairie Profile is its symmetry, as illustrated by: (a) the Brightwater Creek artesian basin west of the Allan Hills, which has its counterpart in the artesian area north and west of Last Mountain Lake; (b) the position of the Darmody and Riverhurst artesian areas, which is symmetrical in relation to the Vermilion Hills; and (c) the Pleistocene aquifers from near Regina (Lissey, 1962) as far as Indian Head, which have artesian conditions at either side of Moose Mountain Upland. The last example represents a situation where the entire profile is developed within Pleistocene deposits.

However, the picture is not always as complete as these examples suggest, because of the insufficient lateral extent of the permeable layer. Often, only half of the profile can be recognized, consisting of a topographically high recharge area and only one adjacent low discharge area. It is probable that such a *partial prairie profile* is the most common setting for artesian areas in western Canada. Recharge takes place through the poorly permeable layer (the "confining layer" of the classical model) and natural discharge occurs as upward leakage in the adjacent lowland. The partial prairie profile may offer a satisfactory explanation of the Carnduff artesian area (Johnston, 1934) and even for parts of the Milk River sandstone (Meyboom, 1960).

## A Comparison with Other Flow Systems

### St. Peter Sandstone in Illinois

Foley and Smith (1954) described how the thick and extensive sandstone aquifers of Cambrian and Ordovician age that underlie southern Wisconsin and Illinois do not receive their recharge at the outcrop area, as was required by the classical model of an artesian aquifer, but rather through several hundred feet of overlying Palaeozoic and Pleistocene strata. The extent of flow systems associated with this aquifer can be seen from their Figure 3. For instance, the flow system between Rock River and Illinois River is about 70 miles, and from the piezometric map of that area, it can be inferred that the system may extend as far as Lake Michigan. Its vertical dimension is 1,200 feet. Thus the hydrogeological setting of the St. Peter Sandstone in Illinois seems wholly analogous to the Prairie Profile in south-central Saskatchewan.

## Dakota Sandstone

At first glance it seems that both Darton (1918) and Hubbert (1953) accepted the coincidence of geological outcrop and topographic high as an essential feature of a recharge area for an artesian aquifer, but Hubbert (1953, p. 2012) did state that:

> . . . even if the strata do not crop out, but extend from a region of higher to one of lower topography, a circulation may result with water entering and leaving through the somewhat permeable overburden.

These, in essence, are the requirements for the Prairie Profile. The piezometric surface of the Dakota Sandstone (Hubbert, 1953, Fig. 36) shows an enormous flow system, extending over 500 miles from the Laramie range to Minnesota and apparently undisturbed by such large rivers as Platte and Missouri. If, indeed, the flow system in this sandstone is influenced so little by the topography, it would be one of the largest flow systems of this nature yet described.

## The Dutch Profile

The entire northwestern Netherlands presents an interesting comparison with the Prairie Profile in that the entire area is underlain by highly permeable alluvial sands, covered by dense clay and peat deposits. Water moves vertically downward through the somewhat permeable clay and laterally in the underlying sands. All reclaimed areas in the province of Noord Holland are thus underlain by a huge unexposed artesian aquifer, for the topographically lower polders are the natural discharge areas for this flow system. The upward leakage into these polders poses serious drainage problems. The situation was first described by Van Royen (1905) and all pertinent information was later summarized by Volker (1954). Figure 12 is a diagram of the Haarlemmermeer polder near Amsterdam.

## Drainage of Stratified Soils

Notwithstanding the difference in size, the Prairie Profile finds another interesting analogy in the drainage systems that were described and calculated by Ernst (1954, 1962). He stated that groundwater flow through an arrangement of permeable and less permeable soils may be schematized by vertical flow through the slightly permeable soil (so-called principle of De Glee), horizontal flow through the permeable soil (so-called principle of Dupuit), and radial flow in the vicinity of open drainage channels. Ernst (1954) pointed out that this approximation is valid as long as the KD value of the poorly permeable soil is less than 10 per cent of the KD value of the permeable soil. If the KD value of the poorly permeable soil is more than 10 per cent of that of the permeable layer, the profile has to be considered homogeneous. Ernst's flow patterns of drainage in multi-layered soils (1962, Fig. 19) show striking resemblances to the patterns of groundwater flow in south-central Saskatchewan.

It seems advisable to investigate briefly whether this comparison is justified. The thickness of the slightly permeable layer in the Prairie Profile of south-central

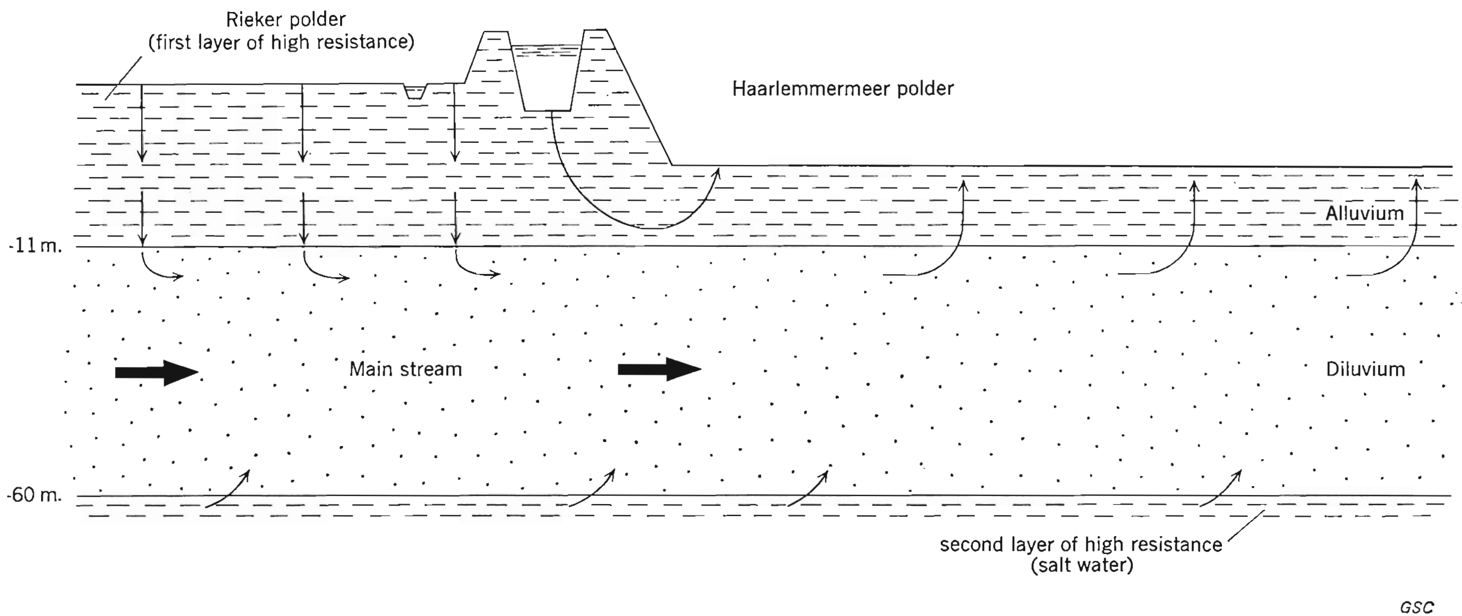



FIGURE 12. Example of a flow pattern comparable to that in the Prairie Profile (*after* Van Royen, 1905, Fig. 4).

Saskatchewan ranges from 100 feet near Last Mountain Lake to 500 feet in the Vermilion Hills. The thickness of the permeable layer may range from 20 feet near Last Mountain Lake to more than 100 feet in the Vermilion Hills, giving rise to a ratio of KD values of at least 1:10. This quick estimate shows that even under the Vermilion Hills the theoretical requirements for a stratified flow medium are probably met.

What other conditions might justify this analogy? Bhattacharyya (1963) calculated the conditions of similitude for model studies of groundwater flow. He found that if the ratio

$$\frac{(K_o/P_o)^{1}{}_{m}}{(K_o/P_o)_{f}}$$

remained unchanged in both systems the time scale of any phenomenon occurring in the model (agricultural drainage) had to be reduced by the scaling factor of length. In other words: if we multiply the length parameter of an agricultural drainage system by 1,000 in order to arrive at a condition of groundwater flow, any phenomenon occurring on the larger scale will take place one thousand times slower than in the small-scale system.

It thus seems justified to utilize this analogy and to employ quantitative drainage solutions for problems of large-scale groundwater flow, provided that the above conditions are satisfied. However, as yet, the available field information regarding hydraulic conductivity and porosity is insufficient to predict the extent to which this analogy may be applied to conditions in western Canada.

[1] K=hydraulic conductivity
P=porosity
$K_o/P_o$=unit quantity of the parameter K/P
m, "model" (agricultural drainage)
f, "field" (groundwater flow)

# MANIFESTATIONS OF THE FLOW SYSTEM

## The Nature of Groundwater Outcrops

To be of any value as a working hypothesis the Prairie Profile must afford certain criteria that can be used to map the various parts of the flow system in a classical geological method, that is, by means of the study of a large number of individual observations. To this end it must be understood in what ways areas of discharge and areas of recharge manifest themselves; in other words, it is necessary to understand the nature of groundwater outcrops.

### Willow Rings

Willow rings commonly occur around small circular depressions about 100 to 500 feet in diameter. About 50 per cent of the rings surround a permanent body of water. The depressions which are completely surrounded by higher ground constitute miniature drainage basins of up to 1,000 feet in diameter. Willow rings are present throughout the prairie but are most characteristic of areas of hummocky moraine, which in central Saskatchewan are more than 2,200 feet above sea-level. Consequently, all principal watersheds are in areas of hummocky moraine, or—in terms of hydrogeology—many important recharge areas are in hummocky moraine.

During the summer of 1962, a preliminary study was made of the groundwater flow in one nearly circular depression 500 feet in diameter with a relief of 25 feet. The depression is one of many in the knob-and-kettle topography that is typical of the Allan Hills (Pls. I A and B) north of Davidson. The position of these hills in the regional flow system is shown on Figure 9.

Early in June the centre of the depression was still occupied by a slough, which was surrounded by a well-developed willow ring, approximately 100 feet in diameter. Early in July, after the slough had dried up, the area within the willow ring became covered by water parsnip (*Sium cicutaefolium*) and wild mint (*Mentha arvensis* var. *villosa*). The vegetation outside the ring consisted of ordinary dry-prairie grasses.

Three nests of three piezometers each, ranging in depth from 5 to 50 feet, were set across the depression in order to obtain a vertical cross-section of the flow pattern. The results of the experiment are shown on Figure 13A. The measurements indicate that most groundwater taking part in the regional flow originated in the immediate vicinity of the knob. Towards the centre of the depression, the flow pattern deviated in the sense that within a region of approximately 50 feet outside the willow ring groundwater flowed towards the willow ring and probably upward into the depression.

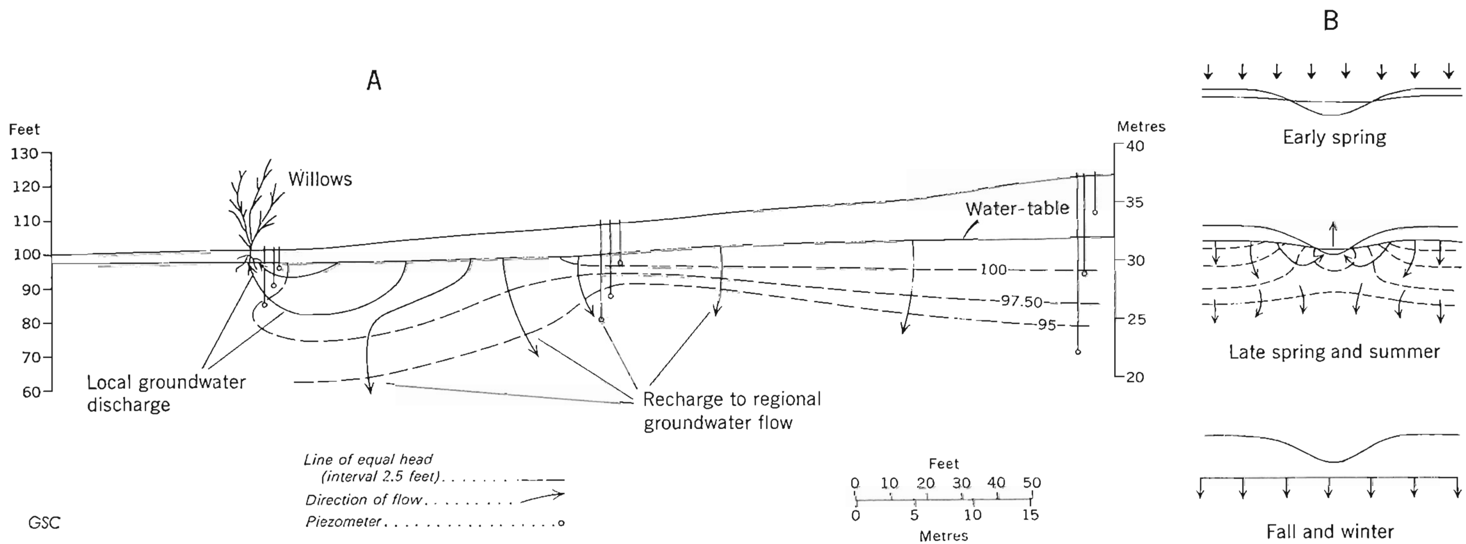



FIGURE 13. Groundwater flow in knob-and-kettle topography, near Davidson, July 7, 1962.

*P.M., 1-5-62*

A. General view of willow rings in the hummocky moraine of the Allan Hills near Davidson.

PLATE I


*P.M., 1-12-62*

B. Close view of a willow ring, showing plant zonation: 1, *Eleocharis palustris* zone; 2, *Mentha arvensis* var. *villosa* zone; 3, *Salix* sp. zone; 4, dry prairie.

*P.M., 1-26-62*

PLATE II. Freshwater phreatophytes in Arm River valley near Chamberlain, Saskatchewan. The chief phreatophytes in the bottom of the valley are wolf willow and willow.

During the time of the experiment the water-table underneath the centre of the depression had receded to 2.7 feet below the surface and all groundwater discharge out of the pothole must have taken place by evapotranspiration through the willows. Towards the end of July the head difference between the piezometers in the willow ring still indicated upward flow, but the water-table had dropped to 3.3 feet below surface. It is inferred on Figure 13B that groundwater discharge out of the depression ceases altogether as soon as the willows become dormant in the autumn, at which time (perhaps in October) the entire region of the hummocky moraine contributes to the regional groundwater flow. The cycle starts anew in the spring (May or June) when melting snow and spring rains cause a rise in the water-table.

It thus appears that many recharge areas are covered with thousands of little discharge areas, each one characterized by a ring of willows.

In places where the willows do not surround permanent water, the increasing moisture content towards the centre of the depression is still marked by concentric rings of vegetation (Pl. II), such as creeping spike rush (*Eleocharis palustris*) occupying the centre area (wet), *Mentha arvensis* var. *villosa* in a ring around the centre (moist), and willows around this zone.

Salinity measurements that were carried out in a great number of ponds surrounded by willows indicate that the willows have a very low tolerance for saline (alkali) conditions. They are generally associated with water that contains less than the equivalent of 25 grains per gallon (gr/g) NaCl, or which has a conductance of less than 700 micromhos per cm. Groundwater of such low concentrations has not travelled far, a fact that is in agreement with the positions of most willow rings on top of the recharge areas. But willow rings are not confined to the watershed areas, and their occurrence elsewhere in the drainage basin may give important clues regarding local flow systems superimposed on the regional groundwater flow.

## Saline Soils

Soils are considered to be saline if their superficial or deeper horizons contain a considerable amount of sodium salts. Saline soils can be differentiated into solonetz soils and solonchak soils. Solonetz soils consist of a grey, loose, stratified A horizon and a dark columnar and very compact B horizon. Solonchak soils have no distinct horizons and contain soluble salts throughout their entire depth. Vilenskii (1957, pp. 390-424) distinguished between solonetz soils and solonchak soils on the basis of salt content rather than on structure, in that solonchak soils contain *white alkali* (sodium sulphates) and solonetz soils contain *black alkali* (sodium bicarbonate). This classification could not be confirmed from the North American literature.

As to the origin of solonchak soils Vilenskii (1957, p. 394) stated explicitly

> Mineralized groundwaters when lying close to the surface ascend to the surface along capilaries and evaporate, leading to an accumulation of readily soluble salts in the superficial soil layers, and the formation of solonchaks.

Polynov (as quoted by Vilenskii, loc. cit.) introduced the concept of *critical depth* of groundwater, meaning the maximum depth of the water-table for which soil salinification is possible.

With regard to vertical zonation of soils Vilenskii reported (1957, p. 395):

> On high areas of the terrain, on water divides lie the non-salted soils, on the second-third of the slope they turn into weakly salinified and sub-salinified soils, that become temporarily salinified in dry years; the solonetz soils are distributed in the lowest third of the slope, while solonchaks are distributed on the floodland banks of the river valleys.

It is of interest to recall here that Kelly and Spillsbury (1949) recognized exactly the same sequence of soil groups in the Okanagan Valley in British Columbia. They simply called the soils in the river valley "groundwater soils".

Saline soils are common on the Canadian prairie and the salts they contain are mainly sulphates of sodium, magnesium, potassium, and calcium, with possible minor amounts of carbonate, bicarbonate, and chloride (Bowser, 1961). Bowser also recognized a vertical zonation of soils, in which the non-saline occupy the highest grounds, various stages of the solonetz occupy successively lower areas, and the solonchak occur in the lowest positions. But, contrary to Vilenskii, Bowser was of the opinion that solonetz soils are derived from solonchak soils whereby the high salt content of the original saline materials is leached out and soil horizons develop by means of a process of deflocculation near the surface and reflocculation at greater depth. This theory might be called the "parent material theory", as opposed to the "groundwater theory" of Vilenskii.

According to Mitchell, *et al.* (1944, p. 77), the saline soils of Saskatchewan are white alkali soils, containing an excess of Glauber salts ($Na_2SO_4$), epsom salts ($MgSO_4$), and common salt ($NaCl$). The soils map of Saskatchewan (op. cit.) shows several areas of saline soils in and around the headwater region of Qu'Appelle River. The writer has studied each of these carefully and can explain their origin in terms of groundwater flow in the Prairie Profile. However, before a systematic description of the saline soils is given, it is necessary to elaborate somewhat on the vegetation of such areas, for plants are the most useful field criteria for saline conditions.

### *The Vegetation of Saline Soils*

Notwithstanding the continuous supply of water that may exist in saline soils, the concentration of salts generally prohibits the development of an ordinary prairie vegetation. Plants that grow under saline conditions are adapted to this unique environment in two ways: (1) they are able to exert high osmotic pressures (Walter, 1960, p. 482), which provides them with a mechanism to maintain a diffusion of water from the saline soil into the plant; and (2) they are able to regulate the salt concentration in their tissue, which safeguards them against the danger of accumulating toxic amounts of salt (regulation type), or the plant is not affected adversely by a continuously increasing salt content (accumulation type). The degree of salt tolerance of the natural vegetation depends solely on the degree to which these factors are developed, and an increase in soil salinity is therefore clearly reflected by marked changes in the vegetation.

The following salt-tolerant plant species are common on the Canadian prairie (Budd, 1957; Dodd, 1960).

Medium salt tolerance:

Greasewood, *Sarcobatus vermiculatus*[1] (Hook.) Torr.
Russian thistle, *Salsola pestifer* A. Nels
Gumweed, *Grindelia perennis* A. Nels
Mat muhly, *Muhlenbergia richardsonis* (Trin.) Rydb.
Poverty weed, *Iva axillaris* Pursh.
Saline plantain, *Plantago eriopoda* Torr.

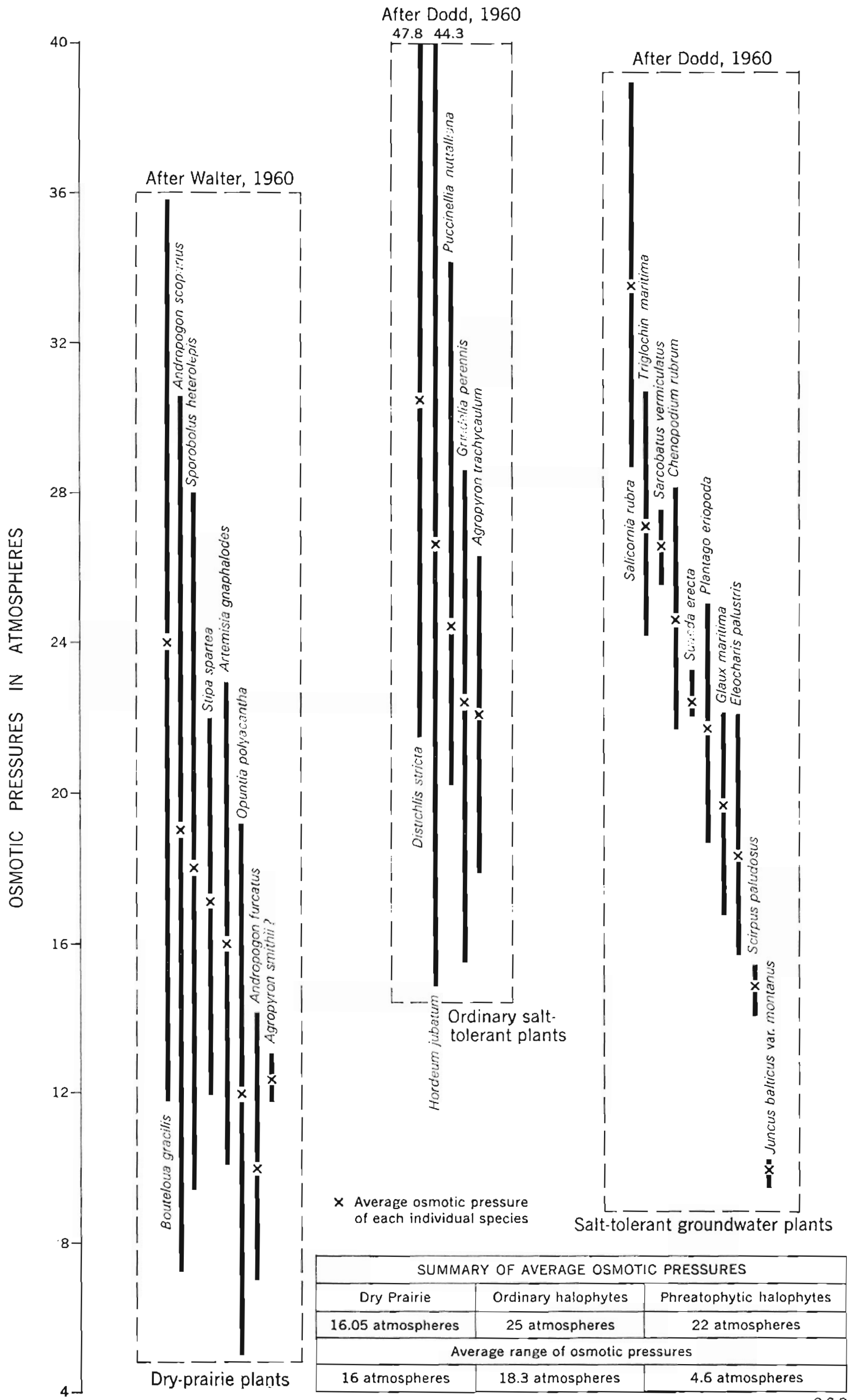
High salt tolerance:

Saline goosefoot, *Chenopodium salinum* Standl.
Creeping spike-rush, *Eleocharis palustris* (L.) R. & S.
Sea milkwort, *Glaux maritima* L.
Perennial sow thistle, *Sonchus arvensis* L.
Salt marsh sand-spurry, *Spergularia salina* J. & C. Presl.
Nuttall's alkali grass, *Puccinellia nuttalliana* (Schultes) Hitchc.
Prairie bulrush, *Scirpus paludosus* A. Nels
Baltic rush, *Juncus balticus*[1] Willd. var. *montanus* Engelm.
Western sea-blite, *Suaeda depressa*[1] (Pursh) S. Wats and *S. depressa* var. *erecta.*
Red samphire, *Salicornia rubra*[1], A. Nels
Red goosefoot, *Chenopodium rubrum* L.
Halberd-leaved orache, *Atriplex hastata*[1] (L.) Gray
Salt grass, *Distichlis stricta*[1] (Torr.) Rydb.
Wild barley, *Hordeum jubatum* L.
Seaside arrow grass, *Triglochin maritima* L.

The coincidence between phreatophytes and halophytes is not so surprising if the function of osmotic pressure is understood. The osmotic pressure can be considered to be a reflection of the various environmental factors on the plant. When the atmosphere removes water from the plant faster than it can be replaced from the soil, water is withdrawn from the plant tissue, resulting in an increase in osmotic pressure. Similarly, the plant has to increase its osmotic pressure if there is an increase in salt content of the soil moisture. Owing to the seasonal variations in soil-moisture concentration, most plants have low osmotic pressures during spring time and maximum osmotic pressures at the end of the summer. Walter (1938), who was the first to use this feature as an ecological criterion, introduced the term *osmotic spectrum* to describe this range between extreme osmotic values during one period of vegetation.

In his extensive study of plant successions in the saline areas of Saskatchewan, Dodd (1960) demonstrated that, compared to ordinary prairie vegetation, some halophytic species have a very narrow osmotic spectrum (Fig. 14). This led him to the conclusion that plants with such limited spectra had to rely on groundwater, this being the only continuous moisture supply of relatively constant concentration

[1] It is worth noting that six of these species are included in Robinson's list of American phreatophytes (Robinson, 1958). Phreatophytes (literally, well plant) are plants that satisfy their moisture requirements from groundwater rather than soil moisture. Meinzer (1923) was the first to recognize their importance as groundwater indicators in arid and semi-arid areas.




| SUMMARY OF AVERAGE OSMOTIC PRESSURES | | |
|---|---|---|
| Dry Prairie | Ordinary halophytes | Phreatophytic halophytes |
| 16.05 atmospheres | 25 atmospheres | 22 atmospheres |
| Average range of osmotic pressures | | |
| 16 atmospheres | 18.3 atmospheres | 4.6 atmospheres |

GSC

FIGURE 14. Comparison of osmotic spectra of dry-prairie vegetation and salt-tolerant vegetation.

(Dodd, 1960, pp. 214-222). It is obvious why this conclusion is of great importance in the understanding of saline areas as groundwater outcrops. He listed the following species as "groundwater species": *Triglochin maritima, Sarcobatus vermiculatus*[1], *Chenopodium rubrum, Suaeda erecta*[1], *Plantago eriopoda,* and *Eleocharis palustris.*

### *Saline Soils Related to Regional Flow Systems*

*Area North of Last Mountain Lake*

The area north of Last Mountain Lake in townships 29-36, within ranges 21-24, W.2 was referred to by early travellers as "The Great Salt Plains" (Macoun, 1882, pp. 84-85). The region occupies the wide depression between Touchwood Hills to the east and Allan Hills to the west, and it is drained by three intermittent creeks that flow from the north into Last Mountain Lake (Fig. 16). The saline soils of this area have developed on sandy loams of the Biggar association, the parent materials of which are glacial outwash deposits and eroded till (Mitchell, *et al.*, 1944). Most of the meadows in the Great Salt Plain show large patches of salt efflorescence on which only a few plant species are able to survive (*Salicornia rubra and Suaeda depressa*).

It seems that all halophytic plant communities in this area are essentially composed of six or seven species, each one of which may be dominant locally. All other conditions being equal, it appears that slight differences in soil texture determine the dominance of a particular species. Another interesting feature is the zonation of plant communities. Figure 15 shows some of these sequences as they were found around sloughs and lakes of the Great Salt Plain. They are all variations of Dodd's classification of "a sequence beginning in a wet saline depression" (Dodd, 1960, Fig. 22). It may be inferred from the osmotic spectra in Figure 14, that a sequence such as the one in SW 1/4 sec. 28-28-22 is entirely dependent on a continuous groundwater supply, whereas the sequence in NW 1/4 sec. 24-28-23 depends on groundwater to a much lesser extent.

The presence of small willow groves in the middle of the salt plains needs to be mentioned. At two places in Tp. 29, R. 23 (Fig. 16) the saline vegetation has given way to freshwater phreatophytes, of which *Salix* sp. is the most conspicuous representative. Close examination revealed that the willows and rose bushes fringe small ridges, which may be sufficiently high to permit the existence of a local flow system superimposed on the regional discharge phenomena. This feature is even more pronounced east of Stalwart and is discussed in more detail under *Stalwart-Holdfast area.*

Two hydrologic features are apparent (Fig. 16): (1) the water-table—or more exactly the non-pumping water level in wells that are less than 20 feet deep—is seldom more than 10 feet below surface; and (2) the area coincides with the artesian basin discussed under *Patterns of groundwater flow in south-central Saskatchewan.* Flowing wells, both in the channel deposits and in the bedrock, that range in depth from 50 to 365 feet are common throughout the area.

[1] Also listed in Robinson's list of American phreatophytes.

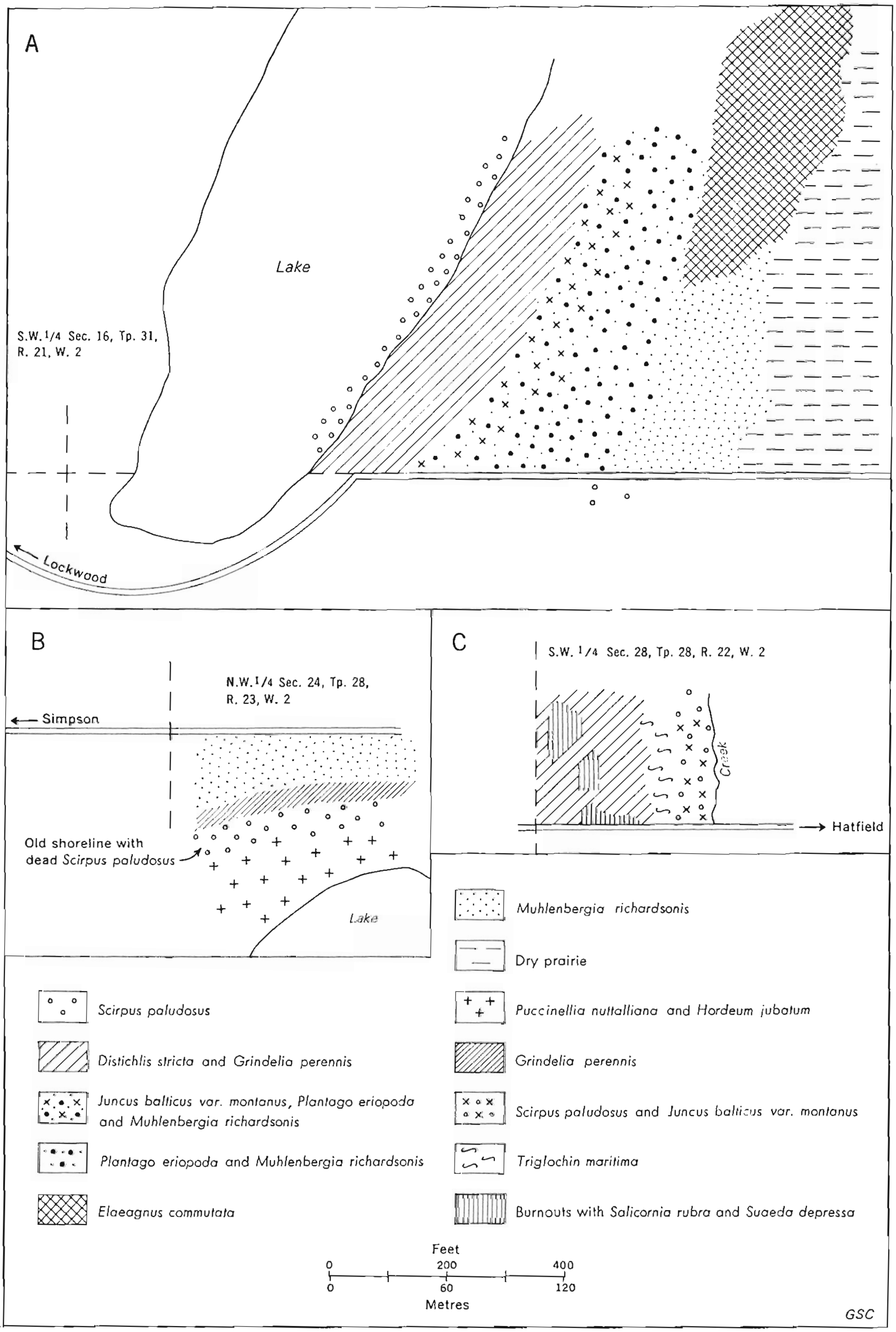



FIGURE 15. Typical zones of plant communities around wet saline depressions in the Great Salt Plain.

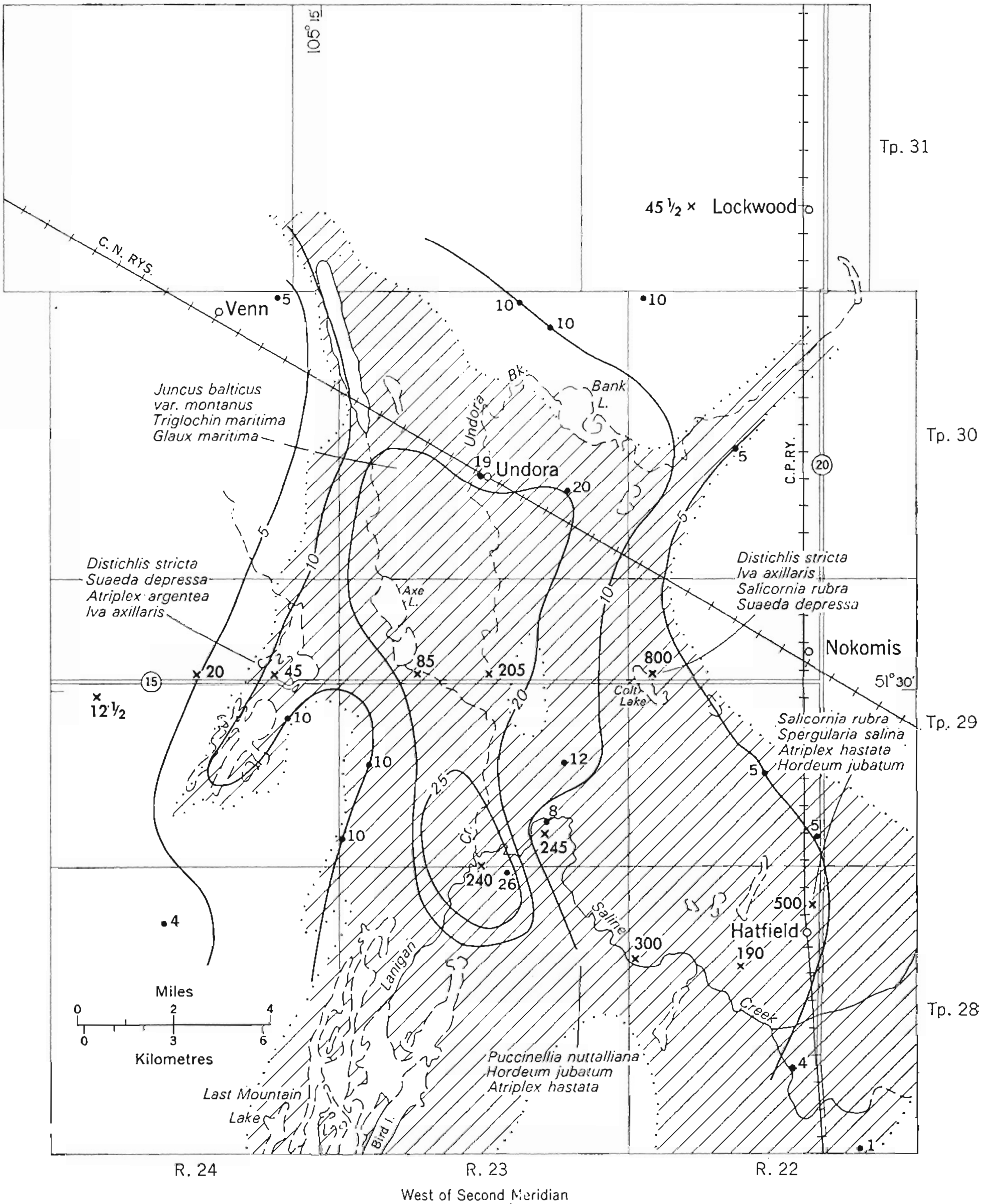
Figure 16 shows lines of equal head difference between the total head in the artesian wells and that in the water-table wells. The maximum head difference is about 25 feet at the axis of the depression. Hence, maximum upward leakage from the underlying artesian aquifer takes place there, whereas upward leakage diminishes towards the margins. These observations indicate that the saline soils north of Last Mountain Lake may be caused by the evaporation of ascending groundwater containing up to 3,000 ppm total solids. As such, the soils of the Great Salt Plain are comparable to the classical examples of "saline soils overlying an artesian aquifer", which were described from the Cache Valley in Utah (Israelsen and McLaughlin, 1932) and from the Imperial Valley in California (Christiansen, 1943).

*Stalwart-Holdfast Area*

The second extensive saline area that is considered to be characteristic for the discharge end of the Prairie Profile exists between Stalwart and Holdfast (Fig. 17) in townships 23-26, within ranges 24, 25, and 26. The saline soils near Stalwart have developed on glacial outwash deposits (Biggar sandy loam) and on till (Weyburn loam). The solodized-solonetz soils east of Liberty belong to the Echo association, whereas the soils near Penzance and Holdfast are Weyburn light loams, developed on till. The position of this area on the gently sloping terrain between the Arm River drainage divide and Last Mountain Lake, makes it also a good example of a discharge area below a "midline" in the sense of Toth (1962).

The area of saline soils coincides to some extent with the Stalwart-Holdfast artesian basin, and the surface manifestations of artesian leakage are similar to those at the Great Salt Plain. The fields are covered with characteristic plant associations and burnouts are numerous. The most extensive salt areas are east of the Canadian Pacific Railway line between Penzance and Holdfast, where the meadows show a sparse vegetation of *Distichlis stricta, Iva axillaris,* and *Suaeda depressa* var. *erecta*. The plant communities of this area are rather monotonous as compared with those of the Great Salt Plain. The fiery red spots of *Salicornia rubra* are uncommon and the pale green colours of the saltgrass community dominate the scene.

A map of the head difference of the artesian wells and water-table wells (Fig. 17) indicates that most upward leakage occurs north and south of Penzance, whereas it seems to be hampered in townships 24, 25, and 26, ranges 23 and 24, probably due to a local flow system that has developed in the slight rise of land between the Canadian Pacific Railway line and Last Mountain Lake. The resulting non-saline area is fringed with willow bushes and low stands of buck brush (*Symphoricarpos occidentalis*). Similar conditions exist east of Liberty and along the ridge of outwash deposits northwest of Stalwart. A working hypothesis to explain this situation is shown diagrammatically in the cross-section on Figure 17. Evidence for the upward flow from the regional system underneath the local flow system in the ridges is indicated by flowing wells in the non-saline area.




## LEGEND

*Saline soil (from Mitchell, 1944, Map No. 3)* . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . .

*Salinity measurement of surface water in equivalent grains per gallon, sodium chloride* . . . . . . . . . . × 400

*Head difference, in feet, between piezometric surface of artesian aquifer and water-table* . . . . . . . . . . • 12

*Approximate line of equal head difference, in feet, between piezometric surface of artesian aquifer and water-table* . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 25

*GSC*

**FIGURE 16. Hydrologic features of the Great Salt Plain.**

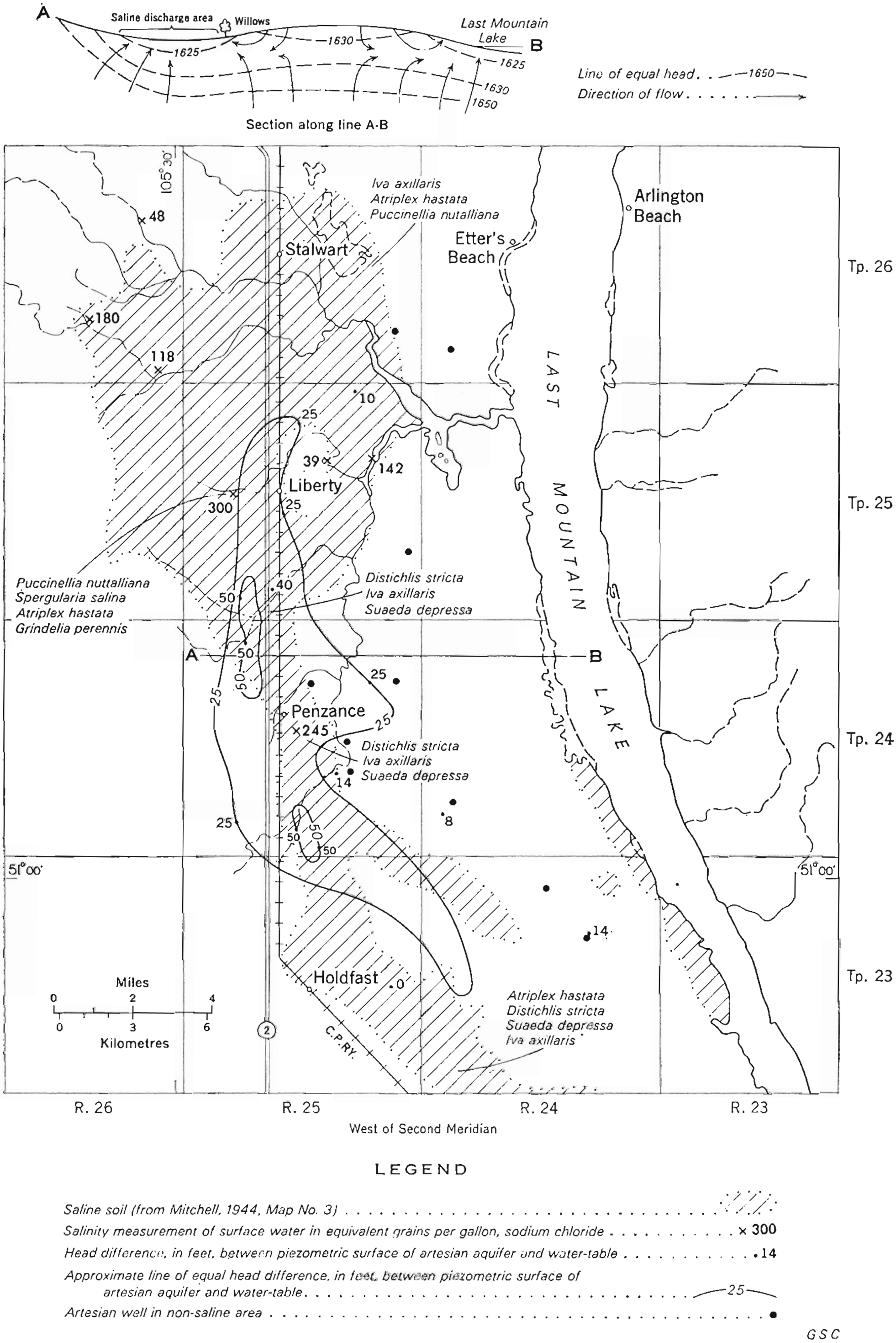
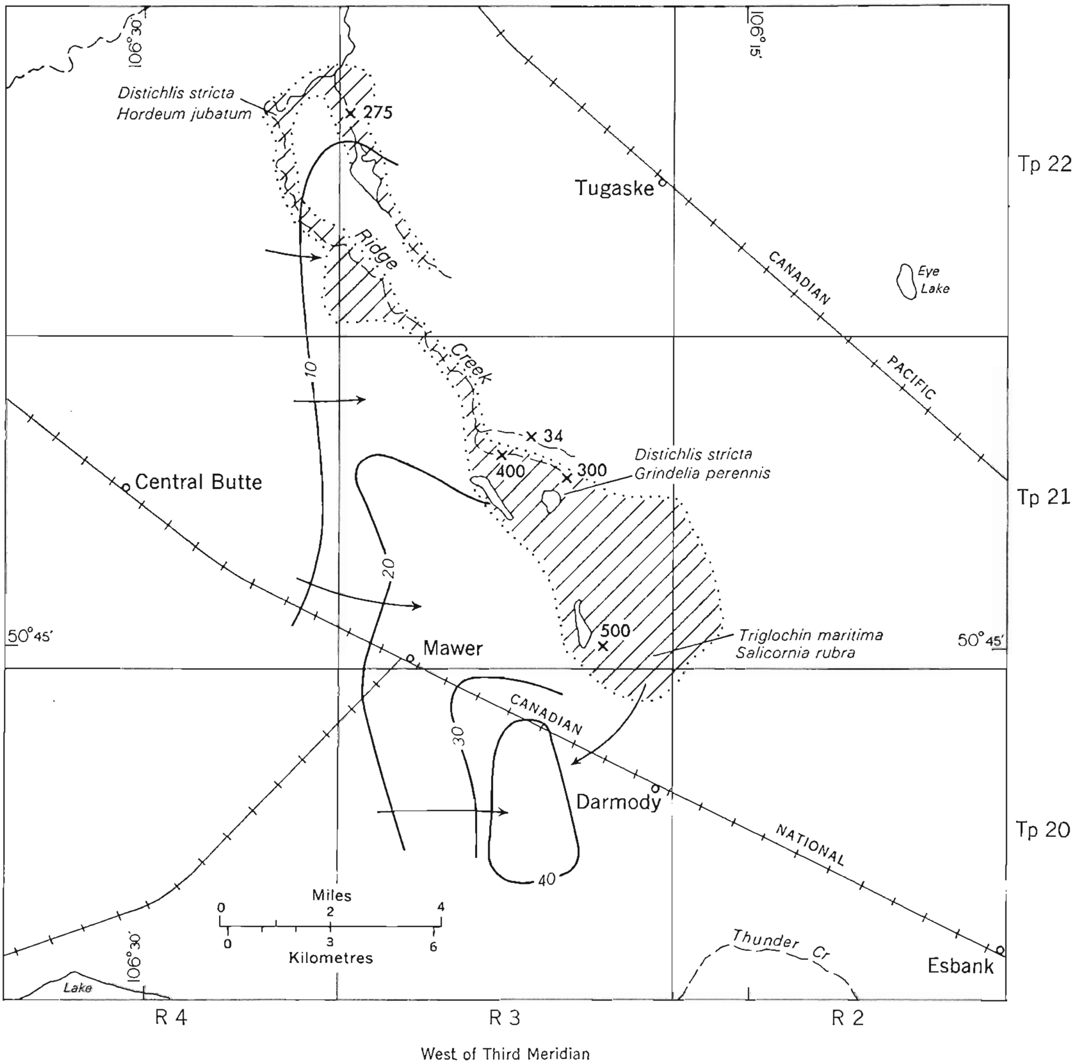



FIGURE 17. Hydrologic features of the Stalwart-Holdfast area.




LEGEND

*Saline soil (revised from Mitchell, 1944, Map No. 1)*

*Salinity measurement of surface water in equivalent grains per gallon, sodium chloride* × 400

*Approximate line of equal head difference, in feet, between piezometric surface of artesian aquifer and water-table* 10

*Direction of horizontal component of upward leakage*

GSC

FIGURE 18. Hydrologic features of the Darmody area.

*Darmody Area*

This area provides the third example of saline soils as a result of upward leakage. The area is relatively small compared to the Great Salt Plain or the Stalwart area, but its hydrogeological setting, situated as it is between Vermilion Hills and Eyebrow Hills and overlying the Bearpaw-Belly River aquifer, makes it rank next in importance to the two larger discharge areas. The solodized-solonetz soils of the Darmody area have developed on till that is "modified by underlying shale", according to Mitchell, *et al.* (1944). However, as previously cited drillers' logs of the area indicate, 100 to 270 feet of till overlies the Bearpaw shale, a fact that makes the modifying influence of the shale doubtful. The salinity of the headwater region of Ridge Creek is up to the equivalent of 500 gr/g NaCl and many of the sloughs can be classified as salinas or playas. The vegetation of the area does not differ from that of the Great Salt Plain.

A map of the head difference between piezometric surface and the water-table (Fig. 18) indicates maximum leakage west of Darmody. The main area of saline soils does not fully overlap the area of maximum possible leakage, a fact that cannot be accounted for by the present study.

In estimating the amount of upward leakage in saline soils, the writer has based his reasoning on the conviction that Thornthwaite's concept of soil-moisture deficiency (Thornthwaite, 1948) is invalid for saline areas, for plants in areas of ascending groundwater can draw on a continuous water supply. In other words, the amount of groundwater that is discharged by halophytic phreatophytes equals at least the moisture deficit that would occur if no other source of moisture were on hand. The average soil-moisture deficiency for the headwater region of Qu'Appelle Valley calculated according to the modulated soil-moisture budget (Holmes and Robertson, 1959) is about 7 inches[1] which is 0.0028 foot per day during the seven months for which the moisture deficit is calculated. If this deficit

**Table IV**

*Estimates of Artesian Leakage in Four Saline Areas*

| Author and Method | Area | Amount of leakage gallons/day per acre |
|---|---|---|
| Israelsen and MacLaughlin, 1932 (calculated from piezometer measurements) | Cache Valley, Utah | 450–562.5 |
| Tomkins, 1954 (exemplary minimum estimate for the accumulation of sodium-sulphate deposits) | S. Saskatchewan | 32 |
| Feth and Brown, 1962 (calculated from rate of salt-crust accumulation and from mud-core experiments) | Great Salt Lake, Utah | 270–810 |
| Meyboom, 1962 (tentative estimate from potential evapotranspiration of phreatophytes) | South-central Saskatchewan | 760 |

[1]The average soil-moisture deficit of 8 stations for the period 1944–61 amounted to 6.91 inches.

were to be made up by groundwater it would require 0.0028 acre-feet per acre per day, spread evenly over the entire period. Table IV presents a comparison between this estimate and estimates of upward leakage by other authors for similar areas.

### *Saline Soils Related to Local Flow Systems*

Where a zone of radial flow is superimposed on the regional downward flow, groundwater moves upward underneath the depression and evaporates through the soil and vegetation. If this local flow system intercepts bedrock sediments that are rich in sodium sulphate (e.g. Bearpaw shale), the ascending groundwater may contain considerable amounts of sodium sulphate, which accumulates at or near the surface upon evaporation of the water. This phenomenon of salinization due to local flow systems is apparent both in river valleys and in the knob-and-kettle topography (*see also* Kelly and Spillsbury, 1949).

It follows from the nature of a local flow system that in saline river valleys the soil salinity increases towards the centre of the valley. This is clearly reflected by the vertical zonation of plant communities, as is demonstrated in Arm River Valley at SE 1/4 sec. 29-29-28, W.2 (Fig. 19). The following four zones can be distinguished there.

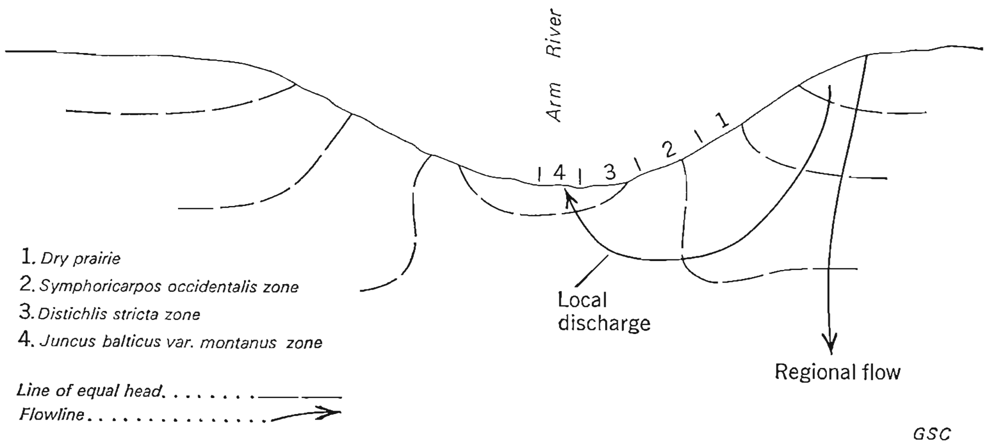



FIGURE 19. Flow diagram showing relationship of groundwater movement and sequence of plant communities, Arm River valley.

Zone 1. Dry prairie.

Zone 2. *Symphoricarpos occidentalis* zone, which indicates the emergence of relatively fresh groundwater. *Muhlenbergia richardsonis* and *Sonchus arvensis* (which occur in the lower reaches of the second zone) seem to be transitional to the third zone, which is distinctly saline.

Zone 3. The third zone is a strip of saline pasture with numerous burnouts. The dominant plant species are *Distichlis stricta* with *Glaux maritima, Atriplex argentea, Suaeda depressa* and *Salicornia rubra* as secondary species. *Suaeda* and *Salicornia* generally occupy the margins or all of the burnouts.

Zone 4. The fourth zone contains the creek bed, which is vegetated with *Juncus balticus* var. *montanus* locally mixed with *Triglochin maritima.*

This sequence of plant communities is an interesting example of Boyko's geo-ecological law of distribution (Boyko, 1947), which states that "the microdistribution of plants is a parallel function of their macrodistribution, since both are dependent on the same ecological amplitudes". The transition from zone 1 to 4 in the saline river valley (microdistribution) is, therefore, essentially the same as the transition from a willow vegetation on the watershed to the halophytic plant communities on the saline soils of the regional discharge area (macrodistribution). In other words, both local and regional flow systems are characterized by the same succession of plant communities, on the condition that the chemical composition of the groundwater that is discharged by each system is the same.

If the zone of radial flow does not intercept sodium-rich deposits, the groundwater of the local system remains fresh and saline zones fail to develop. The entire valley thus becomes occupied with freshwater phreatophytes, like *Elaeagnus commutata*[1] and *Salix* sp. (Pl. II).

Downstream, saline stretches may alternate with "fresh stretches", depending on the materials that constitute the medium of the local flow system. Examples of this exist along Arm River and it seems probable that the fresh stretches near Davidson and Chamberlain (Pl. II) can be correlated with the outwash deposits in those areas, which were described by Christiansen (1962).

### *Patterned Ground in Saline Areas*

Patterned ground may afford another interesting field criterion for saline regions. Nonsorted circles and nonsorted polygons are truly a striking feature in all saline areas in the headwater region of Qu'Appelle River. The nonsorted circles are 5 to 10 feet in diameter and barren in the middle. The material exposed in their centres consists of powdery grey soil, commonly sowing streaks of salt efflorescence. The vegetation around the circles ranges from the extremely salt tolerant *Suaeda depressa* var. *erecta* near the border of the circle to a *Distichlis stricta* community in the interjacent areas. Closer study may reveal that many of the so-called burnouts actually belong to a degraded or otherwise inconspicuous pattern of nonsorted circles. Large areas of nonsorted circles were observed in the fine alluvial clays of Qu'Appelle Valley, near the junction of Qu'Appelle River and Squaw Creek, as well as in the vicinity of the former Eyebrow Lake.

Large nonsorted polygons are also very common, notably in the area east of Penzance and Holdfast, in Qu'Appelle Valley and in the saline area of the Darmody artesian basin. The polygons may be as large as 50 feet in diameter, a fact that makes their pattern rather obscure on the ground but obvious on air photographs.

[1] As to the importance of *Elaeagnus* as a freshwater phreatophyte, Viktorov, *et al.* (1961) reported that "According to observations effectuated in the Kara-Kum (U.S.S.R.), groves of *Populus* and *Elaeagnus* species have also great significance for the detection of the discharge zones of big freshwater lenses in the region of the ancient Uzboi bed".

The cracks are accentuated by dense stands of *Suaeda depressa* var. *erecta,* whereas the more saline centres of the polygons are barren. Often the pattern is degraded and all that remains visible are irregular saline patches that merge with one another without clear-cut vegetational boundaries.

Patterned ground in saline soils of arid and semi-arid areas seems to be the rule rather than exception, as witness reports from Mexico (Lang, 1943), from Oranje Vrij Staat in S. Africa (Walter, 1938), and from New South Wales (Hallsworth, *et al.,* 1955). Similar to those areas, the patterned ground in south-central Saskatchewan is believed to be a desiccation feature, the origin of which may be inherent in the composition of the saline soil. Janzen and Moss (1956) and Cairns (1961) found that solodized-solonetz soils in western Canada are characterized by (1) an increase in total exchange capacity with depth, (2) an increase in clay content with depth, and (3) an increase in exchangeable sodium with depth. If the shrinking and swelling properties at various depths in the soil are directly proportional to these factors, as was found by Hallsworth, *et al.* (1955), one may expect an increase in swelling with depth, leading to the formation of desiccation polygons according to the principles set forth by Leeper, as quoted by Hallsworth (1955). Hallsworth made it clear that the area bounded by the desiccation fissures tends to heave, owing to additional expansion of surface material that has fallen into the cracks. Upon erosion of the centre block, subsoil becomes exposed and the observed centre of higher salinity remains.

## Saline Lakes and Rivers

The permanent saline lakes of Saskatchewan have been studied in great detail by Rawson and Moore (1944), who give an excellent account of this peculiar environment. In imitation of Rawson and Moore (1944), the writer has arbitrarily taken the chemical boundary between freshwater and saline water at 300 ppm total dissolved solids (=375 micromhos/cm=13 eq. gr/g NaCl).

Rawson and Moore noticed that Last Mountain Lake contained more than double the average amount of bottom organisms found in other saline lakes. They ascribed this anomaly to the greater quantity of sodium and lesser amount of magnesium in this lake as compared with other lakes in Saskatchewan. It is tempting to assume that the sodium has its origin in groundwater seepage into the lake. The following example may clarify this point.

Surface flow into Last Mountain Lake is mostly spring run-off during April, May, and June, consisting of bicarbonate water (Fig. 20) containing an average amount of 300 ppm total solids. Although partial evaporation of the surface run-off once it has reached the lake accounts for an increase in concentration, it does not explain the change in composition. Figure 20 shows a Piper diagram on which are plotted the chemical compositions of surface run-off[1], lake waters, and groundwaters from the townships adjacent to the lake. The groundwater samples fall into two groups (1) sulphate water (samples 2, 6, 7 and 8), and

[1] For want of complete chemical analysis of creeks in the Last Mountain Lake basin, analyses of Qu'Appelle River and Moose Jaw Creek were used, as they were reported by Thomas (1959).

(2) chloride water (samples 3, 9, and 10). Surface run-off in central Saskatchewan is bicarbonate water, and it is therefore apparent that lake water is intermediate between groundwater and surface water. However, it is not a simple mixture of the two. The position of the lake samples from Last Mountain Lake in the trilinear diagram may be explained in one of the following manners:

1. the lake water is a mixture of three components, the third being of unknown composition;
2. sulphate groundwater and surface water reacted chemically upon mixing and some product of the reaction formed a solid phase; or
3. the samples of the surface water of south-central Saskatchewan are not fully representative for the conditions in Last Mountain Lake basin.

If the lake water is a mixture of three components, the hypothetical third component has to be high in sodium and magnesium, low in calcium, very high in sulphates and low in bicarbonates and chlorides. The water could be of a composition such as: Ca 3 per cent epm, Mg 44 per cent epm, Na and K 53 per cent epm, $HCO_3$ 18 per cent epm, Cl 0.7 per cent epm, and $SO_4$ 75 per cent epm. Water from Pleistocene aquifers, which is not properly represented in the Piper diagram, has the required percentages of anions (for example, water from a shallow well in NW 1/4 sec. 23-19-20, W.2 contained $HCO_3$ 10 per cent epm, Cl 0.6 per cent epm, and $SO_4$ 84 per cent epm, but the distribution of cations does not meet the requirements (Ca 30 per cent epm, Mg 47 per cent epm, Na 23 per cent epm). Saline groundwater is therefore not a possible third component and the three-component hypothesis has to be rejected.

If the lake water represents the composition of a soluble product after a chemical reaction between surface run-off and groundwater, it should be possible to determine the hypothetical composition of the solid phase, for Piper (1944, p. 922) stated that:

> . . . the chemical character of the products remaining in solution will plot on the extension of the straight line drawn from (1) the point that represents the composition of the solid phase to (2) the point M that indicates the proportionate volumes and compositions of the two reacting waters.

Hence, the solid phase must lie within the sodium-calcium region of the cation triangle and within the chloride-carbonate triangle of the anion area. Considering the high solubility of common salt, it is unlikely that NaCl would precipitate, which leaves $CaCO_3$ as the most probable solid phase. Langbein (1961) as well as Rawson and Moore (1944) did comment on the precipitation of calcium carbonate after spring floods, but the diagram shows that the volumes of the hypothetical mixture ($M_1$) are not truly proportionate in all three fields. Thus one must conclude that the available analyses of surface run-off are not representative enough to warrant further quantitative considerations. The diagram does point out, however, that sulphate groundwater is an essential component of water in Last Mountain Lake. The fact that the influence of the deeper saline water is not noticed to a greater extent may be attributed either to the extremely small contribution of deep groundwater or to the fact that the deep saline waters take part in a larger flow system, which would be one that bypasses Last Mountain Lake as a discharge point. An attempt to prove or disprove the latter consideration might touch upon the unresolved problem of whether a continental flow system underlies the entire plains.

With the existence of a groundwater contribution to Last Mountain Lake established, the significance of Rawson and Moore's observation that a general increase in lake salinity took place between the years 1917 and 1944 may now be investigated. The question to be answered is whether such an increase reflects an absolute increase in groundwater contribution or a decrease in the amount of surface run-off, and thus merely a relative increase in groundwater contribution. This question is closely related to the assumption of steady state groundwater flow in the Prairie Profile.

A continuation in the salinity increase like that observed by Rawson and Moore has not been noticed during the present investigation. On the contrary, analyses reported by Thomas (1959) and the Saskatchewan Fisheries Laboratories (Table V) indicate a decrease in salinity between 1941 and 1953, followed by a significant increase between 1953 and 1959. These fluctuations probably correlate with fluctuations in lake level during the same period, for the water level in Last Mountain Lake declined steadily from 1,611 feet above sea-level in 1929 to 1,599 feet in 1942, then rose to nearly 1,615 feet in the summer of 1955, followed by another decline to 1,607 feet in 1959. The estimates of the total salt tonnage[1] reveal fluctuations with lake volume (Fig. 21) that are similar to those published by Langbein (1961). The coincidence is the more interesting as Last Mountain Lake is considerably less saline than the examples discussed by Langbein, which were true salinas, having concentrations of total solids between 1.5 and 18.5 per cent. Despite the scarcity of information, available streamflow data do show that these fluctuations in lake volume are probably related to variations in run-off from the contributing drainage basin rather than variations in groundwater contribution, and the assumption of steady state groundwater flow does seem to be justified.

Salinity measurements of creek water during July, which is a period of low flow or even stagnant water, yield interesting information as to the nature of groundwater contribution to streams in that area. Three fundamentally different situations were noted in the headwater region of Qu'Appelle River (Figs. 16, 17 and 18):

(1) the salinity of the river water increases downstream;
(2) the salinity decreases downstream; and
(3) conditions (1) and (2) alternate along successive reaches of the stream.

Ridge Creek (Tp. 21, R. 3, W. 3) probably has its origin as upward artesian leakage, which manifests itself in extraordinarily high salinity values of surface waters (500 eq. gr/g NaCl) in the Darmody area. The salinity of Ridge Creek

[1] Salt tonnage is the product of the factor 0.00135, the lake volume in acre-feet, the concentration in parts per million and the density. Lake volumes were estimated from lake hydrographs that were kindly supplied by Mr. F. Durrant of the PFRA in Regina and by the Calgary District Engineer of the Water Resources Branch, Department of Northern Affairs and National Resources.

## Table V

*Chemical Analyses of Last Mountain Lake*
*(Constituents in parts per million)*

| Date | Source of Information | Total Dissolved Solids | Fe | $SiO_2$ | Ca | Mg | Na | K | $HCO_3$ | $CO_3$ | Cl | $SO_4$ | $NO_3$ | Recorded Lake Level | Estimated Lake Volume x $10^6$ acre feet | Estimated Salt Tonnage x $10^6$ tons | Discharge Arm R. Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1937 | Rawson & Moore | 2402 | | | | | | | | | | | | 1606 | 1.196 | 3.878 | |
| June 1938 | Rawson & Moore | 2450 | | | | | | | | | | | | 1603 | 1.025 | 3.391 | |
| July 1940 | Sask. Fisheries[1] | 2549 | nil | 14 | 44 | 167 | 527 | 16.6 | 364 | 34.4 | 178 | 1302 | nil | 1601 | 0.911 | 3.136 | |
| Sept. 1940 | Rawson & Moore | 2676 | | | | | | | | | | | | 1600.5 | 0.883 | 3.189 | |
| Aug. 1941 | Rawson & Moore | 2863 | | | | | | | | | | | | 1599.5 | 0.826 | 3.192 | |
| June 1953 | Thomas | 1702 | — | — | 43.2 | 96 | 330 | 38.2 | 309 | 14.2 | 110 | 768 | 4 | 1608.8 | 1.354 | 3.111 | 5.380 |
| June 1957 | Sask. Fisheries | 1998 | nil | 2 | 70.9 | 121.4 | 346.8 | — | 372.2 | 31.9 | 1315 | 9265 | — | 1609.9 | 1.422 | 3.835 | 11.650 |
| Nov. 1958 | Sask. Fisheries | 2089 | | | | | | | | | | | | 1607.8 | 1.301 | 3.671 | 6.310 |
| April 1959 | Sask. Fisheries | 2400 | (predominantly Na′ and $SO_4^{--}$) | | | | | | | | | | | 1607.8 | 1.299 | 4.210 | |

[1]Analyses have been made available by courtesy of Sask. Dept. of Agr. Water Rights Division.

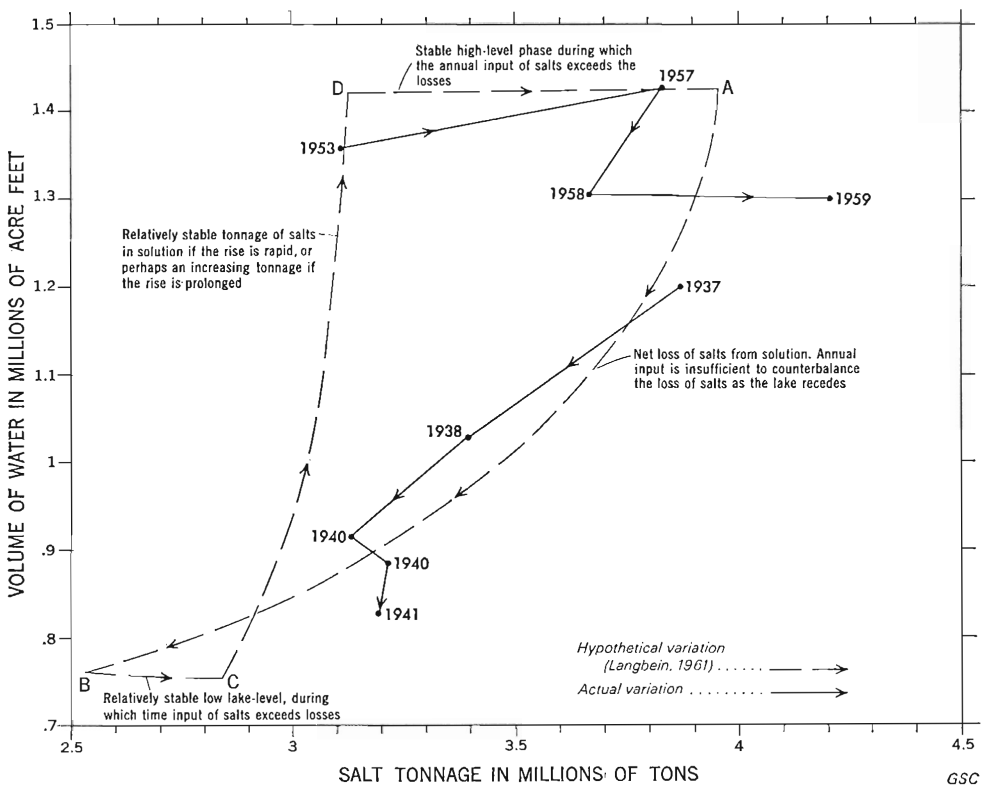



FIGURE 21. Variation of salt content in Last Mountain Lake, 1937-59.

decreases downstream and reaches a minimum value of 60 eq. gr/g NaCl south of the junction with Qu'Appelle River. The decrease in salinity may be ascribed to a downstream increase in freshwater contribution from shallow sandy deposits of both Cretaceous and Pleistocene ages. It can be estimated by Voronkov's method that the proportion between shallow freshwater and deep saline water is of the order of 200:1. Consequently, Ridge Creek is tentatively interpreted as rising in a small regional discharge area of a Prairie Profile and flowing into a local flow system of low salinity.

Qu'Appelle River is the opposite. Its upper reaches are in the above-mentioned zone of radial flow, but it then flows into Eyebrow Lake, which is another area of strong upward leakage from the Bearpaw-Belly River aquifer. Prior to the Eyebrow Lake diversion (in 1960) the salinity of Qu'Appelle River almost tripled in and below Eyebrow Lake (F. Durrant, 1962, pers. com.). At present, the salinity of the river increases gradually downstream, as a consequence of the widening zone of radial flow with increased size of the river valley. The latter feature is believed to be the principal reason for a gradual downstream increase of salinity.

North of Last Mountain Lake, Arm River embraces both saline and fresh-water stretches, depending on the flow medium of the local flow systems that discharge into the stream. The salinity of Lewis Creek decreases downstream, as does the salinity of all creeks that rise west of a line between Stalwart and Penzance. The salinity decrease in Lewis Creek may be attributed to dilution by fresh groundwater from outwash deposits, whereas the downstream decrease in the other creeks might be explained as an indication for either downstream increase in artesian leakage (hence more baseflow and a more rapid turnover of water) or downstream decrease in artesian leakage (hence less water and less salts). The latter suggestion can be ignored in view of evidence for downstream increase of artesian leakage presented under *Area North of Last Mountain Lake.*

Squaw Creek and all creeks west of a line between Imperial and Stalwart show a downstream increase in salinity. This is also true of Saline Creek, Undora Creek, and Lanigan Creek in the Great Salt Plain (Figs. 16, 17). The salinity in the last three creeks is probably related to artesian leakage rather than to the very slight widening of the zone of radial flow.

The picture of surface-water salinity is by no means a clear one. Many interpretations are ambiguous or even contradictory; nevertheless these first attempts do indicate that measurements of stream salinity during low stages are complementary to other field observations.

### Playas, Salinas, and Sodium Sulphate Deposits

Playas are flat plains in the centre of a closed basin. Their surface is composed of a mixture of clay and fine salt crystals. The playas in western Canada originated by evaporation of saline lakes (salinas) in hummocky moraine or in areas of regional discharge.

If the hummocky moraine is developed in areas of sodium-rich till or in areas where the Bearpaw shales are very close to the surface, rain-water will be enriched in sodium salts almost immediately after it enters the ground. This means that even the smallest local flow system in a hummocky moraine will be saline, and, as a consequence, willow rings will not develop. Instead, the ecological place of the willows is taken by alkali-tolerant phreatophytes, notably *Salicornia rubra, Suaeda depressa,* or *Chenopodium rubrum.* If the depression contains water, its salinity may be more than the equivalent of 300 gr/g NaCl by mid-summer. The ponds become white at their edge during June, and when they have dried up completely circular salt flats remain, some of which are occupied by scattered specimens of *Salicornia rubra* or *Triglochin maritima.* Such small playas are a common sight in the hummocky moraine in the Missouri Coteau and their origin is believed to be related to the same small-scale discharge system that characterized the willow rings.

Playas also occur on a much bigger scale. For instance, some of those in the Great Salt Plain extend over square miles in a virtually flat topography. There are vast salt flats, scattered with small salinas that may or may not dry up completely towards the end of the summer. The salts in the salinas and on the playa surfaces are mirabilite ($Na_2SO_4.10H_2O$), commonly called Glauber's salt, and thenardite ($Na_2SO_4$). Several sodium sulphate deposits in Saskatchewan are exploited commercially and yield 20 per cent of the total North American sodium sulphate production (Tomkins, 1954, Fig. 1).

For a proper understanding of sodium sulphate deposits in terms of groundwater outcrops, it should be remembered that:

(1) all sodium sulphate deposits occur in strings of disconnected salt lakes that constitute an inactive drainage system;

(2) the orientation of these inactive drainage systems is generally perpendicular to the direction of regional groundwater flow; and

(3) all substantial sodium sulphate deposits are restricted to regional discharge areas that have a net annual evaporation of at least 15 inches (PFRA, 1952, Fig. 10).

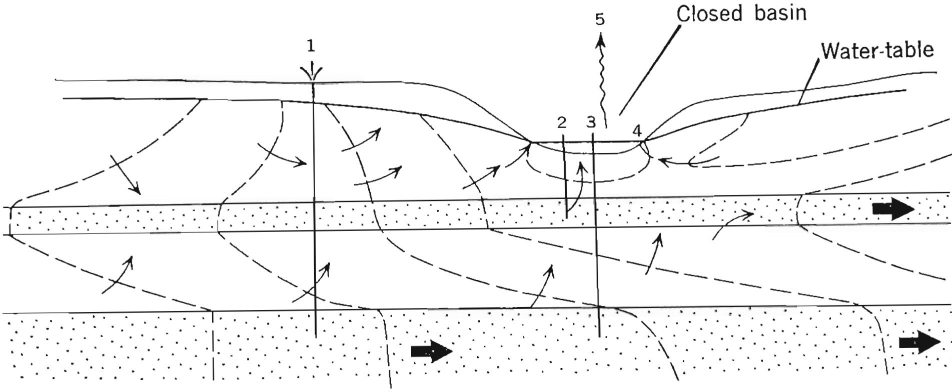
Tomkins (1954) commented that:

> . . . sodium sulfate deposits occur in undrained basins, usually in sandy or gravelly areas. At nearly all deposits seepages are in evidence and artesian water is commonly obtained near them. It appears that these deposits occur where aquifers closely approach the surface and waters containing small amounts of salts accumulate in the low areas.

Cole was somewhat doubtful as to the role of groundwater in the origin of sodium sulphate deposits, for he stated:

> . . . while springs may thus in a small way be supplying salts to the deposits, it does not seem probable that they are the chief source from which the salts are derived.

In this excellent account of the sodium sulphate deposits of western Canada, Cole (1926, pp. 82-83) recognized three types of springs associated with the deposits: (1) marginal springs; (2) freshwater springs; and (3) brine springs. A typical marginal spring, surrounded by a typical freshwater plant community, was observed near one of the brine lakes of Regina Beach (so-called Regina Beach No. 2, Sec. 21, Tp. 20, R. 22, W. 2). Springs of the second or third type were not observed in one of the seven sodium sulphate deposits that Cole listed for the headwater region of Qu'Appelle River, but their existence is a consequence of groundwater flow in a Prairie Profile, as is shown on Figure 22. Figure 22 combines these observations with the pattern of groundwater flow that would occur as leakage from a hypothetical Prairie Profile with two permeable layers. Seen in this light, the groundwater discharge into the inactive drainage systems may be called "fossil baseflow", but it is brought about by the same mechanism as upward leakage into Eyebrow Lake or Thunder Creek. The difference is, however, that the salts get an opportunity to accumulate in the undrained depressions and the well-known deposits result. It is therefore not a matter of high initial salt concentration in the contributing groundwater, but a combination of a slight salt content, high evaporation, sufficient time, and an absence of drainage.




Line of equal head. . . . . . . . . ——

Direction of movement. . . . . . .

Direction of movement in more permeable layers. . . . .

1. *Artesian well*
2. *Fresh-water spring*
3. *Brine spring*
4. *Marginal seepage*
5. *Evaporation*

GSC

FIGURE 22. Hypothetical flow pattern in the vicinity of a sodium-sulphate deposit.

## The Sequence of Magnitude

The writer has presented a hierarchy of phenomena, in which each phenomenon is determined by very definite dimensions and is of a very definite duration. On a small scale, there are very small flow systems, confined to the dimensions of a single pothole in which the water may travel from recharge to discharge area in a matter of seasons. There are small flow systems associated with drainage channels, in which both horizontal and vertical dimensions are measured in a few hundreds of feet and the time between recharge and discharge may be a few years. On a larger scale, there is a flow model the size of the Prairie Profile, tens of miles long, hundreds of feet high, and for which the duration of the water cycle is measured in decades, or possibly centuries. But even the Prairie Profile cannot be considered a closed system and it is necessary to visualize flow systems of an even larger magnitude, of the size of all of western Canada, in which the time span of motion is measured in geological time, and of which the numerous brine springs along the western edge of the Canadian Shield may be the discharge phenomena.

## CONCLUSIONS

The Prairie Profile offers a model of a groundwater flow system to which all discernible groundwater phenomena of a typical prairie region can be related. The groundwater flow in this model may be approximated by steady-state, gravity drainage. By understanding the nature of the surface manifestations, the flow system can be mapped systematically and may be interpreted quantitatively. Knowledge of the stratigraphy of an area is required to test the validity of the assumptions that underlie the model.

In the Great Plains area of western Canada the Prairie Profile offers a more generally applicable model for artesian conditions than the classical geological model consisting of an exposed permeable intake area leading to a confined permeable aquifer.

The writer has shown empirically that the permeability of the poorly permeable layer in the Prairie Profile in south-central Saskatchewan is such that the influence of surface watersheds rising 300 feet or more above the surrounding plains, reaches to a depth of at least 1,000 feet. The Saskatchewan-Assiniboine divide may therefore be taken as the outline of a groundwater basin of the same size as the surface drainage basin to a depth of at least 1,000 feet.

The conventional definition of artesian aquifer has introduced serious misunderstanding about the hydrogeological requirements for artesian conditions. Artesian wells are merely flowing wells, and may exist in a homogeneous aquifer, in stratified flow media, and in areas of downward flow, upward flow, or lateral flow. Most of the piezometric surfaces that have been constructed for areas in western Canada are merely plots of the intersection of virtually horizontal equipotential planes with the topography, and cannot be used quantitatively.

The significance of a baseflow analysis depends entirely on the position of the stream in the groundwater flow-system. Baseflow analysis of streams in a local discharge area, superimposed on a regional flow-system, will be virtually meaningless in terms of regional water yield. A proper study of the significance of baseflow should be preceded by the preparation of a large number of vertical cross-sections through the drainage basin.

It is apparent that most natural groundwater discharge on the prairies occurs as evapotranspiration, either directly through the soil or through the phreatophytic vegetation. Quantitative regional groundwater investigations should therefore give more study to the behaviour of phreatophytes and to the distribution of saline sloughs and soils, than to detailed analyses of occasional sandstone aquifers in a region of downward flow.

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