SURFICIAL MAPPING

OF

GROUNDWATER FLOW SYSTEMS

with application to the

Oak River Basin, Manitoba

A Thesis

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by

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ABSTRACT

The concept of local topographic depressions serving as focal points for groundwater recharge and discharge is presented through the development of transient flow diagrams. By combining this concept with the hydrograph results of type piezometer nests in a prairie upland environment a hydroecological classification of sloughs is developed. This classification is applied to the reconnaissance mapping of flow systems in the Oak River Basin, Manitoba where the mapping is verified by test piezometer nests.
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INTRODUCTION

Location of the Oak River Basin

The Oak River Basin comprises 642 square miles of the Riding Mountain Quadrangle (62K) and 123 square miles of the Virden Quadrangle (62F) in southwestern Manitoba (Fig. 1). It lies within the area of Townships 10 to 19, Ranges 21 to 24, west of the Principal Meridian. This area is between 100°15' and 100°46' West Longitude and between 40°49' and 50°43' North Latitude.

Present Study

The purpose of the present study is to determine whether the recharge and discharge ends of groundwater flow systems are distinguishable on the surface and if so to establish the basic criteria and procedures by which they can be quickly mapped. Such mapping should prove valuable as the initial reconnaissance phase of groundwater evaluation in an area.

The study was approached basically as a field problem. The Oak River Basin was chosen as the field area because its geology was well known and appeared uncomplicated. A total of about 18 months was spent in the basin between 1963 and 1967.

The instrumentation used in this study consists of seventy-three piezometers installed in thirty-three nests spaced to provide several sections across different parts of the basin and forms the basis of a continuing I.H.D. representative basin study for the Inland
Waters Branch of the Department of Energy, Mines and Resources.

Two nests in flowing areas consist of a single piezometer each. Twenty-two nests consist of two piezometers each and nine nests consist of three piezometers each. Within every multiple nest the piezometers are installed about 10 feet apart with each piezometer of the nest being completed at a different depth. The type of installation used is shown in figure 2. Twenty-nine piezometers were installed in 1963, twenty-seven in 1964, fourteen in 1966 and three in 1967. Aside from the actual mapping additional field work consisted of conducting pump tests of the major aquifers and slug or bailer tests in most of the piezometers in 1965 and 1966.

All thirty-three piezometers in fourteen of the nests installed in 1963 and 1964 had attained equilibrium with the pressure of the formation water outside the screen by the summer of 1965. Some of these nests indicated that recharge conditions prevailed while others indicated that discharge conditions prevailed. Field observations in the immediate vicinities of these type nests revealed that the only surficial feature which consistently displayed marked differences between areas of recharge and areas of discharge was the appearance of "sloughs", which are undrained topographic depressions found in glaciated regions of the Canadian Prairies. The locations of these type nests are shown in figure 3. Their hydrographs are presented in Appendix A. By the fall of 1965 the basic theory leading to a classification of sloughs was developed and part of the basin was
Figure 2.— A Typical Piezometer Nest
Figure 3. Location of Type Piezometer Nests

Legend:
- Nest indicating discharge
- Nest indicating recharge
- Nest indicating lateral flow

Legend:
- Twp.
- Rge.
- Steps
mapped using this classification. In 1966 the mapping was completed, independently chosen test nests were installed to check the previous year's mapping, and piezometer reducers were designed, built, and installed in non-equalized piezometers to provide additional test nests for checking the rest of the mapping.

This thesis is presented in two parts. The first part describes the general theory leading to the classification of sloughs and the second part describes the specific application of this classification to mapping recharge and discharge areas within the Oak River Basin. The second part also complements the first by presenting the results of some of the test nests.
PART 1: THEORY

General Statement

The theory of mapping groundwater flow systems is developed firstly by indicating why and how a relationship between sloughs and groundwater flow must exist, secondly by outlining the ecological factors affecting the appearance of sloughs, and thirdly by combining these to present a hydroecological classification of sloughs that will serve as the basis for mapping.

Natural Groundwater Flow Systems

General

The field observation that sloughs in recharge areas differ from those in discharge areas challenges the validity of existing theories on natural groundwater flow. This section summarizes the fundamental principles governing groundwater flow, traces the development of existing theories on natural flow, and by questioning one of the basic assumptions in these theories proposes a new set of theoretical flow patterns that is more in accord with field observations. Completing this section is a summary of the fundamental principles governing groundwater chemistry.

The Fundamental Principles of Potential and Permeability

The natural flow of groundwater obeys Darcy's law which, following Hubbert (1940), may be expressed in differential form by the equation

\[ q = -\sigma \text{grad } \Phi \quad \ldots \ldots \ldots \ldots (1) \]
where \( \mathbf{q} \) = the flow vector whose magnitude equals the volume of water crossing a unit area normal to the direction of flow in unit time,

\[ \sigma = \text{hydraulic conductivity}, \text{ and} \]

\[ \Phi = \text{fluid potential}. \]

It can be seen from equation 1 that the direction of flow is in the direction of decreasing fluid potential.

The fluid potential at any point "X" within the zone of saturation can be determined with a piezometer as shown in figure 4a by measuring the associated heads. The relationship between head and potential is given by

\[ \phi_x = g \cdot \bar{H} \]

\[ \text{(2)} \]

where \( \phi_x \) = fluid potential at X,

\[ g \] = acceleration due to gravity, and

\[ H \] = total hydraulic head.

The components of total hydraulic head are pressure head and gravity head as shown in figure 4a. In figure 4b the pressure head at the point \( X_1 \) is given by the expression

\[ \frac{P_1 - P_a}{\rho g} \]

where \( P_1 \) = the absolute pressure at the bottom of the piezometer,

\[ P_a \] = the atmospheric pressure acting at the top of the water column in the piezometer,

\[ \rho \] = the density of water, and

\[ g \] = the acceleration due to gravity.
Figure 4 -
Hydrologic Terminology Used With Respect to Piezometers And Nests
The gravity head at the point $X_1$ is given by the distance $Z_1$. Thus the total hydraulic head at $X_1$ is represented by the distance $H_1$ above some arbitrary datum. The datum chosen for the study in the Oak River Basin is mean sea level.

In order to determine the direction of groundwater flow at any place within the saturated medium piezometers are completed at different points in the neighborhood of the location in question. Such a cluster of piezometers is called a "nest". In this study a very simple nest was used to determine the direction of the vertical component of flow. This is illustrated in figure 4b. When two piezometers are placed very close together, compared to the distance between their screens ($Z_1 - Z_2$), the points $X_1$ and $X_2$ may be considered to be vertically one above the other and the difference between their respective total hydraulic heads ($H_1 - H_2$), which is directly proportional to the difference in fluid potential between the two points, can be used to determine whether water flows upward or downward. This is done by calculating the vertical head gradient $(H_1 - H_2)/(Z_1 - Z_2)$. For the nest shown a positive gradient indicates downward flow, a negative gradient indicates upward flow, and zero gradient indicates either lateral flow or virtually static conditions.

The hydraulic conductivity ($\sigma$) of equation 1 depends partly on the permeability of the medium and partly on properties of the fluid as shown by the equation

$$\sigma = \frac{k \rho}{\mu} \tag{3}$$

-10-
where $\sigma$ = hydraulic conductivity, 
$k$ = intrinsic permeability, 
$\rho$ = fluid density, and 
$\mu$ = fluid viscosity.

The units of intrinsic permeability are those of area, the standard unit being called a darcy, which is equal to $0.9869 \times 10^{-8}$ cm$^2$. The units of hydraulic conductivity are those of velocity and are usually expressed as cm/sec. or U.S. gallons/day/square foot (Meinzer) when applied to groundwater.

The direction of natural groundwater flow is affected by changes of permeability within the saturated medium as shown in figure 5. Hubbert (1940) showed that if groundwater flows at rate $q_1$ per unit area in a layer of intrinsic permeability $k_1$ and encounters the boundary of a layer with permeability $k_2$ at an angle of $\Theta_1$ from the vertical to that boundary, water will flow through the second layer leaving the boundary at an angle $\Theta_2$ from the vertical such that

$$\frac{k_1}{k_2} = \frac{\tan \Theta_1}{\tan \Theta_2}$$

Equation 4 is known as the tangent law of flow refraction. To illustrate this law assume that $k_1/k_2 = 1/10,000$, which is a typical permeability contrast between till and sand (see Appendix B), and that $\Theta_1 = 1^\circ$, which means that flow through the upper till layer is almost vertical.

By substitution of these values in equation 4, $\Theta_2 = 89^\circ 40'$, so that flowlines are refracted at this permeability boundary to such an extent.
Figure 5 - Refraction of Flow Lines Across a Permeability Boundary
that the direction of flow through the lower sand layer is almost horizontal.

**Steady-State Flow Patterns**

Using equations 1 to 4 several workers have prepared two-dimensional diagrams showing the flowlines that should exist theoretically in various situations for natural groundwater flow under steady-state conditions. As each of these diagrams, or flow patterns, are progressively based on more realistic assumptions it is believed that each one more closely resembles actual conditions encountered in the field than the preceding one. It is hoped that the author's transient flow patterns presented later in this thesis continue this trend.

One of the earliest natural groundwater flow patterns was developed by Hubbert (1940) and is reproduced in figure 6. This flow pattern is based on the following assumptions: (a) recharge is evenly distributed over the entire length of the air-water interface between sinks causing the shape of the water table to resemble a subdued form of the topography, (b) the material is uniformly permeable to an infinite depth, and (c) the topography and resembling water table are symmetrical about the divide between valley sinks. All other flow patterns developed to date use this as a stepping-stone and differ from it only by replacing Hubbert's second and third assumptions with more realistic ones.
Figure 6. — Flow Pattern Between Sources Distributed over the Air-water Interface and Adjacent Valley Sinks (After Hubbert, 1940)
In a non-mathematical treatment Meyboom (1962) replaced Hubbert's second assumption with the introduction of an aquifer at depth. His proposed "Prairie Profile" is reproduced in figure 7.

Simultaneously Toth (1962) in a mathematical derivation of a set of flow patterns replaced Hubbert's third assumption with the assumptions that (a) the topography and resembling water table are asymmetrical about local sinks but that across a basin flank they can be approximated by a sloping sine curve and (b) no flow occurs across the divide between basins or across the main stream of the basin. In this derivation Toth also modified Hubbert's second assumption by assuming that the material is uniformly permeable only to some finite depth below which no flow occurs. The ensuing general steady-state flow diagram is reproduced in figure 8. One of the main contributions resulting from this work is the recognition of flow systems with three orders of magnitude—local, intermediate and regional.

Probably the most realistic patterns of natural groundwater flow developed to date are those presented by Freeze and Witherspoon (1966 and 1967). One of these is reproduced in figure 14. In questioning both Hubbert's second and third assumptions they developed a computer program for constructing steady-state flow diagrams that can handle any water table configuration and any permeability variation including anisotropy. In addition Freeze (1966) has extended the program in an attempt to analyze three-dimensional flow.
Figure 7 - THE PRAIRIE PROFILE  (After Meyboom, 1962)
Figure 8. Flow Systems Across One Flank of a Basin

(After Toth, 1962)
Hydrological Significance of Sloughs

General. -- In the development of each of the previously mentioned steady-state flow patterns Hubbert's first assumption that recharge is evenly distributed over the entire length of the air-water interface between sinks has been retained. The result is a water table configuration that corresponds with the topography and hence the conclusion that every topographic low is a discharge area while every high is a recharge area. If this is the case all sloughs are discharge areas. However this is contradicted in the field by the fact that upward potential gradients were not recorded by all the type nests located adjacent to sloughs, and by the observation that consistent surficial differences exist between sloughs in recharge areas and sloughs in discharge areas. In fact sloughs seem to serve as focal points for recharge as well as for discharge of groundwater.

In Recharge Areas. -- The way in which a slough acts as a focal point of recharge is illustrated in figure 9. In the spring the snow, which has accumulated throughout winter, melts before the ground thaws. Most of this snow is already concentrated in the topographic depressions constituting sloughs (Wolbeer and Husband, 1964). Moreover meltwater from snow on the adjacent topographic highs also accumulates in the sloughs by surface runoff because it cannot infiltrate through the frozen soil. Once the ground beneath one of these sloughs has thawed the ponded water infiltrates through the unsaturated medium below it to form a groundwater mound (Meyboom, 1966). Growth of
Figure 9.- Flow around Recharge Sloughs
the mound continues by infiltration until the rate at which water leaves it to enter a flow system equals the rate at which it is being fed from the slough. Usually this equilibrium position is attained after the mound has intersected the bottom of the slough. In this case the ponded water remaining in the slough is recharged directly into the saturated medium formed by the mound. Once all the ponded water has disappeared either by infiltration or by direct recharge, the mound dissipates and the water table immediately below the slough declines. Rain only modifies the growth and dissipation of these groundwater mounds but does not contribute to groundwater recharge directly beneath local topographic highs. This is evident when one considers that most of the rain falling on such highs accumulates in the sloughs by surface runoff and that the rest is used primarily to make up the soil moisture deficit in the highs (Gray, Dr. D., University of Saskatchewan, personal communication). During the initial stages of mound dissipation part of the downward moving water is diverted and transpired by the phreatophytes which surround these recharge sloughs. This discharge creates the ring-like "cone of depression" in the distribution of equipotential lines shown in Slough A of figure 9. In the fall when the phreatophytes become dormant a partial "recovery" of potentials occurs as the "cone of depression" is dispelled. This is followed by a normal dissipation of the groundwater mound (Slough B of Fig. 9) until spring melt rejuvenates the cycle. This "recovery" has been recorded in 1965 by some very sensitive piezometers in the Oak River Basin as a slight
water-level rise commencing in the late fall (P12 and P13, P20 and P21, P22 and P23, P28 and P29, P49 and P56, P50 and P51, and P58). From head changes in shallow piezometers Meyboom (1966) inferred that the influence of phreatophytes is so great that by fall the potentials beneath the entire slough have been reduced to such an extent that they are lower than the potentials beneath the adjacent topographic highs and a reversal of flow towards the slough causes the "recovery". The piezometers installed by the author are deeper than those used by Meyboom and, perhaps for that reason, no reversal of potential gradient was recorded in the Oak River Basin. Even with reversed flow during the fall Meyboom reported an annual net effect of groundwater recharge below a mound. Hence, because such mounds are only established below topographic depressions, wherein all the water available for recharge collects, sloughs which occupy these depressions act as the focal points of infiltration in a general recharge area.

In Discharge Areas. -- The way in which a slough acts as a focal point of discharge is illustrated in figure 10. Most groundwater discharge in the prairies is characterized by an upward movement of water to the land surface where evaporation returns it to the atmosphere. If the topography of the discharge area contains depressions the potential at the base of any depression is lower than the potentials at the surface of the surrounding topographic highs. This is obvious when one considers that at the land surface the pressure potential is
Legend:

Willows

Cattails & Reeds

Bulrushes

Halophytes

Ponded Water

Water Table

Groundwater Equipotential Line

Direction of Groundwater Flow

Zone of Aeration

Figure 10.— Flow around Discharge Sloughs
everywhere zero; hence the total potential of any point on the land surface is equal to the gravitational potential only which, because it is proportional to elevation, is lower in depressions than on highs. Because these depressions have the lowest potentials of the saturated medium associated with them, discharging groundwater converges toward them. Below some depressions normal convergence (Slough B of Fig. 10) is modified by a phreatophytic ringlike "cone of depression" (Slough A of Fig. 10) which dissipates at the end of the growing season. This constant convergence of upward flow towards topographic depressions explains how sloughs, which occupy the depressions, act as the focal points of emission in a general discharge area.

**Slough-focused Transient Flow Patterns**

**General.** -- If sloughs act as focal points for both recharge and discharge, the configuration of the water table does not correspond to the topography in any but a regional manner and hence a more realistic set of flow patterns is required. The flow patterns presented here are based on replacing Hubbert's first assumption with the slough-focusing concept. These patterns are developed firstly by considering how the basic simple flow system is formed; secondly by considering how local, intermediate and regional flow systems are formed through topographic control only; and thirdly by indicating how all these systems are further controlled through geologically governed permeability variations.
In this thesis all flow diagrams showing the hydrologic conditions around sloughs must be considered as applicable for one instant of time only and represent one stage in a continuous sequence of ever-changing conditions. Although not too apparent in most of the diagrams, the transient nature of these flow conditions can result in a diagram showing flow converging at a point where no discharge occurs but where water accumulates in storage until conditions are such that this water can flow once more. This is particularly noticeable in diagrams showing adjacent recharge sloughs.

The Simple Flow System. -- The simplest flow system is established where only one recharge slough and one adjacent lower discharge slough exist as shown in figure 11. The transient nature of slough-focused flow systems is indicated by the position of the water table at various times in figure 11a. Here the water table is shown to proceed through various stages with Stage 1 and Stage 4 being the ultimate limits of this temporal progression. At Stage 1 the groundwater mound below the recharge slough intersects the slough and forms a direct hydrologic connection between the ponded water and the saturated medium. Under these conditions with no recharge between sloughs the water table constitutes the uppermost flow line of the system. Such conditions are believed to predominate in the early spring in the Canadian prairies. With flow and accompanying dissipation of the mound during the rest of the year the water table gradually recedes through Stages 2 and 3 of figure 11a. Within any basin ultimate
Figure II.- Development of Local Flow Systems
recession is attained at Stage 4 when the water table lies just below the lowest point of discharge within the basin. Under such conditions flow ceases and the water table can be regarded as a static equipotential surface. Because the permeability of most surface material is relatively low and because cyclic recharge occurs annually, it seems improbable that Stage 4 is ever reached in any basin of the Canadian prairies.

Figure 11b is a diagram illustrating the equipotential and flowline network for Stage 1 of the simple flow system shown in figure 11a. Water recharges into the mound directly below slough A and discharges into a lower adjacent slough B. This is termed a local flow system and differs from Toth's local flow system in that both the recharge and discharge ends terminate in sloughs. With the Stage 1 water table condition shown the type of flow is identical to that through an earth fill dam, as described by Casagrande (1940).

**Topographic Control.** -- If the topography of a basin flank is more complex than the simple case shown in figure 11 different flow systems and types of flow develop. The control of flow systems by topography is analyzed by considering firstly a basin flank containing sloughs progressively lower in elevation and secondly a basin flank containing sloughs that are not progressively lower in elevation.

Figure 12a is a diagram illustrating the flow conditions across one flank of a basin containing sloughs progressively lower in elevation. Water recharges below the highest slough (A) and discharges
Figure 12: Development of Interrupted Flow
into the lowest (E). Following the earlier nomenclature of Toth (1962) this is termed a regional flow system. In addition to the classic saturated flow a type of groundwater movement herein termed interrupted flow is recognized. Interrupted flow can be described as either an intermediate or regional flow of water that encounters the land surface at a transitional slough prior to reaching the point of its ultimate discharge. Transitional sloughs are characterized by an inflow or discharge of groundwater at one end and an outflow or recharge of groundwater at the opposite end. Meyboom (1967) verified the theoretical existence of transitional sloughs with electric analog studies and described in detail the flow pattern around two temporary transitional sloughs of an intermediate flow system in the Moose Mountain area of Saskatchewan. South Salt Lake and Shoal Lake in the Oak River Basin are striking examples of large permanent transitional sloughs belonging to a regional flow system. Some of the characteristics of South Salt Lake have been described by Lissey and Wyder (1966). Sloughs B, C and D of figure 12a are transitional sloughs for an interrupted regional flow system.

The prime requisite for interrupted flow is a high regional water table. If the regional water table lies below the bottom of a slough a groundwater mound is established below that slough. Hence what would normally be a transitional slough when the regional water table was high would become a recharge slough when the regional water table was low as indicated by slough B of figure 12b.
Figure 13.— Development of Intermediate Flow Systems
Figure 13 is a diagram illustrating the flow conditions across a basin flank wherein the sloughs are not progressively lower in elevation. If even one slough (Slough D, Fig. 13) is at a higher elevation than the one preceding it in the direction of regional flank slope (Slough C, Fig. 13) both local and intermediate flow systems are established. This is the only way in which either a local flow system, or an intermediate flow system, that does not discharge into the lowest sink can develop in homogeneous, isotropic material. Again it must be borne in mind that the flow conditions shown are only developed when the regional water table is high. If the regional water table were lower, interrupted flow would cease and sloughs B and E of figure 13 would become recharge sloughs. With further lowering of the regional water table even slough C might become a recharge slough.

The amount of regional water table decline or rise required to change the character of a slough depends on the difference in elevation between the slough bottom and the original height of the regional water table. Meyboom (1967) has recorded such changes during the course of one summer.

Geologic Control. -- Besides the relationship between the topography and the regional water table, the presence of more permeable layers within the saturated medium also affects flow conditions and hence the distribution of recharge and discharge sloughs. Figure 14 shows the effect of an aquifer pinchout at depth as determined from computer analysis by Freeze and Witherspoon (1967). Equation 4 is used as
Figure 14—Altered Flow Patterns due to Permeability Contrasts and Aquifer Pinchout at Depth. (after Freeze and Witherspoon, 1967)
the basis of this analysis. The upper diagram of this figure shows the potential and flowline network that exists across one flank of a hypothetical basin where the flow medium is homogeneous and isotropic. The lower diagram shows how this network is altered by the presence of part of an aquifer that is ten times more permeable than the rest of the flow medium. The main difference to note is in region A of the lower diagram. Instead of remaining an area characterized by horizontal groundwater movement as in the case of a homogeneous medium, this region is characterized by upward flow and groundwater discharge when the flow medium includes part of a more permeable aquifer. With greater permeability contrasts than the 1:10 ratio used in the example of figure 14 the discharge area of region A becomes more pronounced and the amount of regional discharge at the bottom of the basin decreases. In practice permeability contrasts of 1:1000 are not unusual. This phenomenon is believed to account for at least two large areas of discharge sloughs in the Oak River Basin.

The presence of less permeable layers within the saturated medium also affects flow conditions. The way in which flow is altered by a less permeable layer overlain and underlain by more permeable layers can be illustrated by once more applying equation 4. Because this phenomenon is believed to be an exception rather than the rule in the Canadian Prairies a theoretical discussion of its effects is not presented. Instead the reader is referred to the upper diagram of figure 31. This diagram illustrates how flow is
altered in an actual case of this rare phenomenon as encountered in the Oak River Basin.

Aside from its effect of altering flow direction due to permeability contrasts within the saturated medium, geology plays a more important role in the preparation of slough-focused flow patterns because the geology of surficial deposits determines where, within a particular area, the sloughs are actually located. The undrained topographic depressions called sloughs are formed in such geomorphological features as kettles, pitted outwash, and blocked drainage channels. The occurrence, distribution, size, and depth of these features are all related to the glacial history of an area. In unglaciated regions, drainage is much better established and the significance of sloughs or surface depressions on groundwater flow conditions is greatly reduced. However in morainic regions, especially where ice has stagnated, drainage is poor and sloughs occupying kettles are abundant. In such regions the significance of sloughs is great and slough-focused flow patterns describe natural groundwater flow conditions accurately.

The Fundamental Principles of Groundwater Chemistry

The process by which groundwater acquires a certain chemical composition consists of initial mineralization and progressive modification (Schoeller, 1959). Initial mineralization takes place within the soil below recharge areas and determines the primary composition
of the groundwater. Modification of this primary composition occurs along the entire length of all flow paths and determines the ultimate composition of groundwater in discharge areas.

Initial mineralization depends on the chemical phenomena associated with infiltration through and evapotranspiration from the soil, the resultant of which is downward moving water that can contribute to recharge. These phenomena are dissolution in the "A horizon" and precipitation in the "B horizon" respectively. Analyses of water from very shallow piezometers suggest that the initial mineralization of recharging water in the Oak River Basin does not exceed 200 p.p.m. of total dissolved solids.

The most important modifications affecting the composition of groundwater are sulphate reduction, base exchange, and concentration. The degree to which each of these is active depends on the geology of the rocks through which the groundwater flows.

Sulphate reductions are caused by biochemical processes associated with anaerobic microorganisms found in organic matter such as decomposing vegetable or animal remains, peat, coal, and petroleum. Groundwater that has been subject to sulphate reduction is usually characterized by a greater proportion of bicarbonates and by the presence of hydrogen sulphide gas. Due to the lack of organic material in the sediments, sulphate reduction is not prevalent in the Oak River Basin, although the occasional presence of hydrogen sulphide gas indicates that it does occur locally in some discharge areas.
Base exchange is the process by which substances referred to as permutalites preferentially exchange some of their own cations for cations contained in the groundwater moving through them. The exchangeable ions are bonded to the molecular lattice-layers of a permutalite by chemisorption (Hem, 1959). The exchange capacity of a permutalite depends on the number of unsatisfied negative bonds remaining in the crystal lattice. Thus there is a general trend for permutalites to adsorb divalent cations from the water and release monovalent cations. Considering the main cations found in groundwater there is a tendency for Na$^+$ > K$^+$ > Mg$^{++}$ > Ca$^{++}$ in the water due to continuing base exchange (Schoeller, 1959). Permutalites occurring in the sediments of the Oak River Basin are montmorillonite, illite, and organic material.

Mineral concentration of groundwater is effected in two ways -- by evaporation and by dissolution. Concentration by evaporation is particularly important during initial mineralization of groundwater when saturation and hence chemical precipitation can occur. Similarly evaporation in discharge areas concentrates groundwater mineralization. However between recharge and discharge areas the principal mechanism of concentration is dissolution. Concentration by dissolution depends on temperature, pressure, area of water-rock interface, volume of water throughput, and duration of movement. The ions taken into solution depend on the composition of the rock, the solubility of the rock material, and the composition of the water moving
through the rock. The principal ions found in groundwater are $\text{Ca}^{++}$, $\text{Mg}^{++}$, $\text{Na}^+$, $\text{K}^+$, $\text{Cl}^-$, $\text{SO}_4^{2-}$, and $\text{HCO}_3^-$. According to Chebotarev (1955) there is a tendency for groundwater to change its chief anion from $\text{HCO}_3^-$ to $\text{SO}_4^{2-}$ to $\text{Cl}^-$ along a flow path because of concentration by dissolution. Accompanying this is a tendency for the chief cation to change from $\text{Ca}^{++}$ to $\text{Mg}^{++}$ to $\text{Na}^+$. This is termed the metamorphic cycle of natural waters. The work of several authors has verified that such changes do occur in the field (Suter et al., 1959; Meyboom, 1960; Lissey, 1962a and Lissey, 1962b). Similar conditions are noted in the Oak River Basin where recharge areas have low concentration bicarbonate waters and discharge areas have either moderate concentration bicarbonate-sulphate waters or high concentration sulphate waters.

The factors affecting the chemistry of groundwater, particularly Chebotarev's metamorphic cycle, play an important role in the hydroecological classification of sloughs.

Plants as Environmental Indicators

General Statement

As shown in the preceding sections the kind of slough to be found at a particular place, in an area geologically favourable for the abundant occurrence of sloughs, depends on the relationship between the topography and the regional water table and on the presence of permeability contrasts within the saturated medium. Because these
Factors determine the types of flow systems developed within a basin. A sound technique for reconnaissance mapping of flow systems is possible if the various kinds of sloughs can be distinguished from each other on the surface. The indicator aspect of plant ecology provides one basis for distinguishing between sloughs that are subject to different groundwater conditions. This section outlines the ecological principles behind the use of plants to indicate environmental conditions.

**Factors Affecting Natural Vegetation**

Plant species vary greatly in their tolerance to environmental factors. The range of tolerance, or ecological amplitude, is a function of the genotype or genetic constitution of the plant. Plants with relatively restricted tolerances are confined to ecologically specialized habitats. The natural occurrence of plants especially adapted to certain conditions is an indication that those conditions exist in the natural environment at the place of occurrence. Such plant indicators can be used to determine areal changes in the factors of plant environment. These factors may be grouped into three major categories: climatic, edaphic, and biotic.

Climatic factors include light, temperature, precipitation, wind, humidity, pressure, and atmospheric composition. Edaphic factors, or soil characteristics, include the type and texture of the parent material, the amount of organic matter, the quality of free water, and the degree of water saturation. Biotic factors include both
disjunctive and conjunctive symbiotic relationships (McDougall, 1918) with both animals and other plants.

Only plant indicators of water quality and degree of saturation are discussed in this thesis because these are the only factors affecting plant growth that can be directly related to groundwater flow.

**Indicators of Water Quantity**

**General.** -- In 1895 Warming became the first to classify plants according to their water requirements. Clements (1920) modified Warming's system into one comprised of three major plant types: hydrophytes, mesophytes, and xerophytes. Each type is adapted to a different degree of water saturation in the soil. Hence naturally occurring plants, representative of a particular type, serve as broad indicators of the quantity of free water available in the natural environment.

**Hydrophytes.** -- Hydrophytes are plants that are adapted to a completely saturated soil environment. They include submerged, floating, and amphibious plants.

The amphibious, or emergent anchored, hydrophytes are especially important as indicators of permanently saturated soil conditions around some of the sloughs in the arid to semi-arid parts of the Prairie Provinces. These plants grow with their roots in waterlogged soil and most often are partly submerged in shallow water. Cattails (*Typha sp.*), spikerush (*Eleocharis palustris*), reed grass (*Phragmites communis*) and whitetop (*Scolochloa festucacea*) are
examples of emergent anchored hydrophytes indicating an excess of free water in the environment.

**Mesophytes.** -- Mesophytes are plants that are adapted to a moist but moderately aerated soil environment. They lack the distinct modifications that hydrophytes or xerophytes possess, hence they cannot inhabit completely saturated soil nor can they survive where the soil water is significantly depleted. Most trees, shrubs and many grasses are mesophytes. The aspen poplar (*Populus tremuloides*), white birch (*Betula papyrifera*), Manitoba maple (*Acer negundo*), bur oak (*Quercus macrocarpa*), snowberry (*Symphoricarpos occidentalis*), wolf willow (*Eleagnus commutata*), reed bentgrass (*Calamagrostis sp.*), water parsnip (*Sium cicutaefolium*), and wildmint (*Mentha arvensis*) are examples of mesophytes indicating a moderate amount of free water in the environment.

**Xerophytes.** -- Xerophytes are plants that are adapted to a physically or physiologically dry soil environment. A soil may have abundant water, even to the point of saturation, but be physiologically dry because: (a) there is an excess of salt in solution, or (b) the water is frozen or at too low a temperature to support plant growth. Physically xeric conditions may exist even in moist climates in places where (a) soil is nonexistent and bare rock is exposed, or (b) soil is well drained because of a sandy or gravelly matrix. In general, xerophytes grow where the soil is physically dry due to a dry climate.

*Wheat-grass* (*Agropyron trachycaulum*), *speargrass* (*Stipa comata*), *ticklegrass* (*Agrostis scabra*), and *cactus* (*Opuntia polyacantha*)
are examples of xerophytes that grow in physically dry soil and indicate a deficiency of free water in the environment.

**Phreatophytes.** -- In addition to Clements' threefold classification, Meinzer (1923) proposed the term phreatophytes to define those plants "that habitually obtain [their] water supply from the zone of saturation, either directly or through the capillary fringe." The earliest list of phreatophytes (Meinzer, 1927) included only specialized mesophytes but later workers have shown that some physiological xerophytes (Robinson, 1958) and some emergent hydrophytes (Meyboom, 1966 and 1967) are also phreatophytic.

Phreatophytes generally have very high transpiration rates hence they can discharge significant quantities of groundwater (White, 1932; Troxell, 1936; and Meyboom, 1965). The willow (Salix, sp.) is the best known phreatophyte. Other examples of phreatophytes listed by Robinson (1958) that are found in the Oak River Basin are: salt grass (Distichlis stricta), baltic rush (Juncus balticus), reed grass (Phragmites communis), saltwort (Salicornia rubra), and sea blite (Suaeda depressa). These plants indicate a shallow depth to the water table and at least a very local zone of groundwater discharge.

**Indicators of Water Quality**

**General.** -- Plants may be classified into halophytes and glycophytes according to the quality of soil water favouring growth. Halophytes were first described by Warming (1909) as those plants adapted to live on saline soil. Stocker (1928) first proposed the term glycophytes to
describe those plants not adapted to live on either saline or alkaline soil.

In saline soils ("white alkali" or Solonchak) the soil water contains neutral soluble salts such as chlorides, sulphates, and nitrates of sodium, calcium, potassium, and magnesium. In alkaline soils ("black alkali" or Solonetz) the soil water contains basic soluble salts such as carbonates of sodium and potassium.

Thus glycophytes serve as indicators of fresh soil water while halophytes indicate saline soil water. Furthermore, because different halophytes vary in their tolerance of salt, the degree of water salinity can be estimated by the presence of particular species.

Halophytes. -- Warming (1909) and Clements (1920) considered the halophyte as one type of xerophyte. Although they grow where the soil is physiologically dry due to an excess of soluble salts, halophytes cannot grow where the soil is physically dry. Thus from the standpoint of the degree of water saturation halophytes can be subdivided into those adapted to hydric (completely saturated) conditions and those adapted to mesic (moist) conditions. Hydric halophytes therefore indicate an excessive amount of free saline water while mesic halophytes indicate a moderate amount of free saline water in the environment.

Examples of hydric halophytes occurring naturally within the Oak River Basin are alkali bulrush (Scirpus paludosus), baltic rush (Juncus balticus), soft-stem bulrush (Scirpus validus), and sea-side
crowfoot (Ranunculus cymbalaria), in order of decreasing salt tolerance. Mesic halophytes occurring naturally within the basin include arrow grass (Triglochin palustris), foxtail (Hordeum jubatum), and gumweed (Grinindelea squarrosa). These are also listed in order of decreasing salt tolerance.

Glycophytes. -- Glycophytes inhabit hydric, mesic, and xeric environments. All plants previously listed as examples of hydrophytes, mesophytes, and xerophytes are glycophytes that occur naturally within the Oak River Basin. Respectively they are indicators of excessive, moderate, and deficient amounts of fresh water in the environment.

Communities as Precision Indicators

The occurrence of a single species can be used in a broad way to indicate the intensity of a particular environmental factor. To obtain a more precise idea about the intensity of that factor the occurrence of two species growing together in the same community can be used provided the intensity of the factor in the community environment is near the lower limit of endurance for one of the species and near the upper endurance limit of the other species.

The principle of using the community rather than a single species to obtain a more precise indication of factor intensity at a particular location is illustrated in figure 15a. In this diagram Sp. C represents a good indicator because it has a short range of endurance with respect to the intensity of factor X. Using Sp. C as an indicator
Fig. 15a.—Value of using the the community rather than a single species as an indicator of factor intensity.

Fig. 15b.—Water conductivity at SW 16-15-23 WI as indicated by a community of Scirpus and Typha

Figure 15—The use of plant communities as indicators
one would conclude that the intensity of factor X at this location was between 2 and 5. Both Sp. A and Sp. B are poor indicators by themselves because both have a wide range of endurance. However, because the minimum intensity of factor X required by Sp. A is 3 and because the maximum intensity of factor X tolerable by Sp. B is 4, it is obvious that if the two species occur together in the same community the intensity of factor X in the community environment must be between 3 and 4.

An example of how this principle can be used quantitatively is shown in figure 15b. From measurements of 80 different sloughs and lakes throughout the Oak River Basin it was found that the minimum conductivity of water where *Scirpus validus* grew was 1300 mmhos/cm and the maximum water conductivity where *Typha latifolia* grew was 1800 mmhos/cm. From this it was expected that at sloughs where both grew in the same community the water conductivity would be between 1300 and 1800 mmhos/cm. A check on one such slough yielded a measured value of 1450 mmhos/cm.

Extensive quantitative work of this nature was not done in this study. However the same principle was applied in the more qualitative sense of deciding the permanency of water in sloughs on the basis of plant associations within them.

**Precautions**

When using plant indicators to determine how the intensity of a particular factor in the natural environment varies from place to
place the investigator must keep in mind a number of precautions.

Foremost of these is the necessity of dealing with undisturbed communities of the natural vegetation only. The reason that wheat grows in one place and alfalfa in another is not necessarily because the quantity of water available for plant growth is greater in the alfalfa field but because it was planted there. Hence one must deal with the natural vegetation. Similarly, an occurrence of *Salicornia rubra* in a highway ditch is not necessarily due to the natural occurrence of saline soil water but may reflect the practice of spraying a solution of CaCl₂ on the road during its construction or later as a dust abatement measure. Hence one must deal with plant communities in undisturbed areas only.

Another precaution is the recognition of ecotypes, or strains of a particular species in which genetically different physiologic features develop in a way that enables each strain to adapt to a different environment. Often the ecotypes of a species display such slight morphologic differences that their differentiation in the field is difficult. Species with many ecotypes can fit into a wide range of habitats and are useless as indicators.

Perhaps the major precaution in using plants as indicators of environmental conditions is the awareness of factor interaction. An example of factor interaction is the effect of soil texture on the degree of saturation. The permeability of a fine-grained soil is lower than that of a coarse-grained soil, with the result that the time required to drain the free water from the former is greater than that required for the latter. Hence fine-grained soils tend to remain saturated longer.
than coarse-grained soils even though both may be subject to identical conditions of precipitation, ponding and drainage. Therefore, although plants may indicate that more water exists in the environment at one locality than another the reason may be due to this particular interaction rather than to a difference in precipitation or groundwater conditions.

While formulating the classification of sloughs presented later in this thesis and while mapping in the Oak River Basin the author kept these precautions in mind.

Hydroecological Classification of Sloughs

Hydrological Differentiation

Sloughs can be differentiated hydrologically on the basis of:

(1) whether water leaves the slough for the saturated zone or whether water enters the slough from the saturated zone, (2) the quality of water entering or leaving the slough, and (3) the rate at which water enters or leaves the slough.

On the basis of whether water leaves or enters the slough with respect to the saturated zone, sloughs can be divided into three basic types: recharge, discharge, and transitional. Water leaves a recharge slough to join the saturated zone. It enters a discharge slough from the saturated zone. In a transitional slough water enters it at one end from the saturated zone and leaves it at the other end to
rejoin the saturated zone.

The quality of water entering or leaving a slough may be either fresh or saline. In all natural recharge sloughs the water is fresh. In transitional and discharge sloughs the water may be either fresh or saline depending on the type of flow system with which the slough is associated. Where these sloughs are associated with local and short intermediate flow systems the water in them will be fresh. Where they are associated with long intermediate and regional flow systems the water will be saline.

Based on the rate at which water enters or leaves it any of the above sloughs may be considered hydrologically as either fast or slow. The speed of a slough depends on the permeability and the head gradient below it because these are the factors determining the rate of flow within the zone of saturation to which the slough is hydrologically connected.

Therefore, considering this trifold hydrologic basis of differentiation there are ten types of natural sloughs that can theoretically exist. The problem now remains of how to distinguish one from another.

**Ecological Distinction**

As mentioned earlier the indicator aspect of plant ecology provides the most promising basis for distinguishing one type of slough from another. This distinction depends on using indicators of water quantity and indicators of water quality in particular.
The second of the three hydrologic differentiation factors that determine the type of slough is immediately apparent using water quality indicators alone. Sloughs that have glycophytes associated with them contain fresh water while sloughs that have halophytes associated with them contain saline water.

The nature of the other two hydrologic differentiation factors determining the type of slough is revealed by the rate of water level recession over the summer months, which in turn is disclosed by water quantity indicators. This follows from consideration of the factors that affect the total amount of water retained in a slough and hence its water level at any particular time. These can be listed as infiltration of water from the slough to the zone of saturation, emission of groundwater from the zone of saturation into the slough, evaporation, precipitation, and the size of the drainage area of the depression containing the slough. The size of the drainage area and the amount of accumulated winter precipitation released by melting determines the amount of water received by the slough from spring runoff. This is the maximum amount of water retained by the slough at any time and determines its periphery, which, except in saline discharge sloughs, is marked by a ring of phreatophytes. If the depression density of a region is uniform these drainage areas and hence the sizes of the sloughs themselves will be the same throughout that part of the region where the precipitation can be considered uniform. Changes in depression density cause variation in the size of
sloughs. Hence although drainage area and snowfall essentially determine the size of a slough and its maximum water level in the spring, the remaining factors determine the rate of water level recession over the summer months. Precipitation in the form of rain during the summer also affects the amount of water in a slough and hence its water level recession rate. However considering that depression drainage areas are usually small and that much of the rain falling on these areas is used to make up the soil moisture deficit, rainfall can be considered to have the long-term effect (over the summer) on water level recession of essentially decreasing the amount of water level recession due to evaporation alone. Hence we are left with the phenomenon that water level recession in a slough over the summer is due to the net effect of infiltration from the slough, groundwater emission into the slough, and decreased evaporation.

In recharge sloughs the water level recedes rapidly because the effects of infiltration and evaporation are additive. If the infiltration rate is fast enough the slough will be dry by fall. In this study such a slough has been arbitrarily designated as a hydrologically fast recharge slough. A slow recharge slough is one in which a central core of open water or completely saturated soil still exists in the fall. Accompanying water level recession in a recharge slough is a temporally and spatially gradational decrease in the degree of soil saturation in the slough. Temporally, the degree of saturation is highest in spring and gradually decreases throughout summer.
Spatially, the centre part of the slough always remains more highly saturated than the edges due to the geometry of the intersection between the slough bottom and the groundwater mound (Fig. 11a). Hence in all recharge sloughs there develops an inwardly expanding band of mesic (moist) conditions that is accompanied by a shrinking core of hydric (saturated) conditions at the centre. Thus depending on the original spring water level in the slough and the rate of infiltration, recharge sloughs at the end of the summer can vary from those being entirely infilled with glycophytic mesophytes to those having a flourishing glycophytic core of hydrophytes surrounded by a broad band of mesophytes. The former are denoted as fast recharge sloughs while the latter are denoted as slow recharge sloughs.

In discharge sloughs the water level recedes slowly because the effects of groundwater emission and evaporation oppose each other. If the emission rate is fast enough it may equal or exceed the evaporation rate so that the water level tends to remain constant or even rise with time. In this study such a slough has been designated as a hydrologically fast discharge slough. A slow discharge slough has a receding water level. Very slow discharge sloughs resemble very slow recharge sloughs. This is understandable when one considers that the lower the speed of a slough the lower the permeability and in theory a slough underlain by impermeable material will have a water level decline due to evaporation alone. Thus if the rate of infiltration in one slough were very low and if the rate of groundwater emission
in another were also very low the water level recessions in the two sloughs would not differ markedly; although theoretically water level recession in the discharge slough should proceed more slowly than that in the recharge slough. Considering the geometry of the intersection between the saturated zone and the slough bottom in a discharge slough (Fig. 11b) there is a tendency for hydric conditions to exist throughout the summer. Only very slow discharge sloughs will have mesic conditions inside and these should only exist in a relatively narrow band within the periphery. Thus sloughs lacking the narrow mesophyte zone are of the fast discharge variety while sloughs with a mesophyte band but in which hydrophytes predominate are slow discharge sloughs. Depending on the quality of water emitted discharge sloughs may contain either glycostytic or halophytic hydrophytes and mesophytes. True perennial discharge sloughs should be saline. Sloughs that change their character from recharge sloughs to discharge sloughs because of a rising regional water table may discharge relatively fresh water.

In a transitional slough the rate of water level recession depends on the net effect of emission at one end, infiltration at the other, and evaporation from the free surface. A fast transitional slough has been arbitrarily chosen as one in which the rate of emission equals or exceeds the sum of the infiltration and evaporation rates. Hence it too will be characterized by a water level that tends to remain constant or even rise with time. In the same general area
where the rate of evaporation can be treated as constant a slough transi-
tional slough is due to either a lower rate of emission or a higher
rate of infiltration and will be characterized by a water level decline
throughout the summer. Despite the hydrological differences, there
appears to be no way of ecologically distinguishing between true dis-
charge sloughs and transitional sloughs. This may not be too serious,
in that transitional sloughs may be considered as places where some
groundwater permanently leaves the zone of saturation by evaporation
from the slough and the only difference between them and true dis-
charge sloughs is the fact that not all the groundwater emitted into
them is lost from the zone of saturation.

The Classification for a Prairie Upland Environment

General. -- A classification of sloughs in a prairie upland environment
is here proposed, based on the theoretical considerations of hydro-
logically differentiating and ecologically distinguishing between slough
types as an outcome of slough-focused flow patterns. The species
listed in the descriptions were chosen by observing sloughs adjacent
to type nests in the Oak River Basin. All descriptions pertain to the
appearance of these sloughs in the fall when the greatest ecological
differences between the various types should exist. The descriptions
pertain to the aspect of eight possible vegetative zones (Stewart
and Kantrud, 1967). Two of these zones are not applicable to the
classification presented here. They are the tillage zone and the
alkaline bog zone. The former does not apply because only undisturbed sloughs are classified and the latter does not apply because the special conditions required for the occurrence of highly alkaline groundwater discharge (Parsons, p. 26, 1967) are not found in the Oak River Basin. The six vegetation zones used to describe the types of slough presented here are: the permanent open-water zone, the intermittent saline zone, the deep-marsh zone, the shallow-marsh zone, the wet-meadow zone, and the low-prairie zone. The relationship between these zones and the classification itself are presented in Plate 1. The remainder of this section is devoted to short descriptions of the major slough types recognized in this classification.

Recharge Sloughs. - In the fall fast recharge sloughs are characterized by the absence of open-water, deep marsh and shallow marsh zones. Very fast recharge sloughs also lack a wet-meadow zone, being entirely infilled with xeric and mesophytic grasses of the low-prairie zone. Most fast recharge sloughs however have their central portion covered by mesophytic grasses of the wet-meadow zone that lie within a narrow encircling ring of phreatophytic willows. In the Oak River Basin the willow ring varies from 10 to 30 feet in width and from 30 feet to 1/4 mile in outer diameter. A typical fast recharge slough is shown in Photograph No. 1.

Unlike the situation in a fast recharge slough, the groundwater mound below a slow recharge slough never dissipates sufficiently to permit the water table to lie far below the bottom. Hence in the fall
Photograph No. 1. - Fast Recharge Slough

Photograph No. 2. - Slow Recharge Slough
these sloughs are characterized by the presence of shallow-marsh hydrophytes in the centre portion which in turn are concentrically fringed by mesophytes of the wet-meadow zone and outwardly encircled by a ring of phreatophytic willows. The wet-meadow zone of slow recharge sloughs contains the same mesophytic species as those found in the equivalent zone of fast recharge sloughs but may occur as only a narrow ring -- some ten feet wide -- just inside the willows, or may cover the entire slough except for a few square feet in the centre where the shallow-marsh hydrophytes occur. In very slow recharge sloughs some ponded water still remains in the centre by fall because the rate of mound dissipation is so slow that the water table has not yet receded below the bottom. In such sloughs there is a small open-water zone in the centre, a narrow deep-marsh zone of emergent hydrophytes, a narrow shallow-marsh zone of hydrophytes, and then a mesophytic wet-meadow zone of variable width. A narrow outer ring of phreatophytic willows denotes the periphery of the slough. The entire diagnostic area of a slow recharge slough is typically about the same as that of a fast one. A typical slow recharge slough is shown in Photograph No. 2.

**Fresh Discharge Sloughs.** -- Fresh water transitional sloughs are included in this grouping because they cannot be distinguished from true fast fresh discharge sloughs brought about by a rising regional water table. Hence wherever the term "fresh discharge slough" appears in this thesis the reader must bear in mind that the slough may in fact be transitional.
In the fall fast fresh discharge sloughs with stable water levels are characterized by an extensive permanent open-water zone which is surrounded by a narrow deep-marsh zone of hydrophytes and a narrow shallow-marsh zone of hydrophytes. The absence of wet-meadow mesophytes within the peripheral ring of willows is a distinctive feature of fast fresh discharge sloughs. Very fast fresh discharge sloughs wherein water levels are rising in the fall are characterized by an expanding permanent open-water zone which drowns earlier vegetation. In some cases a narrow band of willows may be partially re-established during a temporary halt in the expansion of the open-water zone only to be drowned later. Fast fresh discharge sloughs in the Oak River Basin range from 30 feet to 1/2 mile in diameter. A very fast slough of this type is shown in Photograph No. 3.

Slow fresh discharge sloughs are characterized in the fall by a small centrally located permanent open-water zone surrounded by broad deep-marsh and shallow-marsh zones of hydrophytes enclosed within a narrow mesophytic wet-meadow zone. Encircling these zones is a ring of phreatophytic willows. The slough in Photograph No. 4 is a slow fresh discharge slough. The difficulty of distinguishing between a slow recharge slough and a slow fresh discharge slough is evident from a comparison of Photographs 2 and 4 and from the summary in Plate 1. As mentioned earlier this is to be expected.

Saline Discharge Sloughs. -- Again the reader must bear in mind that saline transitional sloughs are also included in this grouping because
Photograph No. 3. - Fast Fresh-water Discharge Slough

Photograph No. 4. - Slow Fresh-water Discharge Slough
they cannot be distinguished from true fast saline discharge sloughs.

Saline discharge sloughs are readily distinguished from fresh dis­
charge sloughs because all the plants are halophytic and no peripheral
band of willows exist in the former.

No fast saline slough with a rising water level was found in
the Oak River Basin. This is understandable when one considers that
saline discharge sloughs are the emission points of long intermediate
and regional flow systems, and that in such systems the flow rate does
not vary as rapidly as in local and short intermediate systems. As a
result equilibrium is established between the rate of emission, rate
of evaporation and extent of open water wherein a stable water level
is maintained. Hence in the fall a typical fast saline discharge slough
is characterized by an extensive permanent open-water zone which is
surrounded by fairly broad deep-marsh and shallow-marsh zones of
halophytic hydrophytes and a relatively narrow wet-meadow zone of
halophytic mesophytes. These mesophytes usually show a zonation by
species according to their tolerance for salt with the more tolerant
plants growing next to the shallow-marsh zone. The fast saline dis­
charge sloughs in the Oak River Basin vary from those that are 100
feet in diameter to large permanent lakes several miles in length and
up to one mile wide. A moderately fast saline discharge slough is
shown in Photograph No. 5.

In the fall, slow saline discharge sloughs are characterized
by the absence of any vegetation or water in the centre. Instead, the

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intermittent saline zone of bare salt deposits is dominant. In most cases a poorly developed wet-meadow zone of very tolerant halophytic mesophytes encircles the intermittent saline zone. In the Oak River Basin slow saline discharge sloughs form salt flats which may extend over several square miles although a single slough will seldom be more than 3/4 miles in diameter. One of the larger slow saline discharge sloughs found in the basin is shown in Photograph No. 6.
Photograph No. 5. - Fast Saline Discharge Slough

Photograph No. 6. - Slow Saline Discharge Slough
PART 2: APPLICATION

General Statement

The theory of slough-focused flow patterns and its outcome of a hydroecological slough classification was tested by applying the classification to map recharge and discharge regions and then checking the map with test nests. This work was done in the Oak River Basin, Manitoba where observations around type nests originally suggested the theory.

The presentation is in three parts. The first describes the physiography and geology of the basin, the second outlines the procedure used to map the recharge and discharge regions of the basin, and the third presents the results of the mapping and of the test nests used to check the mapping.

Description of the Oak River Basin

Physiography

Topography. -- The Oak River Basin lies partly within the Assiniboine River Plain and partly within the Gundy Lake Highland portion of the Riding Mountain Upland (Klassen, 1966). The two physiographic divisions are separated by the 1900 foot contour (Fig. 16).

The southern quarter of the basin is bowl-shaped with well defined divides between the adjoining Minnedosa River Basin to the east and the Arrow River Basin to the west. In this part of the basin the local relief between tributary valley bottoms and the intervening
highs is as great as 75 feet.

The remainder of the basin has a general slope of between 9 and 15 feet per mile to the south-southwest and is separated from the adjoining Minnedosa and Arrow River Basins by poorly defined divides with less than 25 feet of local relief. The local relief between slough or stream bottoms and adjacent highs is between 10 and 25 feet over most of this area.

The maximum relief of the Oak River Basin between its highest point on the northernmost divide and its lowest point at the junction of the Oak and Assiniboine Rivers in the south is 950 feet. Except in the southern quarter of the basin the total lateral relief between the top of the divide and the bottom of the Oak River valley is usually less than 100 feet.

**Drainage.**-- Drainage of the entire basin is afforded by the Oak River and its tributaries. The Oak River is in turn a tributary of the Assiniboine River (Fig. 1). The southern quarter of the basin is well drained by a dense dendritic system of tributaries. The remainder of the basin, however, is poorly drained. With an average of about thirty sloughs per square mile depressional storage is very high in this area. The net drainage area (Stichling and Blackwell, 1957) fluctuates widely between seasons. For this reason, two sub-basins that have internal drainage under normal conditions but which contribute to flow in the Oak River during the spring are included in the gross drainage area of the Oak River Basin. All maps in this
Le cend Soil Association.

- Wolfville Clay Loam
- Erickson Clay Loam
- Newdale Clay Loam
- Newdale Clay Loam (Calcicrete) and Soilized Associates
- Newdale Clay Loam (Smooth Phase)
- Minisota Sandy Loam
- Carroll Clay Loam
- Harding Clay to Silt Clay
- Carroll Loam
- Arrow Hills - Lenore Combination
- Assiniboine Complex
- Soil Zone Boundary

Grey Wooded Soil Zone

Grey-Black Soil Subzone

Degraded Blackearth Transition Subzone

Blackearth Soil Zone

Figure 17 - Soils Map (After Ehrlich et al. 1956)
thesis show the gross drainage area. The smaller of these sub-basins lies southwest of Kenton while the larger, which includes Salt Lake, lies east of Ipswich (Fig. 16).

Soils. -- Soil constitutes the uppermost part of the zone of weathering and is characterized by a high content of recent organic matter. Three distinct layers can be discerned in it: the upper or "A horizon", the intermediate or "B horizon", and the lower or "C horizon". The "A horizon" is the zone of maximum weathering and is characterized by the downward leaching of soluble minerals and by the maximum accumulation of organic matter. The "B horizon", in contrast, is the zone of illuviation wherein material leached from the upper zone is deposited. The "C horizon" is the little-changed parent material from which the soil is derived. These three zones together make up the "soil profile" which, in reflecting the soil-forming processes, differ with each kind of soil.

The main factors that control the soil forming processes and determine the kind of soil are: (1) the type of parent material on which the soil is developed, (2) the type of vegetation, (3) the soil climate, and (4) the length of time during which the soil is under the influence of the soil-forming processes. The first of these determines the type of minerals in the soil; the second determines the amount and type of organic matter; the third, which includes temperature and amount of water in the soil, determines the rate and extent of mineral weathering; while the fourth determines the thickness and
developmental stage of the various zones.

In mapping soils, the soil scientist examines the soil profile at a large number of places in the field. In the office he later interprets the influence of each of the controlling factors that produce a particular profile. On this interpretation soils are divided areally into "soil types" which are grouped into "soil associations". The soil associations in turn are further grouped into "soil zones" by a soil climatologist. The grouping into zones is based on differences in climate and vegetation. The grouping into associations is based on differences in parent material while the division into types depends on differences in secondary factors such as topographical position, soil drainage, soil temperature and cultivation practices.

The soils of the Oak River Basin were mapped by Ehrlich et al. (1956) and the distribution of the various zones and associations is shown in figure 17. These investigators found most of the soils in the basin are transitional types between the Grey Wooded Soil Zone in the north and the Blackearth Soil Zone in the south. They belong to either the Grey-Black Subzone or the Degrading Blackearth Transitional Subzone. Soils of the Blackearth Zone are actually chernozem soils and are developed under prairie grass vegetation in a sub-humid climate while those of the Grey Wooded Zone are developed under boreal forest vegetation in a humid climate.

Climate. -- The closest meteorological station with records of over ten years' duration is located at Rivers (S.17, T.12, R.21, W.1). The monthly averages of daily mean temperature and precipitation are shown in figure 18. The mean annual temperature at Rivers is

-66-
Figure 18 - Average Monthly Temperature and Precipitation at Rivers

Mean Annual Temp. is 35.1°F

Average Annual Precipitation is 19.09 inches
and the average annual precipitation is 19.09 inches. (Climatology Division, 1959).

The distribution of 1966 annual precipitation throughout the Oak River Basin is shown in figure 19.

**General Vegetation.** -- The Oak River Basin lies within the aspen parkland which consists of inter-mixed areas of grassland and forest (Bird, 1961). The grassland communities are of the *Agropyron - Koeleria - Agrostis - Stipa* type described by Bird. The forested part of the basin supports primarily aspen poplar (*Populus tremuloides*) with lesser communities of white birch (*Betula papyrifera*) in the very northern part of the basin, Manitoba maple (*Acer negundo*) along the Assiniboine flood plain in the southern part of the basin, and bur oak (*Quercus macrocarpa*) along the banks of the Oak River and its tributaries in the southern half of the basin. All stages of vegetational succession are represented in the sloughs which occur in both the grassland and forested parts of the basin.

Farming is carried on throughout the basin with the southern half being the more extensively cultivated.

**Geology**

**Bedrock.** -- The Riding Mountain Formation of Late Cretaceous age forms the bedrock in the Oak River Basin. It consists of the soft Millwood Shale and the overlying hard Odanah Shale (Tyrell, 1892).

The Millwood beds, underlying the entire basin, are 400 to
Figure 19—Annual Precipitation in 1966 in Inches

Note: Contours are adjusted to records at:
- Rossburn
- Birtle
- Virden
- Wasagaming
- Minnedosa
- Brandon
450 feet thick (Bannatyne, 1966) and consist of soft, massive, non-calcareous, grey to greenish-grey clay shale. They contain numerous seams of bentonite and layers of iron-stone concretions near the top. Baculites sp. and Inoceramus sp. commonly form the nucleus of the larger concretions. The concretions vary from less than one inch to several feet in diameter. Selenite crystals are found rarely within these beds. The Millwood Shale does not crop out within the basin but is exposed in several places along the Assiniboine Valley to the west.

The Odanah beds reach a thickness of 250 feet in the northern part of the basin, thin southward, and do not occur in the southeastern part (Fig. 20). They consist of a hard, siliceous, medium-grey shale which is highly jointed, presenting a blocky appearance in outcrop. They weather into light-grey fissile fragments. A few thin beds of limestone and bentonite were encountered near the bottom of the section in one test hole. Few fossils have been collected from the Odanah Shale. The only outcrops of Odanah Shale within the basin are found near Bars Lake, in the southwest.

Wickenden (1945, p. 48), Kerr (1949, p. 31), and Klassen (1966, p. 8) regarded the Odanah and Millwood Shales as facies equivalents of each other while Davies et al. (1962, p. 145) and Bannatyne (1966) considered them to be distinct, stratigraphically successive members of the Riding Mountain Formation. The author's own work tends to support the latter contention. Five test holes drilled in the basin penetrated the Odanah Shale. In three of these, the Millwood-
Figure 20—Bedrock Topography and Subcrop Pattern

Legend

- Iron Drill hole with elevation of bedrock surface
- Drill hole with elevation of top of Millwood
- Elevation contour on surface of bedrock
- Trace of bedrock Twp. 10 valley

Millwood subcrop (remainder of area underlain by Rge. XXI Odanah)
Odanah contact is marked by a sharp change in lithology, while, in the other two, it is gradational and lies in a zone of alternating hard and soft shales, up to 20 feet thick. Using the base of the gradational zone as the top of the Millwood Shale, the contact strikes N 42° W, dips 9.7 feet per mile to the southwest, and intersects the bedrock surface as shown in figure 20. Information from drilling near Maskawata, Kenton, Oakner, Hamiota, Lavinia, and Myra supports this subcrop pattern.

The Riding Mountain Formation is equivalent to the upper part of the "Marine Shale Series" of central and eastern Saskatchewan described by Fraser et al. (1935), and Price (1955) showed it to be equivalent to those beds lying between the bottom of the Lea Park Formation and the top of the Bearpaw Formation in Alberta. Wickenden (1945) equated the Riding Mountain to the Pierre Shale of North Dakota.

The general slope of the bedrock surface in the Oak River Basin is towards the south (Fig. 20). The main feature of this surface is a major valley that trends southeastward through Hamiota, then turns south through Bradwardine to parallel the Oak River to its outlet. This valley has three tributaries: two trend southward through Shoal Lake and the Salt Lakes; the other trends to the southeast through Kenton. Except for elongation of the lakes mentioned, there are no surface features to indicate where these valleys lie.

Glacial Drift. -- Glacial drift of Pleistocene age unconformably mantles the bedrock and forms the surficial material of the Oak River Basin.
It consists of unconsolidated till, gravel, sand, silt, and clay.

On the surface, till is the most widespread material, and it covers all of the basin north of Bradwardine. The part of the basin south of Bradwardine is covered by lacustrine and deltaic deposits, which are underlain by till. The thickness of the till varies from a few feet near Bars Lake to over 200 feet in the center of the bedrock valley between Oakner and the town of Oak River. Clays and silts, forming the lacustrine deposits, are up to 100 feet thick south of Harding, and outwash sands and gravels, forming the deltaic deposits, are reported by Bostock (1965) to be over 175 feet thick in a well south of the Rivers airdrome. The distribution of these surficial deposits within the basin is shown in figure 21 after mapping done by Elson (1961) and Klassen (1966).

In the subsurface, only three mappable deposits of glacial sand and gravel occur in the Oak River Basin. These are limited to the buried valleys of the bedrock surface, north of Bradwardine, where they are overlain by till. Their extent is shown in figure 22.

The largest of these deposits is confined to the buried valley that trends through Hamiota, where it is covered by 80 to 150 feet of till. Over most of its extent, it is between 30 and 50 feet thick but attains a maximum thickness of 200 feet three miles south of the town of Oak River. Between Hamiota and Oak River, the deposit thins to between 10 and 20 feet. At Hamiota, it is underlain by 40 feet of till but, south of Oak River town, it lies directly on the bedrock.
Legend:

- Hummocky Moraine (till)
- Ground Moraine (till)
- Lacustrine Depositions (Clay and Silt)
- Ice Contact Deposits (Sand and Gravel)
- Kame - eskerine Complex
- Esker
- Meltingwater Channel
- Flutings
- Outwash (Sand and Gravel)

Figure 21 - Surficial Geology (After Klassen, 1966 and Elson, 1961)
Legend
- Location of drill hole used to delineate deposit
- Extent of subsurface gravel deposit

Figure 22.— Location of Subsurface Glacial Gravels
Throughout most of its extent, the deposit consists entirely of sand and gravel however, between Norman and Oak River, it contains interbedded clays up to 10 feet thick. The sand and gravel is believed to be a proglacial outwash deposit. Between Hamiota and Oak River, where the gravels are coarser, this outwash was deposited as channel-fill but, south of Oak River, it grades into a finer-grained deltaic deposit, indicating that drainage was to the southeast at the time of deposition. A readvance and subsequent retreat of ice over the area buried the deposit beneath till.

Another subsurface deposit of glacial sand and gravel is confined to the buried valley that trends through the Salt Lakes. Its extent has been traced by surface electrical resistivity techniques combined with drilling (Lissey and Wyder, 1966). The deposit is covered by 50 to 60 feet of till. At the south end of North Salt Lake, the sand and gravel deposit is 40 feet thick and rests on bedrock. It thins southward and becomes both finer grained and more shaly in that direction. Four miles south of South Salt Lake, the sand and gravel unit interfingers with till, has a cumulative thickness of 19 feet, and again rests on bedrock but, at the south end of the lake, it is separated from the bedrock by 45 feet of till. This spread of sand and gravel appears to be a deposit of glacial outwash in a former drainage channel that carried water southward. After deposition, these gravels were overridden by ice.

The smallest deposit of subsurface glacial sand and gravel underlies the north end of Shoal Lake. In a well at the town of Shoal
Lake, its top occurs at a depth of 151 feet, it is 36 feet thick, and it overlies 69 feet of till, which itself overlies the bedrock. Pumping tests on this well indicate that the producing gravel has some lateral extent. The depth of occurrence and extensive drilling in and around the town suggest that it is confined to the bedrock valley, however piezometers in the valley centre, northeast of the town, and test holes at the south end of Shoal Lake did not encounter this same gravel. This deposit is similar in origin to the gravels beneath the Salt Lakes.

Mapping Procedure

Hydroecological mapping of the Oak River Basin was carried out partly in September 1965 and partly in August 1966. In 1965 the northern third of the basin plus a small portion in the southwest corner was mapped by driving along each road in the area, deciding into which category each slough fell, and marking it accordingly on a 1:50,000 topographic map. In 1966 the process was hastened by flying at an altitude of 500 feet along east-west lines through the centre of every section and later checking the positioning of boundaries with a ground vehicle.

The precaution of using only the natural vegetation around undisturbed sloughs was adhered to while mapping. Although the interaction between soil texture and degree of saturation was recognized as making some sloughs appear "fast" and others as "slow" this factor was not taken into account on the maps. Another precaution
taken was that all mapping was done in the early fall because this is the time when the ecological differences between the various types of sloughs are most distinct.

The results of the mapping are shown in plate 2.

Mapping Results

Occurrence of Recharge and Discharge Areas

General.-- The distribution of recharge and discharge areas in the Oak River Basin is shown in plate 2. The discharge areas, which occupy 28 percent of the basin's surface, can be divided into five major regions. These are the Pope-Lenore-Maskawata discharge region, the Chumah-Oakner-Alloway discharge region, the Salt Lakes discharge region, the Menzie-Shoal Lake-Raven Lake discharge region, and the Duck Lake-Seech-Wisla discharge region. Except for the latter, each discharge region is characterized by an area of fresh-water discharge sloughs in its higher part and an accompanying area of saline discharge sloughs in its lower part. The saline part comprises one-half to three-fourths of the total discharge region. The Duck Lake-Seech-Wisla discharge region contains only fresh-water discharge sloughs. The inferred hydrologic conditions giving rise to each of these discharge regions are shown in the cross-sections of plate 3.

The Pope-Lenore-Maskawata Discharge Region.-- The occurrence of the Pope-Lenore-Maskawata discharge region is controlled partly
by topography and partly by a permeability contrast at depth. The regional topographic slope at the north end of this region is to the southwest. Hence both the slope of the regional water table and the direction of general groundwater movement is to the southwest. However, because of increased elevation a belt of recharge sloughs occurs along the basin divide which gives rise to northeasterly flowing local flow systems. Discharge of the opposing flows takes place in the sloughs lying east of the divide. The principle of topographic control on the occurrence of a discharge area is illustrated in figure 13. South of Kenton the divide becomes more pronounced and the basin more bowl-shaped so that the direction of regional groundwater flow in the vicinity of Maskawata is to the northeast. However discharge is concentrated in the sloughs west of Maskawata rather than in the lower part of the basin south of Harding because of permeability contrast between the till and the Odanah Shale. This contrast is in the order of 1:1000 (see Appendix B). Flow through the Odanah Shale is almost horizontal because of its high permeability. The principle of permeability contrasts controlling the occurrence of a discharge area is shown in figure 14. This aspect of the occurrence of the Pope-Lenore-Maskawata discharge region is indicated in cross-section C-C of plate 3.

The Chumah-Oakner-Alloway Discharge Region. -- The occurrence of the Chumah-Oakner-Alloway discharge region is a classic example of control by permeability contrasts due to an aquifer pinchout at depth.
In the extreme northwestern portion of the fresh-water discharge part of this region, the aquifer is the highly permeable Odanah Shale and the pinchout is due to removal of this shale by erosion, forming the bedrock valley trending through Hamiota. The permeability contrast between the till infilling the valley and the Odanah Shale is about 1:1000 (see Appendix B). In the remainder of this discharge region the aquifer is the highly permeable sand and gravel valley fill and the pinchout occurs at the lateral limit of this deposit. In this part of the discharge region the greater permeability contrast between the till and the gravel (1:10,000) causes less displacement of the discharge area from the pinchout position than is found northwest of Hamiota.

Cross section C-C of plate 3 illustrates the hydrologic conditions governing the occurrence of Chumah-Oakner-Alloway discharge region.

The Salt Lakes Discharge Region. -- The occurrence of the Salt Lakes discharge region is also controlled primarily by topography as shown in cross section B-B of plate 3. Regional groundwater flow in the Salt Lake sub-basin is believed to be to the west southwest. A belt of recharge sloughs occurring at higher elevations along the divide through Ipswich gives rise to easterly flowing local flow systems. Discharge of these opposing flows takes place in the low lying sloughs and lakes east of the divide. The western divide of this sub-basin becomes progressively less pronounced southward until southwest of South Salt Lake its influence in producing easterly flowing local systems
ceases entirely and discharge by this mechanism no longer occurs on its regional upslope side. In fact, recharge sloughs are found immediately south of South Salt Lake. The lake itself is a large transitional slough with inflow of groundwater at the north end and outflow at the south end as shown in cross section C-C of plate 3. The permeable gravel within the Salt Lake bedrock channel acts as a conduit for groundwater to flow from the Salt Lake Basin southward into the Oak River Basin proper (Lissey and Wyder, 1966). With decreasing permeability of this aquifer towards the south it is believed that groundwater flow is directed upward to discharge into sloughs and tributaries of the Oak River immediately south of nest P49, P56. South of these sloughs the aquifer's permeability is further decreased by partial cementation and by a higher shale content and, in fact, becomes lower than that of the till (see Appendix B). It then acts as a barrier to groundwater flow at depth (cross section C-C of plate 3 and Fig. 31).

The Menzie-Shoal Lake-Raven Lake Discharge Region. -- The occurrence of the Menzie-Shoal Lake-Raven Lake discharge region appears to be controlled by permeability contrasts at depth. The more permeable upper part of the Odanah shale was eroded from the bedrock valley that trends from Shoal Lake up to Menzie. The permeability contrast between the till that now infills the valley and the uneroded shale ranges from 1:100 to 1:100,000. Such variations create varying displacements of the discharge area from the position of the permeability break and also cause the width of the discharge area to vary. It is believed that this is why the Menzie-Shoal Lake-Raven Lake discharge region does
not correspond to its associated bedrock valley as does the Chumah-Oakner-Alloway discharge region. The hydrologic conditions governing the occurrence of the Menzie-Shoal Lake-Raven Lake discharge region are shown in cross section A-A of plate 3. It can be seen that Shoal Lake is similar to south Salt Lake in that it is also transitional in nature.

The Duck Lake-Seech-Wisla Discharge Region. -- The hydrologic conditions governing the occurrence of the Duck Lake-Seech-Wisla discharge region are not clearly defined by the limited subsurface information available in this area. Although there is a till-filled depression in the bedrock topography beneath the lakes in this discharge region (cross section A-A of plate 3) it is not deep enough to produce a discharge area by permeability contrasts as in the Menzie-Shoal Lake-Raven Lake discharge region. Neither does the type of topographic control exhibited by the Salt Lakes and the Pope-Lenore-Maskawata discharge regions apply. It is believed that the primary control for the occurrence of the Duck Lake-Seech-Wisla discharge region is an abrupt change in the slope of the regional water table as described by Freeze and Witherspoon (1967). The change is from a steep slope to a more shallow slope in the direction of regional flow. The change in slope of the regional water table roughly corresponds to the change in topographic slope shown in figure 16. In addition it is believed that interbasinal flow (Lissey and Wyder, 1966) from the adjoining Minnedosa Basin to the north contributes some of the groundwater discharged in this region.
Other Discharge Regions. -- Aside from the five major regions minor groundwater discharge occurs in the tributary valleys of the Oak River south of Harding, in a narrow belt between Brumlie and Myra, and in the area southwest of McConnell. Only local flow systems discharge into the valleys south of Harding (cross-section C-C of plate 3). The discharge area southwest of McConnell is associated with the large esker shown in figure 21. It is believed that due to increased elevations along the esker small depressions on its surface recharge groundwater and cause small local flow systems which discharge into the sloughs along the flanks of the esker. Sufficient information is lacking to afford an explanation of the occurrence of the discharge belt between Brumlie and Myra.

Reliability of the Mapping as Checked with Test Nests

General. -- Eighteen piezometer nests were used to test the reliability of mapping recharge and discharge areas in the Oak River Basin (Fig. 23). These can be divided into eight specially chosen nests and ten reducer-equipped nests.

The locations of six of the specially chosen nests were selected by Dr. A. J. Broscoe to eliminate any bias on the part of the author. The locations of the other two specially chosen nests were selected by the author. Seven of these nests were installed in 1966 to check mapping done in 1965. One of the specially chosen nests selected by the author was installed in 1967 to check mapping done in 1966.
The reducer-equipped nests consist of the twenty-one piezometers installed in 1963 and 1964 that had not attained equilibrium prior to mapping. It became feasible to use these as additional test nests after equipping them with reducers in 1966. The reducer (Fig. 24) and the associated electrical probe (Fig. 25) for water level measurement were developed by the author to decrease the time lag and so allow a piezometer to attain equilibrium quickly (Lissey, 1967).

The hydrographs of all but two of the test nests (Fig. 26 to Fig. 30 and Appendix A) yielded results which, as interpreted by the author, confirm the mapping. One of the nests with questionable results (P16, P17) is reducer-equipped while the other (P74, P75, P76) is a specially chosen nest selected by the author and installed in 1967. The piezometers in these nests may not yet have attained equilibrium with the pressure in the screened formations. One of the reducer-equipped nests (P55, P57) yielded hydrograph results that at first glance appear to conflict with the mapping. However, slug tests (Appendix B) revealed that the deeper piezometer (P55) was completed in a partially cemented dirty gravel having a much lower permeability than the overlying till. The upper interpretative transient flow diagram of figure 31 indicates how the hydrograph results obtained can be explained by taking into account permeability contrasts at depth. Permeability contrasts associated with most of the other nests did not create conflicting results with the mapping but did alter the magnitude of head gradients from what would be expected in the homogeneous case. A summary of the results obtained from all piezometers is presented in table 1.
Figure 24. - Piezometer Reducer

1/2" 0" 1" 2" 3" 4" 5"
SCALE

VALVE STEM
3/8" SCREW-TYPE HOSE CLAMP
2" Ø 1/4" PLYWOOD BUTTS ON 2" PIPE INSIDE TOPMOST COUPLING OF PIEZOMETER TO KEEP MEASURING LINE STRAIGHT

HEAVY CORD FOR PULLING OUT OF PIEZOMETER WHEN DESIRED

AIR LINE

MEASURING LINE
1/4" I.D. FLEXIBLE PLASTIC TUBING
3/8" SCREW-TYPE HOSE CLAMP

1 1/2" I.D. COPPER TUBING (CRIMPED)

1 1/4" I.D. NONREINFORCED RUBBER TUBING (MADE FROM SHEET RUBBER 1/8 THICK WITH A SLOW RATE VULCANIZED LONGITUDINAL SEAM TO RETAIN ELASTICITY)

COUNTER-SUNK HOLES FOR SOLDERING COPPER TUBES IN PLACE

AIR TUBE
1/4" I.D. COPPER TUBES SOLDERED IN PLACE
1" O.D. MILD STEEL PLUG THREADED & SOLDERED IN PLACE

STANDARD 3/4" GALVANIZED COUPLING

STANDARD 3/4" GALVANIZED PIPE

MEASURING TUBE

1/4" AIR HOLE

STANDARD 3/4" GALVANIZED COUPLING

COUNTER-SUNK HOLE FOR SOLDERING COPPER TUBE IN PLACE

1" O.D. MILD STEEL PLUG THREADED & SOLDERED IN PLACE
Figure 25. - Electric Probe for Measuring Water Levels in Reducer-equipped Piezometers
Table 1 - Summary of piezometer nest results.

<table>
<thead>
<tr>
<th>Piezometers in Nest</th>
<th>Nest Classification</th>
<th>Gradient Between Piezometers A&amp;B (in ft/ft)</th>
<th>Gradient Between Piezometers C&amp;D (in ft/ft)</th>
<th>Approximate Water Level of Nearest Slough (in feet)</th>
<th>as indicated by gradient between A &amp; B</th>
<th>as indicated by relation between Slough &amp; A</th>
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<td>-0.12</td>
<td></td>
<td></td>
<td>Recharge</td>
<td>Recharge</td>
</tr>
<tr>
<td>P10 P11</td>
<td>Test</td>
<td>-0.45</td>
<td></td>
<td></td>
<td>Recharge</td>
<td>Recharge</td>
</tr>
<tr>
<td>P12 P13</td>
<td>Type</td>
<td>-0.10</td>
<td></td>
<td></td>
<td>Discharge</td>
<td></td>
</tr>
<tr>
<td>P14 P15 P24</td>
<td>Type</td>
<td>+0.08</td>
<td>-0.03</td>
<td></td>
<td>Discharge</td>
<td>Recharge</td>
</tr>
<tr>
<td>P16 P17</td>
<td>Test</td>
<td>+0.14</td>
<td></td>
<td></td>
<td>Discharge</td>
<td>Recharge</td>
</tr>
<tr>
<td>P18 P19</td>
<td>Type</td>
<td>-0.42</td>
<td></td>
<td></td>
<td>Discharge</td>
<td></td>
</tr>
<tr>
<td>P20 P21</td>
<td>Type</td>
<td>-0.05</td>
<td></td>
<td></td>
<td>Discharge</td>
<td></td>
</tr>
<tr>
<td>P22 P23</td>
<td>Type</td>
<td>+0.01</td>
<td></td>
<td></td>
<td>Lateral Flow</td>
<td></td>
</tr>
<tr>
<td>P25 P26 P27</td>
<td>Type</td>
<td>+0.42</td>
<td>0.00</td>
<td></td>
<td>Discharge</td>
<td></td>
</tr>
<tr>
<td>P28 P29</td>
<td>Type</td>
<td>-0.08</td>
<td></td>
<td></td>
<td>Discharge</td>
<td></td>
</tr>
<tr>
<td>P36 Ham 2</td>
<td>Type</td>
<td>-0.24</td>
<td></td>
<td></td>
<td>Discharge</td>
<td></td>
</tr>
<tr>
<td>P37 P38 P39</td>
<td>Test</td>
<td>-0.03</td>
<td>0.08</td>
<td>20</td>
<td>Recharge</td>
<td>Recharge</td>
</tr>
<tr>
<td>P40 P41 P42</td>
<td>Type</td>
<td>-0.03</td>
<td>0.00</td>
<td></td>
<td>Recharge</td>
<td></td>
</tr>
<tr>
<td>P43 P44</td>
<td>Test</td>
<td>-0.07</td>
<td></td>
<td>10</td>
<td>Recharge</td>
<td>Recharge</td>
</tr>
<tr>
<td>P45 P46</td>
<td>Test</td>
<td>-0.31</td>
<td></td>
<td>20</td>
<td>Recharge</td>
<td>Recharge</td>
</tr>
<tr>
<td>P47 P48</td>
<td>Test</td>
<td>-0.06</td>
<td></td>
<td>no sloughs in vicinity</td>
<td>Recharge</td>
<td></td>
</tr>
<tr>
<td>P49 P50</td>
<td>Type</td>
<td>+0.01</td>
<td></td>
<td></td>
<td>Lateral Flow</td>
<td></td>
</tr>
<tr>
<td>P50 P51</td>
<td>Type</td>
<td>-0.05</td>
<td></td>
<td></td>
<td>Discharge</td>
<td></td>
</tr>
<tr>
<td>P52 P53 P54</td>
<td>Type</td>
<td>+0.72</td>
<td>0.00</td>
<td></td>
<td>Discharge</td>
<td></td>
</tr>
<tr>
<td>P55 P57</td>
<td>Test</td>
<td>-0.01</td>
<td></td>
<td>5</td>
<td>Recharge</td>
<td>Lateral Flow Recharge</td>
</tr>
<tr>
<td>P58 P59</td>
<td>Type</td>
<td>-0.12</td>
<td></td>
<td></td>
<td>Recharge</td>
<td></td>
</tr>
<tr>
<td>P60 P61</td>
<td>Test</td>
<td>-0.01</td>
<td></td>
<td>7</td>
<td>Discharge</td>
<td>Lateral Flow Discharge</td>
</tr>
<tr>
<td>P62 P63</td>
<td>Test</td>
<td>-0.10 (See hydrograph re difficulties with re-</td>
<td>5</td>
<td></td>
<td>Recharge</td>
<td>Recharge</td>
</tr>
<tr>
<td>P64 P65</td>
<td>Test</td>
<td>-0.02</td>
<td></td>
<td></td>
<td>Discharge</td>
<td>Lateral Flow Discharge</td>
</tr>
<tr>
<td>P66 P67</td>
<td>Test</td>
<td>Pielometer Flows</td>
<td></td>
<td></td>
<td>Discharge</td>
<td></td>
</tr>
<tr>
<td>P67</td>
<td>Test</td>
<td>Pielometer Flows</td>
<td></td>
<td></td>
<td>Discharge</td>
<td></td>
</tr>
<tr>
<td>P68 P69 P73</td>
<td>Test</td>
<td>-0.09</td>
<td>+0.12</td>
<td>15</td>
<td>Recharge</td>
<td>Recharge</td>
</tr>
<tr>
<td>P70 P71 P72</td>
<td>Test</td>
<td>-0.12</td>
<td>0.00</td>
<td>2</td>
<td>Discharge</td>
<td>Recharge</td>
</tr>
<tr>
<td>P74 P75 P76</td>
<td>Test</td>
<td>+0.21</td>
<td>-1.00</td>
<td>10</td>
<td>Discharge</td>
<td>Recharge</td>
</tr>
</tbody>
</table>

**NOTES:**

1. piezometer A = shallow piezometer in nest; piezometer B = intermediate piezometer in nest; piezometer C = deep piezometer in a triple nest.
2. Positive head gradient indicates increasing head with depth or an upward component of flow.
3. Negative head gradient indicates decreasing head with depth or a downward component of flow.
4. Head gradients between -0.03 and +0.03 assumed to indicate lateral flow.
5. No hydrographs prepared for P66 or P67.
6. One nest (P54 & P55) abandoned in 1966 because basket failed and screen was cemented off in P54.

*Location selected by Dr. A. J. Broscoe.*
To complete this section, only interpretations of the hydrograph results of the six specially chosen nests selected by Dr. Broscoe are presented. Although other interpretations are possible the author feels that those presented here are realistic and plausible.

**Nest P60, P61.** -- Nest P60, P61 was installed in a road allowance about 30 feet away from what was mapped as a fast saline discharge slough four miles west and one mile north of Kenton (Plate 2). The surface elevation at the nest is about 11 feet above the water level in the slough. Both piezometers were completed by filling them with water so that prior to equalization water would flow from the piezometer into the formation. This was accompanied by a lowering of the water level in the piezometer. Reducers were installed shortly after completion, however the Odanah Shale, in which these piezometers are screened, is so permeable that the piezometers were already stabilized and the reducers had no apparent effect (Fig. 26). Comparison of stabilized water levels in July, 1967 as shown on the hydrograph in figure 26, reveals a gradient of -0.01 feet per foot of depth. This is interpreted as indicating lateral flow through the highly permeable shale. Comparing heads in the piezometers with the water level in the slough indicates that flow is towards the slough. Such results may be expected around a discharge slough where the flow medium is highly permeable.

**Nest P62, P63.** -- Nest P62, P63 was installed in a road allowance about 800 feet north of what was mapped as a fast recharge slough four miles east of Lenore (Plate 2). The surface elevation at the
TEST NEST

Hydrographs for Piezometers P60 and P61
Oak River Basin
Location NW9-12-24W1
From July 11, 1966 to July 28th, 1967

Ground Level

Legend

- - P60 Depth to bottom of screen B7.14
     Finished in shale

- - P61 Depth to bottom of screen 46.46
     Finished in shale

Figure 26- Hydrograph for P60 and P61
nest is about the same as the bottom of the slough. Both piezometers were completed by filling them with water and installing reducers one month later. As can be seen in figure 27 the effect of a reducer in the shallow piezometer (P63) on the hydrograph is negligible while the effect on the pressure equalization rate of the deeper piezometer (P62) is pronounced. This suggests that the upper part of the till is more permeable than the lower part. Unfortunately because of vandalism and inadequate repairing the reducer installed in P62 never functioned properly. However as shown by the equalization rate prior to installation of the reducer and by the accelerated equalization rate for a short time immediately after installation of the reducer the stabilized water level in P62 was calculated (Hvorslev, 1951) to be at an elevation of 1462 or less. By comparing this water level with the stabilized water level of P63 a downward decreasing head gradient of about 0.10 feet per foot can be calculated. This gradient plus the fact that the water level in the nearest slough is about 5 feet above the head in the shallow piezometer suggests that this was correctly mapped as a recharge area.

**Nest P64, P65.** -- Nest P64, P65 was installed in a road allowance about 200 feet west of what was mapped as a fast saline discharge slough one mile west of Maskawata (Plate 2). The surface elevation at the nest is about 8 feet above the level of water in the slough. Both piezometers were completed by filling them with water and installing reducers about three weeks later. Because the Odanah Shale, in which both piezometers are completed, is so permeable the piezometers
Hydrograph for Piezometers 62 and 63
Oak River Basin
Location: NE 26-11-24 W1
From June 27, 1966 to July 26, 1967

LEGEND

- P62 Depth to bottom of screen 59.00
  Finished in till
- P63 Depth to bottom of screen 30.05
  Finished in till

Reducer deflated
Reducer removed (damaged)
Reducer reinstalled
Reducer not functioning properly
  (requires reinflation every week)

P63
P62

Figure 27 Hydrograph for P62 and P63

Stabilized water level in P62
(based on pressure equalization rate
observed in July 1966 prior to
installation of reducer)
stabilized quickly and the reducers had no apparent effect on the hydrographs (Fig. 28). A comparison of stabilized water levels reveals a gradient of -0.02 feet per foot of depth. This is interpreted as indicating lateral flow through the shale. Because the water level of the slough is below the heads of both piezometers flow must be towards the slough. As with nest P60, P61 the author believes that such results may be expected around a discharge slough where the flow medium is highly permeable.

**Nest P66.** -- Nest P66 was installed in a road allowance that bisected what was mapped as a slow saline discharge slough four miles north and one-half mile west of the town of Shoal Lake (Plate 2). Because the nest is located in the centre of the slough its surface elevation is the same as that of the bottom of the slough. After 39 feet of till and 30 feet of permeable Odanah Shale were penetrated by the drill, water began to flow from the hole at a rate of 100 gallons per minute. After flow control measures were taken the piezometer was installed with a screen interval of 67 to 68 feet below the surface. Pressure measurements at the surface indicated that the head in P66 was about seven feet above ground. This is interpreted as evidence of groundwater discharge into the slough.

**Nest P68, P69, and P73.** -- Nest P68, P69 and P73 was installed in a road allowance about 100 feet south of what was mapped as a fast recharge slough two miles south and two miles east of Oakburn (Plate 2). The surface elevation at the nest is about five feet below the bottom of the slough. All piezometers were completed by filling them with water and installing reducers immediately. The Odanah Shale, in which the
TEST NEST

LEGEND

- - - P64 Depth to bottom of screen 73.87
     Finished in shale

x-x-x P65 Depth to bottom of screen 35.93
     Finished in shale

Ground Level

Both piezometers fitted with reducers

Hydrograph for Piezometers 64 and 65
Oak River Basin
Location: NE 24-10-24 W1
From June 27, 1966 to July 26, 1967

Figure 28 Hydrograph for P64 and P65
deepest piezometer (P68) is screened, is very permeable hence P68 stabilized very quickly and the reducer had no apparent effect on the hydrograph shown in figure 29. The upper part of the till, where the shallowest piezometer (P73) is screened, while less than that of the shale, also has a fairly high permeability. This is indicated by only a slight alteration of the hydrograph in June, 1967 when a new reducer was installed. The lower part of the till, where P69 is screened, has a lower permeability and the effect of installing a reducer produced a pronounced change in the hydrograph of figure 29. Comparing the water level in the slough with the head in the shallowest piezometer indicates that water should infiltrate below the bottom of the slough. Comparing the stabilized piezometric heads of July, 1967 reveals a downward gradient of -0.09 feet per foot between the shallow and intermediate piezometers and a gradient of +0.72 feet per foot between the intermediate and deep piezometers. These apparently conflicting gradients are believed to be due to the large permeability contrast between the till and the shale. The second transient flow diagram of figure 31 illustrates how such results may be explained in terms of a recharge slough beneath which a sudden increase in permeability is found at depth.

Nest P70, P71, and P72. -- Nest P70, P71, and P72 was installed on the northeast side of what was mapped as a fast fresh water discharge slough one mile west and three miles south of Wisla (Plate 2). The piezometers are spaced 15 feet (P72), 90 feet (P70), and 140 feet (P71) away from the slough. Their surface elevations are about 3 feet (P72),
Hydrograph for Piezometers 68, 69 and 73
Oak River Basin
Location: SW 13-18-23 W1
From Aug 8, 1966 to July 26, 1967

LEGEND
- - P68 Depth to bottom of screen 151.01
Finished in Odanah shale
- - P69 Depth to bottom of screen 53.50
Finished in till
- - P73 Depth to bottom of screen 26.20
Finished in till

Figure 29 Hydrograph for P68, P69, and P73
9 feet (P70), and 10 feet (P71) above the water level in the slough. All piezometers were completed by filling them with water. A reducer was installed in the shallowest piezometer (P71). However, because the screen in P71 was set opposite a two-foot thick sand lens in the till the reducer was not required. Because the permeability of the gravel, in which the other two piezometers were screened, is so high reducers were not installed in them. A comparison of the water level in the slough and stabilized piezometric heads (Fig. 30) suggests that water should flow from the slough. Similarly calculations of head gradients between piezometers (Table 1) also suggest that the slough recharges groundwater. However, if the permeability contrast between the till and the underlying more permeable gravel is taken into account and if the slough is regarded as being transitional in nature rather than a true discharge slough, such discrepancies can be explained. The lower diagram of figure 31 illustrates how such results may be explained by assuming a transitional slough beneath which the permeability of the flow medium suddenly increases at depth.
TEST NEST

Ground Level 1890

LEGEND
- P70 Depth to bottom of screen 115-19
  Finished in gravel
- P71 Depth to bottom of screen 46-87
  Finished in till
- P72 Depth to bottom of screen 110-82
  Finished in gravel

Hydrograph for Piezometers 70, 71, and 72
Oak River Basin
Location: SE 22 - 18 - 22 WI
From June 27, 1966 to July 26, 1967

Figure 30 Hydrograph for P70, P71, and P72
Figure 31. Interpretative cross-sectional transient flow diagrams with apparently conflicting results.
CONCLUSIONS

The theory behind slough-focused flow patterns and the ensuing hydroecological classification of sloughs is verified by the mapping and subsequent piezometer testing in the Oak River Basin. Although the descriptions apply to sloughs in a prairie upland environment the specific classification proposed here (Plate 1) may be applicable throughout most of the Canadian prairies because the plant types listed are widespread and bear the same ecological significance everywhere. The general principles given in the sections Hydrological Differentiation and Ecological Distinction can be used anywhere to establish specific slough classifications for other environments.

Application of slough classifications to map recharge and discharge areas has the practical benefit of providing a rapid reconnaissance tool for determining patterns of natural groundwater flow which are useful in evaluating the groundwater resources of an area. A future use might be the combining of hydroecological mapping with a three-dimensional computer analysis of the type developed by Freeze (1966) to locate aquifers with a minimum of exploration.

The reconnaissance-type of hydroecological mapping done in the Oak River Basin revealed two problems that would have to be overcome before detailed mapping of this nature were feasible. The first problem, which is a minor one, is that it was found difficult to distinguish slow recharge sloughs from slow fresh-water discharge sloughs. The other problem is that transitional sloughs could not be
distinguished from true discharge sloughs. Independent work on water
level recessions of fresh discharge sloughs in the basin (Parry, 1968)
plus the results of some of the author's own test nests indicate that
almost all of the sloughs mapped as fresh-water discharge types are
actually transitional in nature. This remains a major problem to
detailed hydroecological mapping.
LIST OF REFERENCES


Lissey, Allan, 1962a, Ground-water resources of the Regina area, Saskatchewan: City of Regina, Engineers Dept., Hydrology Div., Rept. no. 1, 89 p.


APPENDIX A

Hydrographs
Hydrograph for Piezometers Land 2
Oak River Basin
Location: NW26-19-2S
From Aug 2nd 1965 to July 26th 1967

LEGEND
- - - P1 Depth to bottom of screen = 99.30
      Finished in till
--- P2 Depth to bottom of screen = 50.35
      Finished in till
TEST NEST

Hydrograph for Piezometers 3 and 4
Oak River Basin
Location: SE 15-19-23 WI
From Aug 2nd 1965 to July 26th 1967

LEGEND
- P3 Depth to bottom of screen = 50\(^\circ\) 50'
  finished in till
- P4 Depth to bottom of screen = 104\(^\circ\) 33'
  finished in till

Depth to bottom of screen = 50\(^\circ\) 50'
finishecl in till

Depth to bottom of screen = 104\(^\circ\) 33'
finishecl in till

Cleanout
Reducer installed
Reducer deflated
Reducer inflated
Stabilized head
Assuming constant formation pressure
Till oxidized
Till unoxidized

Legend:
- P3 Depth to bottom of screen = 50\(^\circ\) 50'
  finished in till
- P4 Depth to bottom of screen = 104\(^\circ\) 33'
  finished in till
Hydrograph for Piezometers 5, 6 and 7
Oak River Basin
Location SE 22-19-23 W1
From Aug 2nd 1965 to July 26th 1967

LEGEND
- - - P5 Depth to bottom of screen = 75-50'
   Finished in till
- - - P6 Depth to bottom of screen = 125-75'
   Finished in till
- - - P7 Depth to bottom of screen = 174-45'
   Finished in shale

- - - No readings taken
TEST NEST

Hydrograph for Piezometers 8 and 9
Oak River Basin
Location: SW27-1B-3W1
From Aug 2nd 1965 to July 26th 1967
Ground Level = 1906

LEGEND

- P8 Depth to screen = 102'56
  Finished in shale (Odanah, fractured)

- P9 Depth to screen = 52'34
  Finished in till

slug test
reducer deflated
till oxidized
till unoxidized
reducer installed
reducer deflated
reducer re-inflated
TEST NEST
Ground Level 2032

Hydrograph for Piezometers IO and II
Oak River Basin
Location: NW 16 - 19 - 23 W1
From Aug 2nd 1965 to July 26th 1967

LEGEND

- PIO Depth to bottom of screen 125.75
  Finished in Odanah shale

- PII Depth to bottom of screen 75.85
  Finished in till

Cleanout
Reducer Installed

Slag Test Attempted

Shale
TYPE NEST

Hydrograph for Piezometers 12 and 13
Oak River Basin
Location: NW 34—7—22 W1
From Aug 2nd 1965 to July 26th 1967

LEGEND
- - - P12 Depth to bottom of screen = 48.41
Finished in shale (Odanah)
- - - - P13 Depth to bottom of screen = 27.16
Finished in till

cleanout June 13th
2.5 feet of water removed from P13
P12 pumped.
Hydrograph for Piezometers 14,15 and 24
Oak River Basin
Location NW9 — 17 — 23 WI.
From Aug 2nd 1965 to July 26th 1967

LEGEND

- B-B P14 Depth to bottom of screen = 102.35
  Finished in shale

- *-* P15 Depth to bottom of screen = 50.0
  Finished in till

- * * * P24 Depth to bottom of screen = 125.20
  Finished in shale (Odanah).

--- No readings taken
Hydrograph for Piezometers 16 and 17

Oak River Basin

Location: SWIG - 17 - 23 W1

From Aug 2nd 1965 to July 26th 1967

slug test attempted

LEGEND

--- P16: Depth to bottom of screen = 126.86 ft
--- P17: Depth to bottom of screen = 76.38 ft

No readings taken

0 - 8 ft

0 - 8 ft

0 - 8 ft

0 - 8 ft
Hydrograph for Piezometers 18 and 19
Oak River Basin
Location: S19-16-23W1
From Aug 2nd 1965 to July 26th 1967

LEGEND
-—— P18 - Depth to bottom of screen = 45'29
Finished in till
-—— P19 - Depth to bottom of screen = 88'90
Finished in shale (Odanah)
Hydrograph for Piezometers 20 and 21
Oak River Basin
Location: NE 2-17-23 WI
From Aug 2nd 1965 to July 26th 1967

LEGEND
- - - P 20 Depth to bottom of screen = 27'38
Finished in till
- - - P 21 Depth to bottom of screen = 51'46
Finished in shale
Hydrograph for Piezometers 22 and 23
Oak River Basin
Location: SE 6 — 17—22 WI
From Aug 2nd 1965 to July 26th 1967

LEGEND
- - - - P22 Depth to bottom of screen = 27'11
Finished in shale
- - - - P23 Depth to bottom of screen = 51'80
Finished in shale
----- ----- No readings taken
Hydrograph for Piezometers 25, 26, and 27
Oak River Basin
Location: NW 34-18-22W1
From Aug 2nd 1965 to Jul 26th 1967

LEGEND
- P25 Depth to bottom of screen 120.59
  Finished in shale
- P26 Depth to bottom of screen 65.40
  Finished in gravel
- P27 Depth to bottom of screen 37.14
  Finished in till

Unable to read P26
(buried beneath snow)

Pressure caps installed in P25 and P26
Reducer deflated
Reducer inflated
Reducer installed

Cleanout water added

Gravel
Odanah shale

Till oxidized
Till unoxidized

Slug test attempted
Reducer deflated
Reducer inflated

Depth to bottom of screen
Finished in shale
Finished in gravel
Finished in till

LEGEND
TYPE NEST

Hydrograph for Plezometers 28 and 29
Oak River Basin
Location: NE 35-16-22 WI
From Aug 2nd 1965 to July 26th 1967
Hydrograph for Piezometers 36 & Ham2
Oak River Basin
Location: SE13-14-24W1
From Aug 2nd 1965 to July 26th 1967
Ground Level = 170.1

LEGEND
--- P 36 Depth to bottom of screen = 199.24
Finished in shale (Odenah)

--- Ham2 Depth to bottom of screen = 108.00
Finished in gravel

--- No readings taken
Hydrograph for Piezometers 37, 38 & 39
Oak River Basin
Location: SWII-14-23WI
From Aug 2nd 1965 to July 26th 1967
Ground Level = 1715

LEGEND
- P37 Depth to bottom of screen = 249'27
  Finished in shale (Millwood)
- P38 Depth to bottom of screen = 149'34
  Finished in shale
- P39 Depth to bottom of screen = 74'24
  Finished in shale (Odanah)
Hydrograph for Piezometers 40, 41, and 42
Oak River Basin
Location: SE15-13-23-W1
From Aug 2nd 1965 to July 26th 1967

LEGEND

- - P40 Depth to bottom of screen = 276'26
  Finished in gravel

- - P41 Depth to bottom of screen = 165'99
  Finished in till

- - P42 Depth to bottom of screen = 80'69
  Finished in till

...
TEST NEST

Hydrograph for Piezometers 43 & 44
Oak River Basin
Location: NE 15 - 12 - 23 WI
From Aug 2nd 1965 to July 26th 1967

LEGEND
-*** P43 Depth to bottom of screen = 201'20
  Finished in shole (Millwood).
-*** P44 Depth to bottom of screen = 111'20
  Finished in till.
--- No readings taken.

Hydrograph shows water levels and readings taken from piezometers P43 and P44.
Hydrograph for Piezometers 45 and 46
Oak River Basin
Location: NW 4-11-23W1
From Aug 2nd 1966 to July 26th 1967

LEGEND
- - - - P45 Depth to bottom of screen 154.23
  Finished in shale (Millwood)
- - - - P46 Depth to bottom of screen 105.66
  Finished in till
- - - - No readings taken

TEST NEST

Water frozen in measuring line??

63 -- -- Ground Level

1360

45

51

41

31

21

11

01

LEGEND

- - - - P45 Depth to bottom of screen 154.23
  Finished in shale (Millwood)
- - - - P46 Depth to bottom of screen 105.66
  Finished in till
- - - - No readings taken

TEST NEST

water frozen in measuring line??

63 -- -- Ground Level

1360

45

51

41

31

21

11

01
Hydrograph for Piezometers 47 and 48
Oak River Basin
Location: NW 9-10-22 WI
From Aug. 2nd 1966 to July 26th 1967

LEGEND

--- P47 Depth to bottom of screen = 89.29
Finished in shale (Millwood)

--- P48 Depth to bottom of screen = 40.97
Finished in till

--- No readings taken
Hydrograph for Piezometers 49 and 56
Oak River Basin
Location: SW26—15—22WI
From Aug 2nd 1965 to July 26th 1967
Ground Level = 1831

LEGEND
-**** P 49 Depth to bottom of screen = 64'25
  Finished in gravel
-**** P 56 Depth to bottom of screen =124'13
  Finished in shale (Odanah)
Hydrograph for Piezometers 50 and 51
Oak River Basin
Location: SW3 — 16 — 22 W1
From Aug 2nd 1965 to July 26th 1967

LEGEND

- P50 Depth to bottom of screen = 77.24
  Finished in gravel

- P51 Depth to bottom of screen = 407.48
  Finished in shale (Odanah)

--- No readings taken
Pressure build-up due to capping of flowing farm well one mile east and one mile south of this nest by Manitoba Government.

Pressure caps fitted to P52 and P53

LEGEND

- - - P52 Depth to bottom of screen 230.43
   Finished in gravel

- - - P53 Depth to bottom of screen 180.18
   Finished in gravel

- - - P54 Depth to bottom of screen 130.65
   Finished in till

Hydrograph for Piezometers 52, 53 and 54
Oak River Basin
Location: SE 33-12-22 W1
From Aug 2nd 1965 to July 26th 1967

Pressure caps

Reduction installed

Ground Level

Till oxidized
136
163
197

Till unoxidized

Sand and gravel

Gravel

Till unoxidized

Gravel
Hydrograph for Piezometers 55 & 57
Oak River Basin
Location: SE 19-15-32 W1
From Aug 2nd 1965 to July 26th 1967

 LEGEND

- P55 Depth to bottom of screen = 115'10"
  Finished in gravel (partially cemented)

-- P57 Depth to bottom of screen = 35'36"
  Finished in till (commination)

- - - No readings taken

--- Gravel

--- Till oxidized
--- Till unoxidized
--- Till comminution
--- Till unoxidized
--- Till oxidized
--- Water added
--- Reducer inflated
--- Reducer deflated
--- Clean out.
Hydrograph for Piezometers 58 and 59
Oak River Basin
Location SE5—17—22W1
From Aug 2nd 1965 to July 26th 1967
Ground Level 1885'

LEGEND

- P58 Depth to bottom of screen = 228.95'
  Finished in shale
- P59 Depth to bottom of screen = 118.48'
  Finished in shale
- No readings taken
Hydrograph for Piezometers 74, 75 and 76
Oak River Basin
Location: SE 35-13-24 W1
from June 30 to Nov. 20, 1967

LEGEND

- P 74 Depth to bottom of screen = 51.3'
  Finished in sand
- P 75 Depth to bottom of screen = 33.55'
  Finished in till
- P 76 Depth to bottom of screen = 13.18'
  Finished in till
APPENDIX B

Permeability Determinations
### PUMPING TESTS

<table>
<thead>
<tr>
<th>Location</th>
<th>Type of Aquifer</th>
<th>in l. g. p. d.,/ft.²</th>
<th>in cm/sec</th>
<th>Analyzed by</th>
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<td>SW 28-15-22 W1</td>
<td>Sand and Gravel</td>
<td>165</td>
<td>$9.31 \times 10^{-3}$</td>
<td>Parry (1966)</td>
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<td>$3.86 \times 10^{-2}$</td>
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<td>Odanah Shale</td>
<td>1375 *</td>
<td>$7.77 \times 10^{-2}$</td>
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* aquifer thickness assumed = 100 feet
SLUG AND BAILER TESTS ( $\phi$ in cm/sec)
Analyzed by Time-Lag Method (Hvorslev, 1951)

<table>
<thead>
<tr>
<th>Piezometer Number</th>
<th>Material in which piezometer is screened</th>
<th>Sand &amp; Gravel</th>
<th>Till</th>
<th>Odanah Shale</th>
<th>Millwood Clay</th>
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Notes:  
(A) Aquifer underlying South Salt Lake (Permeability decreases southward)  
(B) Aquifer underlying Hamiota  
* These values are abnormally low because piezometers were not thoroughly cleaned immediately after installation. Rapid recoveries after clean out procedures in June 1966 indicate that $\sigma = 1 \times 10^{-3}$ cm/sec.
APPENDIX C

Chemical Analyses
### Surface Waters

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<tr>
<th>Location</th>
<th>Hardness (ppm)</th>
<th>pH</th>
<th>[Fe] ppm</th>
<th>[Cl] ppm</th>
<th>Conductivity micromhos/cm</th>
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<td>pH</td>
<td>[Fe] ppm</td>
<td>[Cl] ppm</td>
<td>Conductivity micromhos/cm</td>
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Plate 3 - Sectional Flow Diagrams across the Oak River Basin