RELATIONS BETWEEN HYDROGEOLOGY AND SOIL CHARACTERISTICS NEAR DELORAINE, MANITOBA

A Thesis

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by

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ABSTRACT

The influence of hydrogeologic factors on genetic soil distributions near Deloraine in southwestern Manitoba was studied during a two year period. Emphasis was placed on determining the detailed hydrogeologic characteristics along a narrow 25 mile long strip of terrain between Turtle Mountain and the Souris Plain. To characterize the hydrogeology, 15 nests of piezometers were installed in the Quaternary and bedrock deposits. Hydraulic head data and samples of the groundwater were obtained from the piezometers. The hydraulic head data, chemistry of the groundwater and knowledge of the stratigraphy were used to interpret the patterns of groundwater flow. Seven hydrogeologic areas were established. The hydrogeological characteristics of each area were described and related to the pedological characteristics of the soils. In addition, a detailed sampling of the soil and sub-soil was conducted to evaluate the degree and source of salinity in the soil.

The pedologic, hydrogeologic, and geochemical data indicate that the general soil salinity pattern is controlled by a complex configuration of the groundwater flow system. Saline soils occur in areas of dominant groundwater discharge. Leached soils occur in areas of dominant groundwater recharge. On a micro-scale local groundwater flow systems and the vertical and lateral distribution of salinity are governed by micro-relief and micro-stratigraphy of the surface deposits. In some areas thin sand and gravel lenses above and slightly below the water table strongly influence the distribution

of soluble salts in the soil. The major source of soluble salts in the region was attributed to the dissolution of sulphate minerals in the glacial till.

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CHAPTER I

INTRODUCTION

The classification of soils, based primarily on morphological and chemical characteristics, has led pedologists to concentrate their attention primarily on the upper 36 to 48 inches of the soil. As a result, references to groundwater in relation to soil development studies have been brief, usually including only the depth to water table level and degree of groundwater mineralization. On the other hand, hydrologists have generally studied groundwater phenomena without considering in detail the relations between the groundwater environment and the soil genesis zone near the ground surface. Consequently, the two disciplines evolved with little attention being paid to the relations which exist between genetic soil development and groundwater flow. This thesis attempts to clarify some of these relations occurring in an area of dominantly chernozemic soils in southwestern Manitoba.

I OBJECTIVE OF STUDY

This thesis evolved, for the most part, from attempts to characterize certain genetic soil distribution patterns encountered during the resurvey of the Southwest Map Area of Manitoba (49°00'-49°32' N. Lat. and 100°00'-100°22' W. Long.) which was conducted from 1965 to 1969. During the resurvey it was thought that the distribution of imperfectly drained saline and non-saline soils developed on the same parent material, could be due to subsurface groundwater flow rather than due to surface drainage. Therefore, it was decided to investigate the groundwater flow phenomena and to determine their relationships to soil formation as expressed by the distribution of soil profile types. The main objective of this thesis, therefore, is to describe the hydrogeology of a representative area of soils for the purpose of determining the relations between groundwater flow systems and the general distribution of genetic soil profiles. To achieve this objective the investigation included:

1. The installation of nests of piezometers arranged in a cross-section through the study area,

2. A compilation of preliminary soil survey data, and

3. A detailed soil inspection at preselected sites along the cross-section giving careful consideration to the local factors of micro-topography, micro-stratigraphy, soil parent material, and genetic profile distribution.

II GEOGRAPHIC SETTING

The area studied lies immediately to the west of the town of Deloraine in Southwestern Manitoba (Figure 1). This area was chosen for three reasons: firstly, it included representative areas of each of the major soil subgroups and catenas in the Southwestern Area of Manitoba; secondly, it included representative areas of each of the major soil climatic zones of southern Manitoba; and thirdly, it transected the total range in topographic relief for the area.

The layout of the study area is located along the regional

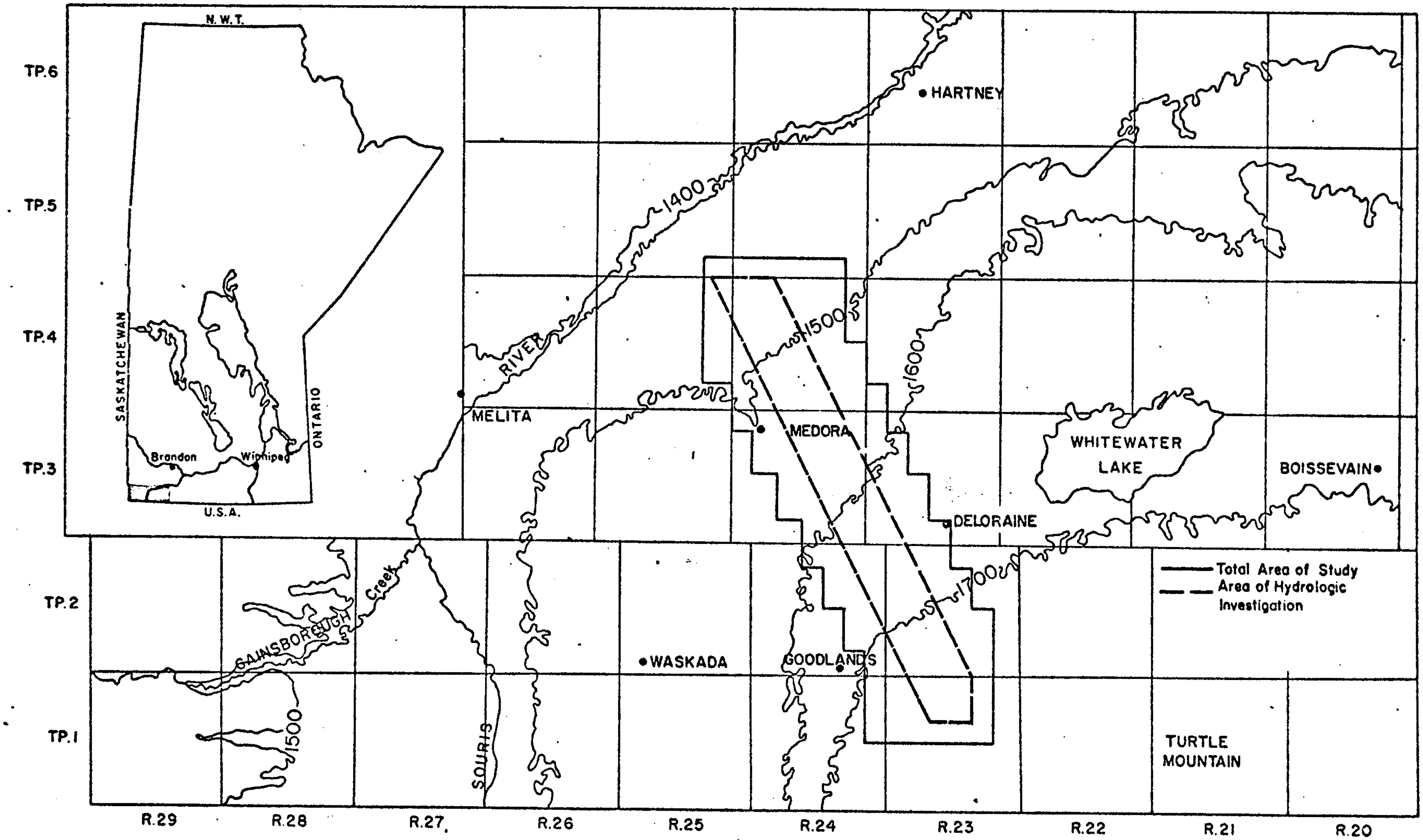


Figure 1. Location of Study Area near Deloraine in Southwestern Manitoba.

slope of the surface topography. It was thought that in this location the area would be parallel to the slope of the regional water table and that the flow of groundwater would be parallel to the long axis of the study area. In this position, the various groundwater flow regimes within the area could be observed.

The study area occupies approximately 96,000 acres of land composed of glacial tills and thin lacustrine sediments. The tills are typically dead ice deposits characterized by knoll-depression topography. The topography varies from high relief on top of Turtle Mountain, which has very steep slopes ranging from 30 per cent to 60 per cent, to very low relief in the Boissevain Till Plain, having slopes generally less than 5 per cent. The Turtle Mountain Upland slopes steeply to the surrounding lowlands at approximately 250 feet per mile. The shallow glacial lake sediment in the Souris Plain and Whitewater Lake Basin areas is characterized by very low relief with slopes generally less than 2 per cent. Local variations in relief in the Souris Plain are commonly due to aeolian modification of the coarse lacustrine sediments.

The specific area of the hydrologic investigation, enclosed by the two dashed, parallel lines, as shown in Figure 1, constitutes approximately 38,400 acres.

Weir (1960) reports that the area has an average annual potential evapotranspiration of 21 to 65 inches and an average annual precipitation of 20 inches of which 12 to 14 inches fall during the growing season from May 1 to September 30. Weir (1960) also reports that the average annual January temperature ranges from

0.5° to 5°F while the average annual July temperature ranges from 63.5° to 68°F.

CHAPTER II

REVIEW OF LITERATURE

I HYDROLOGY

The hydrologic cycle as defined by Davis and De Wiest (1967, p. 15) is the "ever changing migration of atmospheric, surface, and groundwater as a complex interdependent system". Although the movement of groundwater is the main concern of this study, it is important that all aspects of the hydrologic cycle be understood in a general way in order that an accurate picture of the subsurface portion of the cycle be achieved.

Using a two dimensional model (Figure 2), Toth (1962) showed that the theoretical groundwater flow system in an isotropic homogeneous porous medium with a uniformly sloping topography is composed of a recharge area and a discharge area. The recharge area which is upslope from the midline position is characterized by downward moving groundwater, that is, water movement away from the water table level. The discharge area, which is downslope from the midline position is characterized by upward moving water, that is, water movement toward the water table level.

In general, groundwater flow systems are influenced by three basic components: topography, geology, and climate. Topography in a broad sense determines the scale of the hydrological system. Hitchon (1969) in a study of the Western Canadian Sedimentary Basin, concluded that major upland topographic features are major recharge regions and that major lowlands are major regional discharge areas.

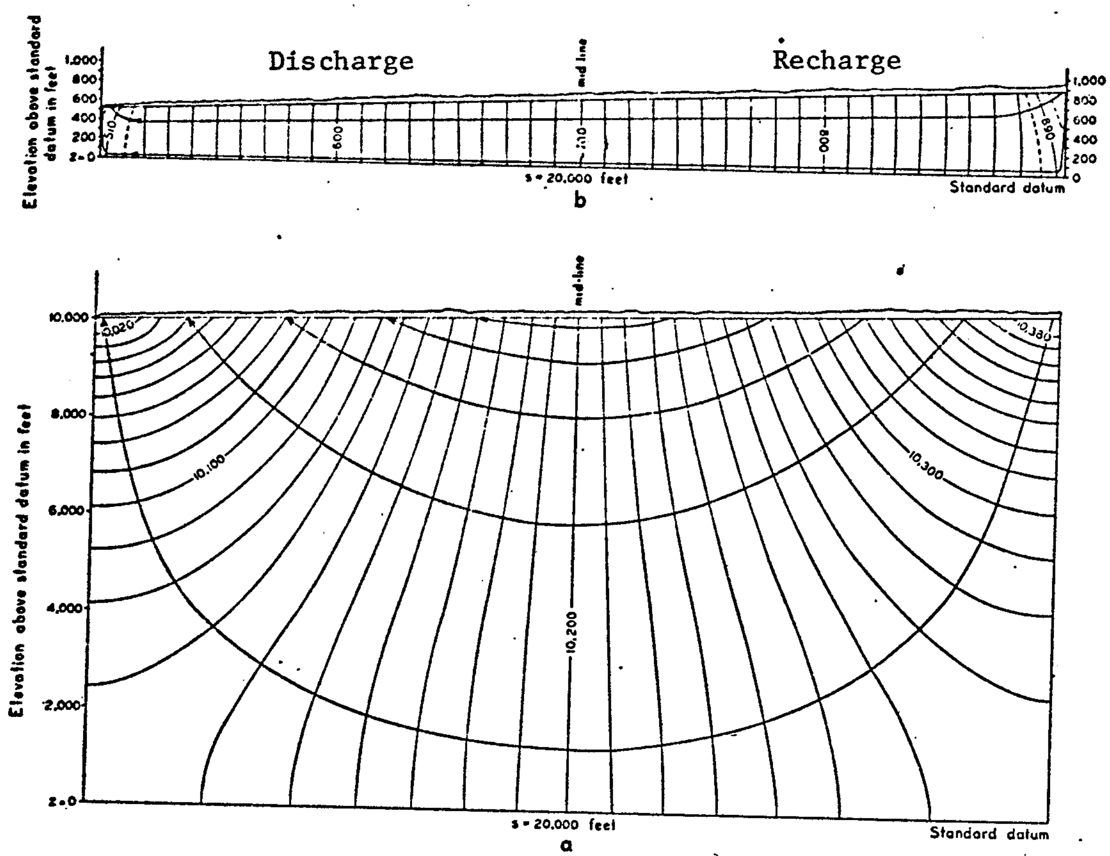


Figure 2. Two-dimensional theoretical potential distributions and flow patterns for different depths to the horizontal impermeable boundary (after Toth, 1962).

In his model he refers to the foothill region of Alberta as regional recharge and the exposed outcrops of sedimentary rocks near the contact of the Precambrian Shield to the east as the regional discharge area. On the other hand, Toth (1963) showed that minor irregularities in the surface topography resulted in local flow systems being superimposed on intermediate and regional flow systems (Figure 3). By applying Toth's (1963) theoretical flow systems (Figure 3) to the Western Canadian Basin, as discussed by Hitchon (1969) the area of the Turtle Mountain Upland and the Whitewater Basin is analogous to a local flow system superimposed on the regional discharge area for Western Canada. The terms regional, intermediate, and local defined in this sense therefore have little meaning for purposes of this study. For this study the term local flow system will be defined as the flow of groundwater from a slough or depression at a given elevation to an adjacent slough or depression of slightly lower elevation. This definition is analogous to the local flow systems as described by Lissey (1968) in the Oak River Basin of Manitoba.

Hitchon (1969) also states that the "dominant fluid potential in any part of the basin corresponds closely to the fluid potential at the topographic surface in that part of the basin". Therefore, topography determines the magnitude of the hydraulic potentials within the hydrologic system. He also concluded that variations in geology such as the presence of highly permeable beds, significantly affected the regional fluid potential distribution.

Geology, according to Davis and De Wiest (1967, ch. 10 and 11)

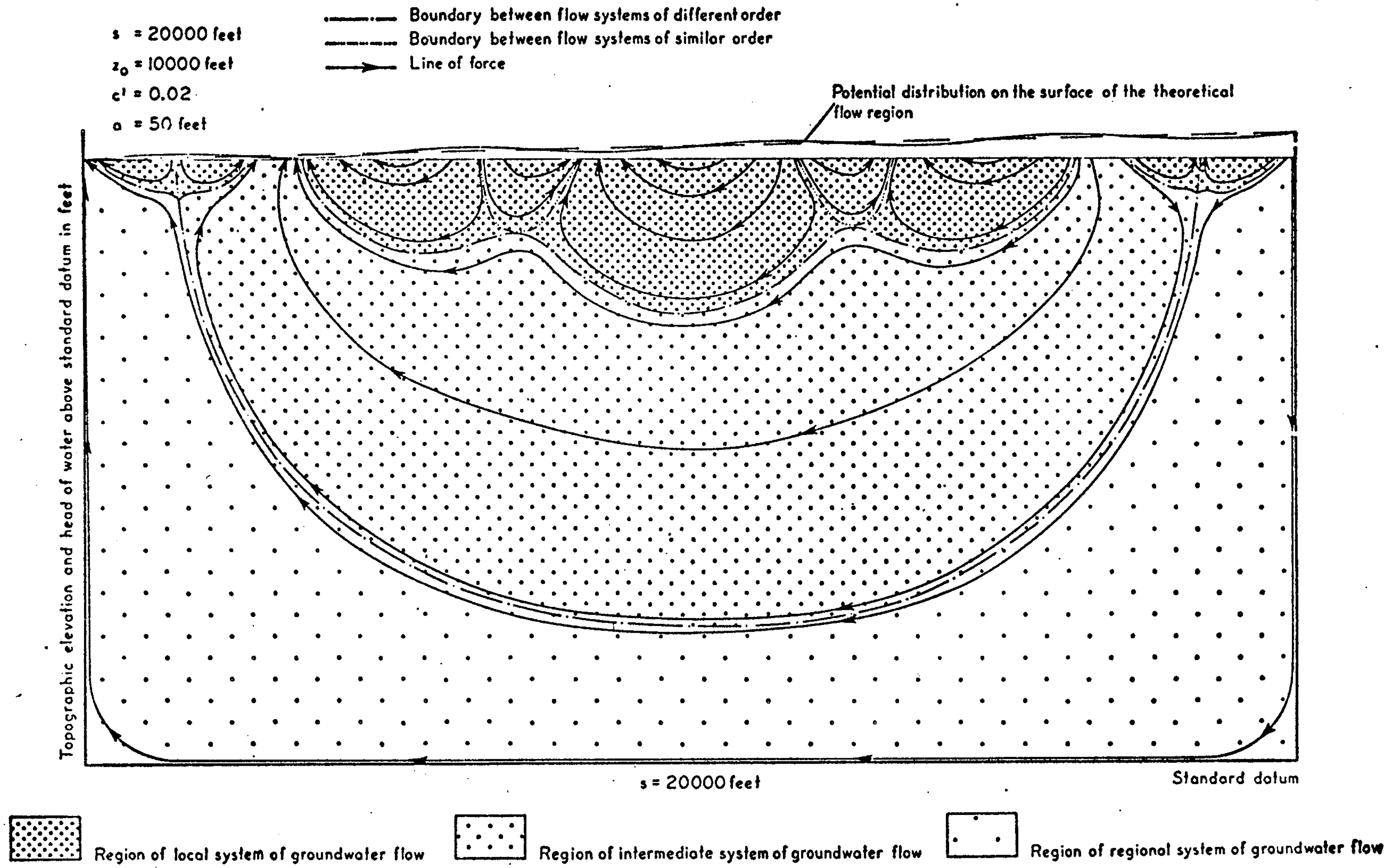


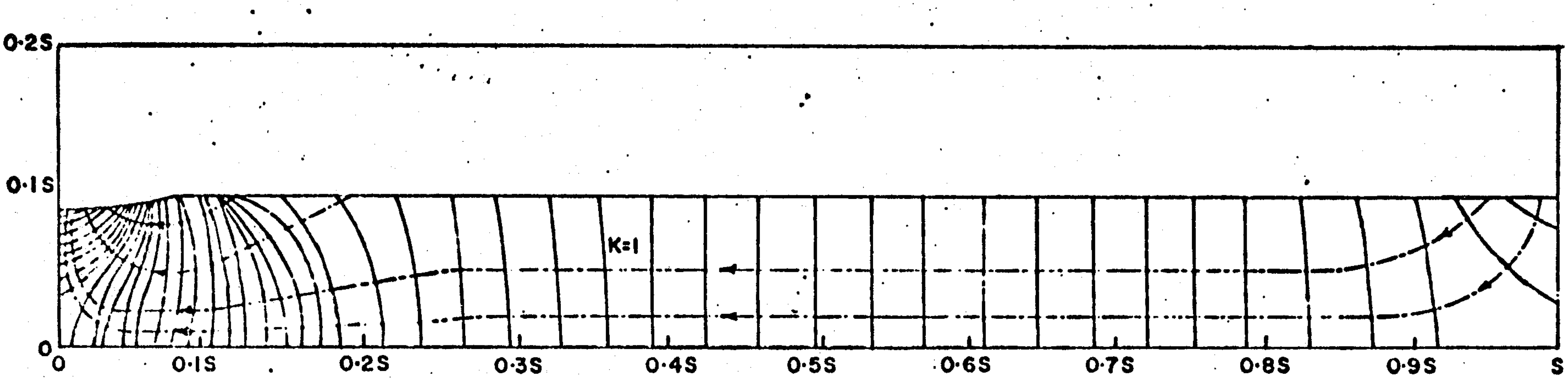
Fig. 3. Theoretical flow pattern and boundaries between different flow systems. (after Toth, 1963).

plays a significant role in determining the characteristics of groundwater flow systems. Pore and grain size, sedimentation and orientation of rock structures and the size and shape of the drainage basin are three aspects of geology which are important in determining the volume, rate and direction of groundwater flow.

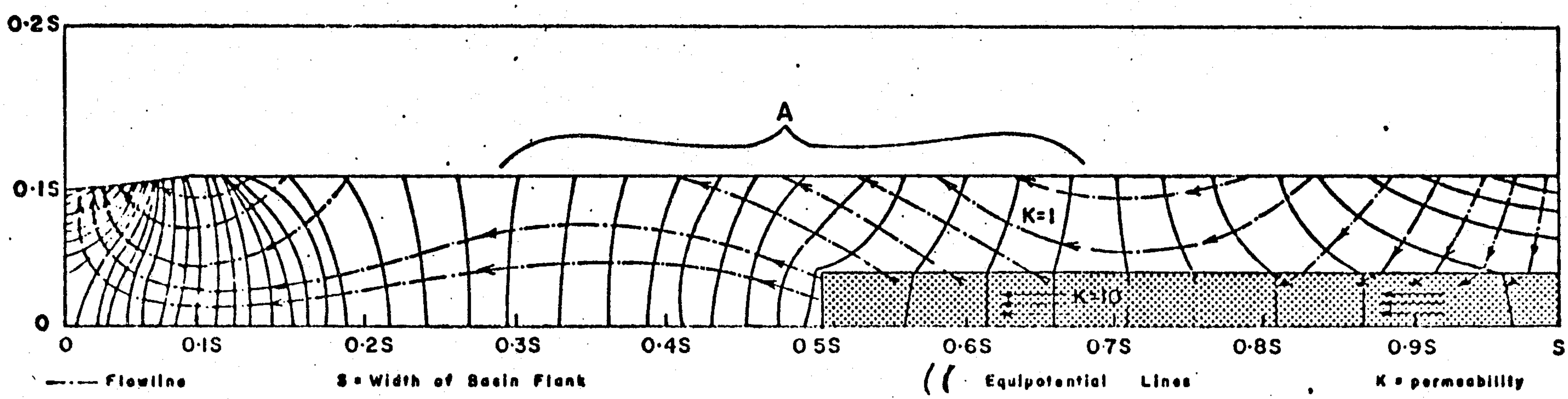
The pore and grain size of geologic material determine permeability or hydraulic conductivity. Sediments such as clay which have high porosities, generally have low hydraulic conductivities. Sands, on the other hand, with low porosities, generally have a higher percentage of macro pores than clays and consequently have higher hydraulic conductivities. Baver (1963, p. 252) has shown that under saturated conditions the velocity of water flow through soils decreases in the order of sand > fine sandy loam > light clay > and clay. Freeze and Witherspoon (1967) have shown that lenses of contrasting permeability within homogeneous deposits alter the direction of normal groundwater flow and result in the occurrence of discharge areas in the centre of regional flow systems (Figure 4).

Davis and De Wiest (1967, ch. 11) suggest that the size and shape of the hydrologic basin determines the volume of surface and sub-surface water, the direction of water movement and the velocity of groundwater flow within the basin. In addition, the size and shape of the basin will determine the length of time that the water is in contact with the basin and thereby influence the quality of the water.

Climatic factors such as the seasonal distribution of precipitation and temperature which determine the amount of evaporation



Hydraulic Potential and Flowline Network across one Flank of a Hypothetical Basin with a Homogeneous Isotropic Flow Medium.



Flow Network Altered by the Presence of Part of an Aquifer with a Larger Permeability than the Rest of the Flow Medium. The Midslope Discharge Area A is a Direct Result of the Aquifer Pinchout.

Figure 4. Theoretical Patterns of Groundwater Flow (after Freeze and Witherspoon, 1967).

and evapotranspiration have a significant influence on the water budget of the hydrologic cycle. According to Davis and De Wiest (1967, ch. 12) variations in climate affect the amount and distribution of recharge and discharge, the magnitudes of the hydraulic gradients, the continuity of aquifers and the distribution of poor quality water within a given hydrologic environment. In addition, Lissey (1968) reports that the influences of climate dictate, either directly or indirectly, the type and quality of vegetation which may develop in a basin. Vegetation then may influence the processes of recharge and discharge either by enhancing or inhibiting infiltration, evapotranspiration and evaporation. By the use of piezometers, Meyboom (1966) has shown that the vegetation on hummocky glacial drift in the Canadian Prairies influences the local groundwater flow systems and thereby influences the larger flow systems beneath.

Continuity Between Saturated and Unsaturated Systems

According to Moore (1939, as stated in Baver, 1963, p. 252) the same properties which affect water flow in the saturated soil zone also affect water flow through the unsaturated soil zone with the exception that the order of permeability is reversed. Freeze (1967) states that the unsaturated flow processes of infiltration and evaporation are in physical and mathematical continuity with the parallel saturated processes of recharge and discharge, that is, the terms infiltration and evaporation in the unsaturated soil zone are continuous with the terms recharge and discharge in the saturated soil zone, respectively.

Freeze (1967) states that "a given meteorological condition which gives rise to a certain flux at the ground surface will create different pressure head, total head, and moisture content profiles depending on the conditions of groundwater recharge and discharge which underlie the unsaturated soil". Freeze (1967) also states that "soil moisture conditions can therefore be expected to show areal variations even under homogeneous meteorological conditions and uniform soil type".

As a result of the continuity between the saturated and unsaturated soil zones, surface soil moisture conditions are a direct reflection of the depth to and the range of fluctuation of the water table level. Freeze (1967) shows that water table fluctuations result when the rate of groundwater recharge or discharge is not matched by the rate of infiltration or evaporation in the unsaturated soil zone and the end result is a water table which is almost never stable.

Groundwater Chemistry

According to Davis and De Wiest (1967, ch. 4) the chemistry of groundwater is basically determined by the composition of the geologic materials through which it flows. For example, groundwater from limestone aquifers has dominantly a Ca^{++} and HCO_3^- ion composition whereas groundwater in marine shales generally has a Na^+ and Cl^- ion composition. Rozkowski (1967) in a hydrological study of glacial tills in the Moose Mountain area of Saskatchewan reports that the most common ions found in groundwater of calcareous glacial drift are Ca^{++}, Mg^{++}, Na^+, $SO_4^=$, and HCO_3^-.

Since the degree of mineralization of groundwater is dependent upon: temperature, pressure, area of interface between minerals and groundwater, volume and time of water contact, it is expected that discharging groundwaters would be more mineralized than recharging groundwater. Rozkowski (1967) and Lissey (1968) applied this concept to their studies in glacial drift and found that the groundwater chemistry patterns substantiated the groundwater flow patterns which had been interpreted from hydraulic head data. It is apparent, therefore, that areal and vertical distributions of ionic concentrations in groundwater are a valuable aid for interpreting the characteristics and direction of groundwater movement.

II SOIL GENESIS

Soil genesis is basically a two-fold process which involves firstly the formation of the soil parent material and secondly the formation of the soil profile. The formation of soil parent material has resulted from the physical and chemical weathering of geologic materials and the subsequent redistribution of these products by water, wind, and ice.

The formation of the soil profile, on the other hand, has resulted from the dynamic interaction of the six basic factors of soil formation, namely: climate, vegetation, parent material, topography, time, and man. The result of this interaction is the formation of various layers or horizons within the parent material. These horizons constitute the soil profile. Horizon differentiation is the result of additions, removals, transfers and transformations within the soil system. Each of these processes depend greatly on the presence and movement of water through or within the soil.

The concept of an interrelationship between soil development and the movement of groundwater is relatively new. Studies in pedology have recognized the depth to groundwater as an important property of soil, however as Cairns and Bowser (1969) have stated, "the function of groundwater in the development of the soil profile is still not clearly understood".

Significance of Water in the Soil System

Water is the key element in the genesis of soil profiles. It is responsible for nearly all chemical reactions in the soil and provides a means of transport for all moveable soil constituents. The physics of water movement in the unsaturated zone has been studied at great length, however, the role of water movement as a factor in soil genesis has received little attention.

The development of soil profiles results from the flow of water in both the saturated and unsaturated soil zones. According to Toth (1962) groundwater is generally in a state of constant motion and is therefore capable of dissolving and transporting mineral matter from one part of a flow system to another, following flow trajectories defined by well known physical principles. He also shows that if the pattern of groundwater movement and its controlling factors were better understood, conclusions regarding both general principles and specific local features associated with the removal, transport and deposition of salts in soils, could be derived.

III SOIL-GROUNDWATER RELATIONS

For the most part, studies relating soil genesis to groundwater flow have centered on saline and solonetzic soils. For example, Pawluk, et al. (1969) concluded from field observations that: the Black Solod profile occurs in recharge areas, the Orthic Black and Solodic Black profiles occur in either midline or recharge areas, the Black Solonetz occurs in the lower parts of midline areas or the higher parts of discharge areas, and that the Saline Solonetzic Black soils occur in discharge areas. These observations, however, were not substantiated by hydrogeologic data. Other scientists such as Rozkowski (1967) and Sandoval, et al. (1961) studied soil salinity and groundwater in relation to topography. They concluded that soil salinity was the result of groundwater flow and that topography was a significant factor influencing the distribution of soluble salts. However, they did not relate groundwater flow and soil development.

More recently, studies in the glacial drift of Western Canada have indicated that a direct relationship exists between groundwater flow and genetic soils other than those associated with salinity. Leskiw (1971), in a study near Vegreville, Alberta, examined surficial phenomena such as genetic soil type, soil salinity, vegetation, natural springs, soap holes, surface lakes, streams, sloughs and domestic water wells and interpreted them as indicators of specific types of groundwater flow. Based on these observations and interpretations, he proposed a generalized classification scheme for soils in relation to their expected hydrologic nature (Table I). His

POTENTIAL

←--------------- GROUNDWATER RECHARGE GROUNDWATER DISCHARGE -------------------------→

*Amount of Water Entering the Saturated Zone: Low ←-- --→ High

Groundwater Recharge		Groundwater Discharge
Humic Eluviated Gleysol		Carbonated Saline Gleyed Regosol
Orthic Humic Gleysol		Carbonated Saline Rego Humic Gleysol
Rego Humic Gleysol		Carbonated Saline Humic Gleysol
	Carbonated Gleysols	
	Rego Black	
	Carbonated Eluviated Black	
Gleyed Eluviated Black		Thin Black Solonetz
Eluviated Black		Black Solonetz
Truncated Eluviated Black		Solodic Black and Black Solod

*Amount of Water Leaving the Saturated Zone: High ←-- --→ Low

TABLE I. Proposed Generalized Classification in terms of Spring Season Groundwater Flow Patterns at the Vegreville Study Area.
* Amount per unit area of the particular soil (after Leskiw, 1971).

observations and conclusions were not substantiated, however, with subsurface measurements of the potentiometric or hydrochemical parameters. Leskiw (1971) based much of the hydrological interpretation on local flow systems similar to those described by Lissey, 1968.

Although Lissey (1968) did not study soil-groundwater relationships, his interpretation of local flow systems has had considerable influence on pedology.

In a hydro-ecological investigation in the Oak River Area of Manitoba, Lissey (1968) concluded that shallow depressions and sloughs could be classified in terms of their ability to transmit water. He identified depressions as having fast and slow recharge, fast and slow discharge, and transitional groundwater flow systems. He showed that maximum infiltration to the groundwater zone occurred through the depressions rather than the local topographic highs. His study, however, did not relate the movement of groundwater to the development of soil profiles.

IV PREVIOUS WORK IN THE STUDY AREA

Ellis and Shafer (1940) conducted a reconnaissance soil survey of Southwestern Manitoba in which the soils were mapped according to soil associations. Areas of saline and solonetzic soils were recognized and delineated but no attempt was made to relate these soils to groundwater flow systems. The soil map was published at a scale of 1:125,000 and therefore, only broad areas and general soil conditions could be presented.

Elson (1952) studied the glacial history of the area and produced a general surface deposits map at a scale of 1:125,000. Elson's map shows the rather intricate nature of the various surface deposits but no direct mention of soils or groundwater was made.

A survey of the general groundwater conditions of the area was made in 1949 by Halstead and Elson for the Geological Survey of Canada. The groundwater flow systems in the area were not studied, since the primary purpose of the survey was to determine the occurrence of aquifers and the quality of water available for domestic use. Most of the well information was based on personal contact with farmers. A few water samples were analyzed by the National Testing Laboratories, Limited, Winnipeg and by the Bureau of Mines, Ottawa but the number of samples analyzed were not sufficient to characterize the area in terms of detailed hydrochemical patterns. The hydrochemical data were of little use, therefore, for interpreting the direction of groundwater flow.

CHAPTER III

METHODS AND MATERIALS

The methods and materials used in this investigation can best be described in terms of three categories: hydrological, pedological and analytical.

I HYDROLOGICAL

Piezometers were constructed of 0.8 inch outside diameter, semi-rigid, polyvinylchloride (P.V.C.) tubing. A 2-foot section at the bottom of the piezometer was slotted and wrapped with fiber glass. Fiber glass was used to prevent the accumulation of silt in the intake zone of the piezometer. Most of the piezometers were installed using a truck mounted rotary hollow stemmed auger. Once the auger reached the desired depth the piezometer was inserted into the hollow core of the auger. Coarse silica sand was added to the bottom of the bore hole to a thickness of about 30 inches. Six inches of fine silica sand were added on top of the coarse sand. The coarse silica sand pack at the bottom of the piezometer formed a small porous volume around the intake zone. The fine silica sand was added to prevent contamination of the intake zone by the cement grout. The auger was subsequently removed and a mixture of water and portland cement was added to form a grout plug above the sand. The hole was finally back filled to the surface with the extracted soil. Other piezometers were installed following basically the same procedure except that a solid stem auger was used to drill the hole. Due to the fact that the auger stem was solid, it had to be removed from the hole prior to installing the piezometer. The piezometers were installed in groups or nests of 4 to 6 at various depths ranging from 10 to 98 feet below ground level. This enabled water samples and hydraulic head measurements to be obtained from various depths below the water table. The particular piezometric design used in this study has been described in more detail by Schwartz (1970). A water table observation well was installed at each piezometer nest using a truck mounted Giddings Drill. The wells were constructed of P.V.C. tubing and placed at depths of 10 to 18 feet. The P.V.C. tubing was slotted to within 3 to 4 feet of the ground level. The location of the piezometer sites is shown in Figure 5.

The water level in the piezometers and wells was measured about twice a month during the summer and about once every six weeks in the winter. Water samples were taken from each well and piezometer in 1970 and 1971. A more detailed procedure for the hydrological investigation is presented in Appendix A.

II PEDOLOGICAL

Pedological investigations of the soils within this study area were limited to very intensive examinations of several specifically chosen areas. Two small areas (3/10 mi. x 3/10 mi. each), one on stratified lacustrine soil, the other on very gently sloping glacial till, were surveyed to determine the genetic soil distribution at each site. Soil inspections were made using a 30-foot grid pattern. Other pedological investigations were conducted using a cross-sectional approach to determine the chrono-

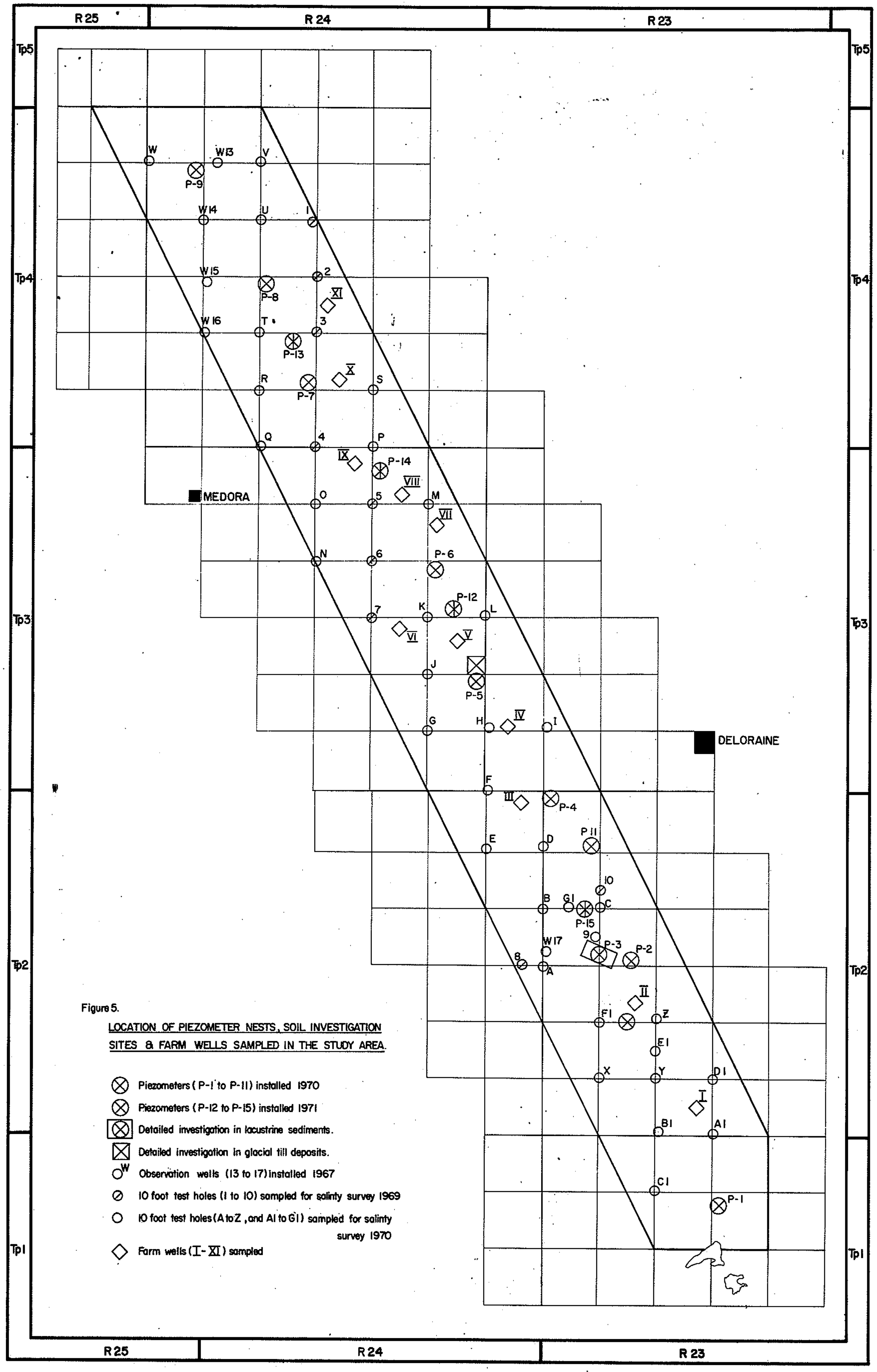


Figure 5.

LOCATION OF PIEZOMETER NESTS, SOIL INVESTIGATION SITES & FARM WELLS SAMPLED IN THE STUDY AREA.

sequence of profiles developed in knoll-depression type topography. Schematic diagrams were prepared showing the observed profile chronosequences at both sites.

Previous Pedological Investigations

Previous pedological investigations in the area were conducted by Ellis and Shafer (1940) and as recently as 1968 and 1969 in a resurvey of the soils by the Manitoba Soil Survey. The recent survey data has been used for the compilation of the generalized soils and salinity map of the particular area of this study.

The two scales or degrees of intensity of soil survey used during the recent resurvey program for the Southwest Area of Manitoba has resulted in a greater quantity of soil data for the lacustrine areas than for the areas of glacial till. A detailed or high intensity survey, which consisted of three traverses per square mile with systematic soil inspections every 1/10 mile along each traverse, was conducted in the Souris Plain and the Whitewater Basin Areas. The soil data collected was plotted on air photographs at a scale of 3 1/2 inches equal 1 mile. The basic map unit used in this survey was the single soil series. The medium intensity of reconnaissance survey consists of systematic soil inspections adjacent the the accessible roads bordering each section of land. It was used to map the soils of the Turtle Mountain and the Boissevain Till Plain. The soil information was plotted on air photo mosaics at a scale of 2 inches equal 1 mile. A complex map unit consisting of a number of soil series arranged in order of decreasing significance was used to describe these soil map units.

Criteria for Map Presentation

The soil catena map and the detailed soil salinity map for this study were prepared by transferring the preliminary soil survey map data at the scales previously described onto NTS base maps at a scale of 1:50,000. This base map was then photographically reduced for inclusion in the thesis.

The utilization of catenary map units, the conversion to a uniform scale and the subsequent reduction of scale accounts for the apparent lack of detail in some of the till portions of the map. Each area, however, has been described in terms of its catenary description and composition.

Salinity Survey

In conjunction with the genetic soil survey, soil samples were collected from approximately 3 sites per traverse (9 sites per square mile) at the 0 to 6 inch and 12 to 24 inch depths, analyzed for electrical conductivity and occasionally for the major soluble ions. In addition, soil samples were collected at 1 foot intervals to a depth of 10 feet from the auger stem of a Giddings Drill. These samples were also analyzed for EC to determine the characteristics and degree of the sub-surface (soil parent material) salinity. Composite soil samples were collected from the auger flights of the deep drill used to install piezometers and later analyzed for EC and soluble salt content. The salinity data thus collected was used in addition to the visible presence of salts (crystals) within the soil profile to prepare the soil salinity map.

III ANALYTICAL

The analytical methods used in this study are all standard procedures. A portable conductivity bridge (Beckman Co.) with an extended cable electrode was used to measure in situ electrical conductivities of the groundwater. A portable pH meter was used to measure the pH of groundwater samples in the field following a method described by Barnes (1964).

Initially two samples of water were collected from each piezometer. One sample was used for anion analysis, while the other sample was acidified with a few drops of HCl after reading the pH. It was later used for cation analysis. The addition of HCl to the sample proved to be detrimental to the ionic equilibrium of the sample. In many of the samples there was sufficient sediment of calcareous origin that a reaction with the HCl resulted in erroneous quantities of Ca^{++} ions in solution. All subsequent samples were not acidified, therefore necessitating the collection of only one sample for pH, anion and cation analysis.

The electrical conductivity and the major ions in both the groundwater samples and the saturated soil paste extracts were determined according to the methods described by the United States Salinity Laboratory staff (1954).

CHAPTER IV

RESULTS AND DISCUSSION

PART I

GENERAL DESCRIPTION OF THE AREA

I PHYSIOGRAPHY AND SURFACE DEPOSITS

The distribution of surface deposits in the Western Uplands Region of Manitoba and their division into physiographic subdivisions is shown in Figure 6. The study area is comprised of portions of the Turtle Mountain, the Boissevain Till Plain, the Whitewater Lake Basin, and the Souris Plain subdivisions.

The Turtle Mountain subdivision is characterized by moderately calcareous, moderately fine textured (clay loam) glacial till. The surface topography is irregular with slopes ranging from undulating (2 to 5 per cent) to very hilly (over 60 per cent). The landscape has innumerable depressions and small permanent and semi-permanent lakes. The Turtle Mountain slopes abruptly to the northwest and intersects the Boissevain Till Plain near the 1850 foot elevation.

The Boissevain Till Plain is characterized by strongly to moderately calcareous, medium to moderately fine textured (loam to clay loam) glacial till. The topography is typically irregular with slopes ranging from undulating (2 to 5 per cent) to moderately rolling (9 to 15 per cent). The slopes generally become more subdued as elevation decreases to the Whitewater Basin. At the higher elevations the till is commonly dissected by ephemeral stream channels

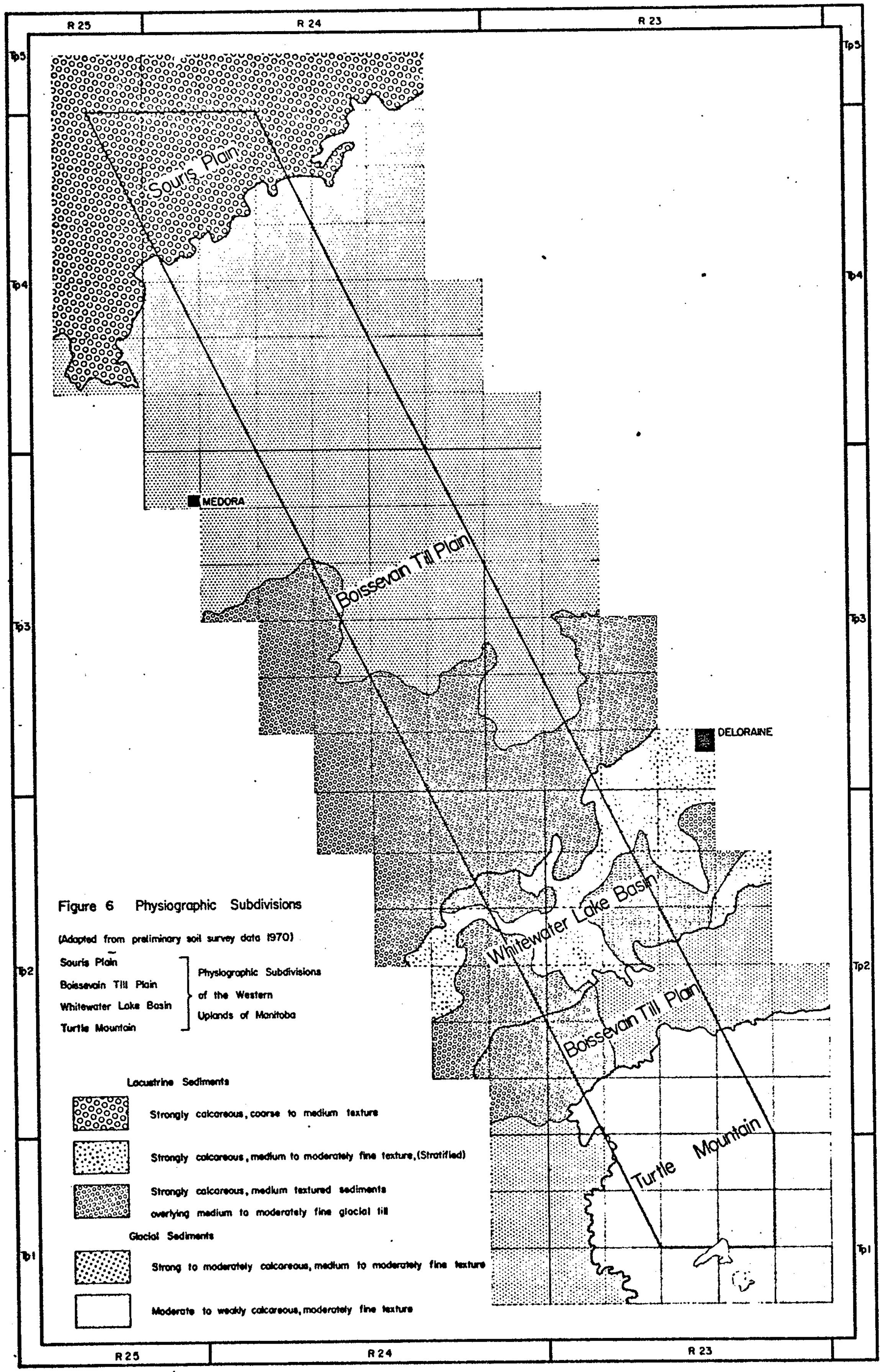


Figure 6 Physiographic Subdivisions

(Adapted from preliminary soil survey data 1970) which gradually disappear in the vicinity of the Whitewater Basin. Northwest of the basin, surface drainage patterns become less pronounced, with surface waters generally collecting in shallow closed depressions.

The western end of Whitewater Lake Basin lies between 1625 and 1675 feet above sea level within the Boissevain Till Plain. The surface topography of the basin sediments consists of regular singular slopes ranging from 0.5 to 2 per cent. The basin has a gentle slope. The surface deposits consist of numerous layers of alluvial and lacustrine sediments ranging in texture from sands to clay loams. The thickness and stratification of these sediments decreases downslope. A moderately fine-textured till underlies the thin alluvial and lacustrine surface deposits at depths ranging from 2 to 15 feet. A layer of poorly sorted outwash gravels (1 to 3 feet thick) usually occurs at the till contact.

Below the 1625 foot elevation, the Boissevain Till Plain continues and slopes gently northwestward to the Souris Plain at 1475 foot elevation. The Souris Plain consists of strongly calcareous, coarse to medium textured (sands to loams) lacustrine sediments which slope very gently to the Souris River. The sediments in the Souris Plain area are generally less stratified than those of the Whitewater Basin; however, they have similar conditions of high moisture status and high concentrations of soluble salts. Local changes in topographic relief occur as a result of wind action on the coarse textured lacustrine sediments.

II RELIEF AND SURFACE DRAINAGE

The overall topographic relief for the study area ranges from a high of 2300 feet above sea level north of Flossie Lake on Turtle Mountain to 1450 feet above sea level near the northwest corner of the study area in the Souris Plain giving a maximum change in relief of 850 feet (Figure 7).

The topography slopes very steeply (200 to 250 feet per mile) between the 2300 and 1700 foot elevations in a northwest direction from Turtle Mountain to the Boissevain Till Plain. The slope gradually decreases to less than 50 feet per mile across the Boissevain Till Plain and finally to less than 8 feet per mile through the Souris Plain Area.

Numerous ephemeral stream channels leading from Turtle Mountain disappear abruptly between 1650 and 1675 foot elevations. Other small intermittent streams originate and disappear in the vicinity of the 1625 foot elevation. Some streams originate in the area of the 1575 and 1550 foot elevations and subsequently disappear into the coarse sediments of the Souris Plain. The only major water course in the area is Medora Creek which flows intermittently throughout the year, primarily after spring thaw and occasionally after heavy summer rains.

III GEOLOGY

Although the regional geology of Southwestern Manitoba has been described by Bannatyne (1970), a more detailed knowledge of the Quaternary geology, bedrock topography, and upper bedrock units in

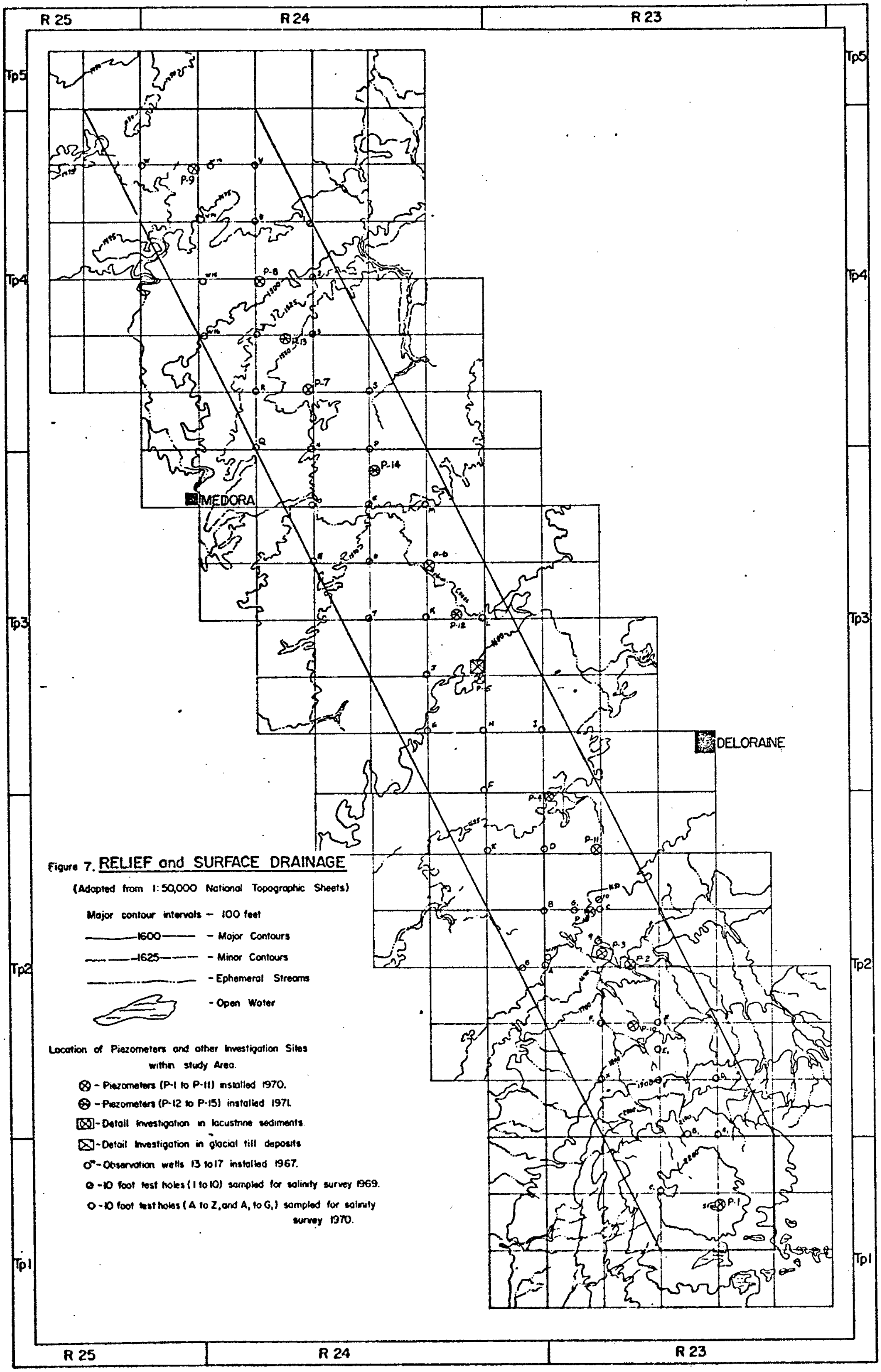


Figure 7. RELIEF and SURFACE DRAINAGE

the study area was obtained during the drilling program. Geologic contacts and various outcrops of the underlying deposits were also observed in road cuts and erosion channels during the course of this study.

Bedrock Geology

The bedrock geology of the study area is composed of three distinct geologic units of Cretaceous and Tertiary age: the Riding Mountain Formation, the Boissevain Formation, and the Turtle Mountain Formation (Figure 8a).

The Riding Mountain Formation is composed of two members: an upper member (Odanah) composed of hard grey siliceous shale and a lower member (Millwood) composed of a softer greenish brown bentonitic shale.

A shale outcrop resembling the Odanah member occurs in a road cut through the Dand Channel in the vicinity of the Chain Lakes which lie 6 miles to the east of the study area. This shale is thought to be continuous with the shale which occurs as bedrock in the minor escarpment which divides the Souris Plain and the Boissevain Till Plain. A hard fractured, non-calcareous shale was encountered at a depth of 10 feet on this escarpment at piezometer nests 7 and 13. This shale is similar to the Odanah member as described by Bannatyne (1970).

The shale encountered in the remainder of the study area was softer and appears to be more typical of the Millwood member. Bannatyne (1970) states that occasional outcrops of the Millwood

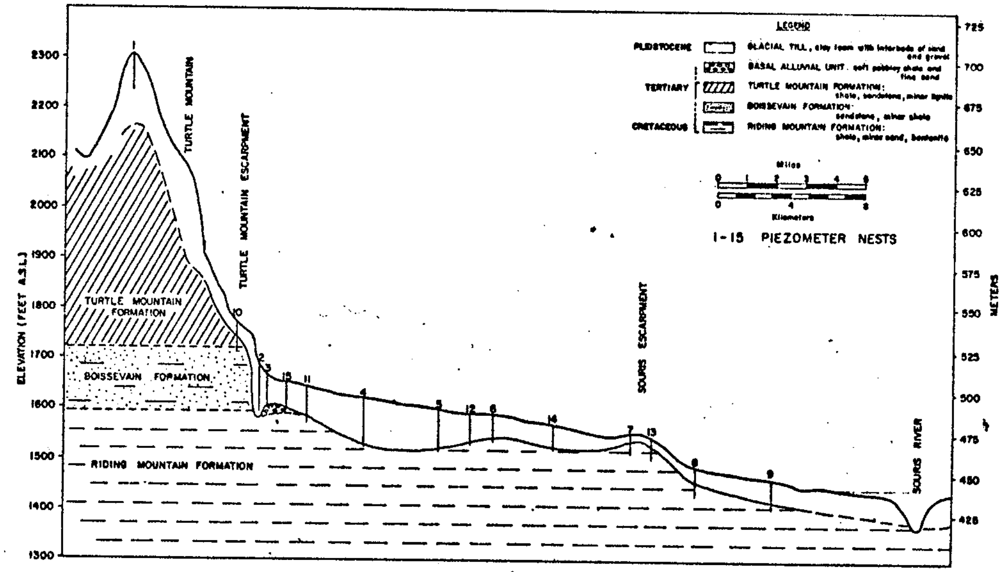


Figure 8a. Regional bedrock geology of hydrologic cross-section.

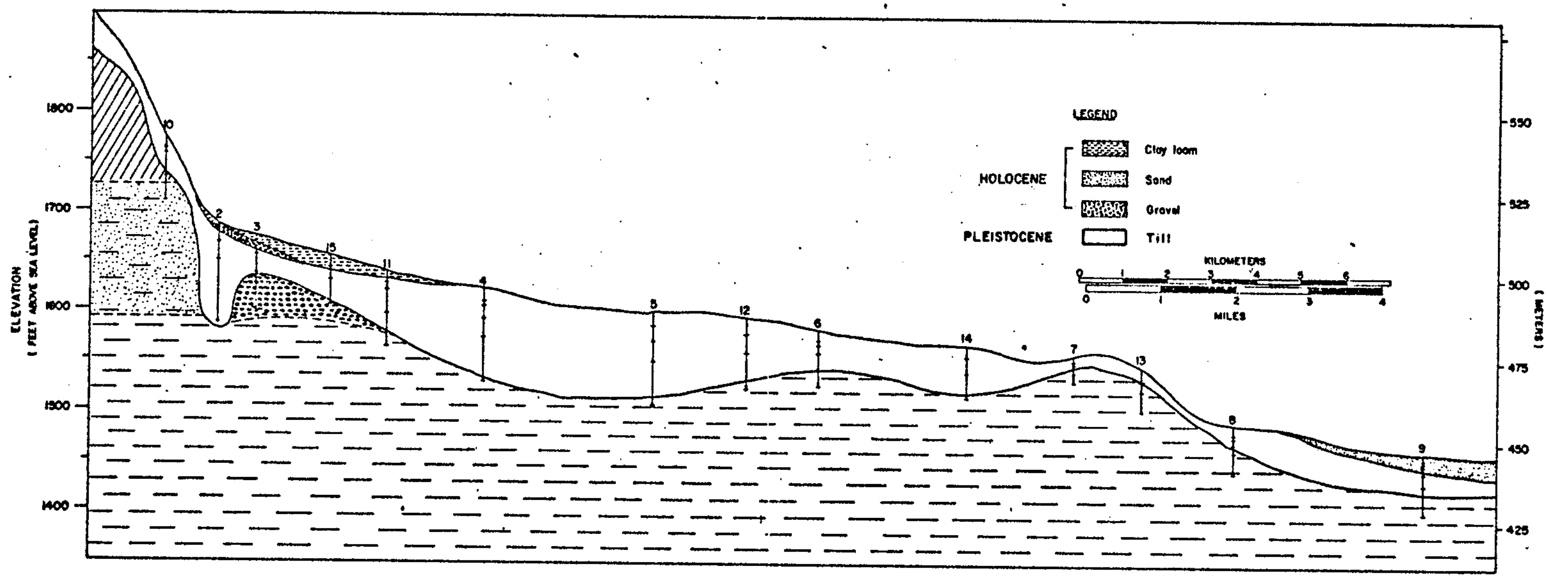


Figure 8b. Surficial geology of hydrologic cross-section.

occur along the Souris River Valley but are usually accompanied by a cap of the harder Odanah member.

In the vicinity of Turtle Mountain the Riding Mountain Formation is overlain by the Boissevain Formation. The Boissevain Formation consists basically of sandstone and shale and is approximately 140 feet thick. Bannatyne (1970) has described this formation in a drill log (Hole MNR No. 1: NW15-32-1-22 WPM Elev. 1970 feet) located approximately three miles east of this study area. According to Bannatyne the Boissevain Formation consists of a fine to medium grained "salt and pepper", non-calcareous sandstone alternating with thin (6 to 10 feet) layers of non-calcareous grey shale with light grey, feldspathic siltstone, and inclusions of plant and lignite fragments. He also reports that the top of the Boissevain Formation occurs in several outcrops on the northwest slope of Turtle Mountain which show sandstone with kaolinized feldspar, kaolinitic sand or kaolinitic shale. One outcrop which Bannatyne describes (SW corner sec. 17, tp. 2, rge. 23 WPM) occurs in the study area very close to the piezometer cross-section and places the contact between the top of the Boissevain Formation and the bottom of the Turtle Mountain Formation at an elevation of 1740 feet above sea level.

The Turtle Mountain Formation consists of approximately 480 feet of sandstone, shale, and thin lignite beds. Bannatyne's (1970) drill logs show that these materials are present in alternating layers. The sandstones are generally very fine to medium grained, impure, and non-calcareous. The shales are usually silty, micaceous, grey to light grey, and interbedded with bentonite and siltstones. Lignite is present as mixed fragments.

At the contact between the Boissevain Formation and the underlying Riding Mountain Formation, a shaley gravel deposit, herein referred to as the Basal Alluvial Unit, was encountered and sampled at sites 3 and 15 (Figure 8b). This unit is composed of loose, rounded, fragments of shale in a matrix of fine grained sand and silt. This deposit probably was laid down in an alluvial environment which probably existed along the escarpment during Pre-glacial times.

A small depression or channel exists between the Boissevain Formation and the Basal Alluvial Unit (Figure 8b, p. 32), which could have been formed by Pre-glacial groundwater springs eminating from the Boissevain Formation or by surface runoff from the Turtle Mountain Formation. Kohut (1972) also encountered a similar unit in the vicinity of Whitewater Lake. However, he found it to be continuous with the Boissevain Sandstone and concluded that it was an inter-glacial deposit. The drill holes at nests 3 and 15 did not completely penetrate this Alluvial Unit but, on the basis of other geological elevations, it is thought to be deposited on the Riding Mountain Formation and to gradually pinch out at some point between nest 15 and 11.

Quaternary Geology

Throughout the study area the Cretaceous and Tertiary units are blanketed by deposits of glacial till. The thickness of till ranges from 15 to 30 feet in the Souris Plain area below the escarpment and from 10 to 90 feet in the Boissevain Till Plain above the Souris Escarpment. Bannatyne (1970) reports that in some places on Turtle Mountain the drift is over 400 feet thick. However, the average depth to shale along the major part of the study area was found to be approximately 50 feet (see Drill Logs, Appendix B). Kohut (1972) found that the depth to shale often exceeded 100 feet in the vicinity of Whitewater Lake and that there appears to be a pre-glacial bedrock depression or valley beneath the lake. This difference in till thickness indicates that the surface of the shale slopes gently to the east.

The till covering the study area is believed to be composed of two units. This statement is based partly on the fact that a distinct change in color was observed in the till near the 25 foot depth, and partly on hydrological data which will be discussed in a later chapter. Kohut (1972) describes two tills occurring in the vicinity of Whitewater Lake. According to him, the upper part of the lower till is well fractured and marked by iron and manganese staining. The contact with the overlying till is generally sharp. Kohut (1972) found that the upper till in the Whitewater Lake Area was approximately 30 feet thick.

The upper till in the area of this study is approximately 20 to 25 feet thick, well fractured, oxidized and generally olive (5Y 4/4) in color. The lower till is dark to very dark grey (5Y 4/1-3/1) in color and the upper part of it appeared to be more fractured and jointed than the overlying till. Both tills are predominantly clay loam in texture and appear to correspond to the tills described by Kohut (1972) in the vicinity of Whitewater Lake.

Holocene Deposits

The Whitewater Basin and the Souris Plain are overlain by Holocene deposits of lacustrine, alluvial, and aeolian origin. The Whitewater Basin sediments are generally thin, stratified deposits of sands, loams, and clay loams. The dominant texture is clay loam. A very thin deposit of aeolian silt is commonly found along the northern and western edges of the basin.

The surface deposits of the Souris Plain are predominantly stratified, fine to medium lacustrine sands. The dominant texture of the soils is loamy fine sand. Much of the area in the vicinity of the Souris River has been modified and reworked by wind, resulting in a fairly extensive area of sand dunes.

PART II

CONSTRUCTION OF FLOW SYSTEMS FROM HYDROLOGIC DATA

The nature of the groundwater flow systems for the study area, as shown in Figure 9, has been derived by considering the measured hydraulic head, the distribution of the major ion chemistry, and the most probable influence of surficial and bedrock geology. Using this criteria, seven hydrologic regimes were identified.

Hydraulic Head Data

The interpretations of the hydraulic head data (Appendix C) were based on the theories and procedures developed by Toth (1962), Meyboom (1966), and Freeze and Witherspoon (1967). The vertical direction of groundwater flow was determined by comparing the hydraulic heads of piezometers in each nest. The horizontal direction of groundwater flow was determined by comparing water level differences between piezometer nests.

In homogeneous geologic deposits, nests in which piezometer water levels (hydraulic head) are below the water table level (Figure 10A) indicate groundwater recharge; that is, the direction of groundwater movement is downward from the water table zone. On the other hand, piezometer water levels above the water table (Figure 10B) indicate groundwater discharge; that is, groundwater movement is upward toward the water table zone. Piezometer water levels coinciding with the water table and with each other indicate zero vertical hydraulic gradient and are interpreted as indicating lateral groundwater flow.

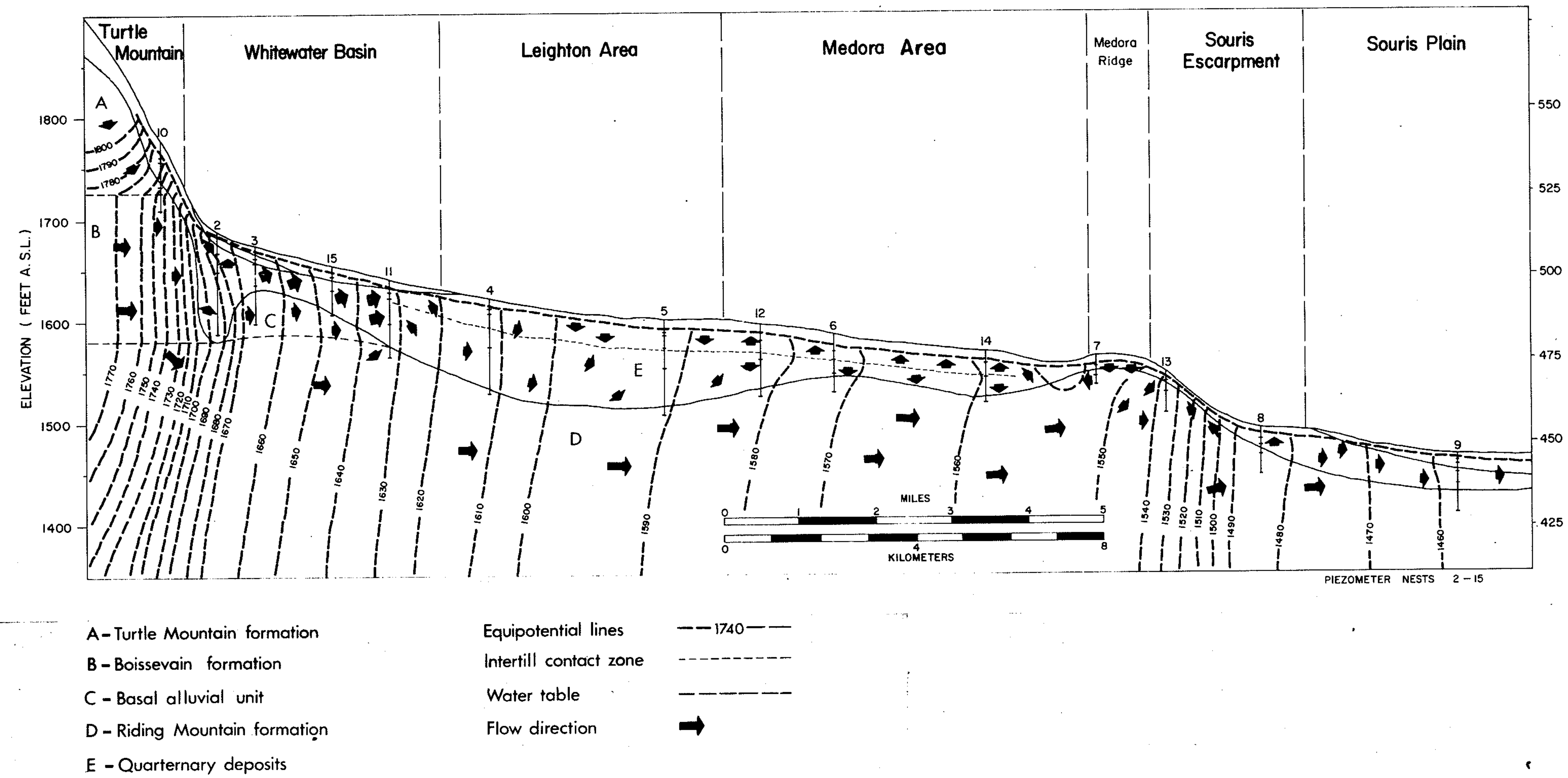


Figure 9. Groundwater Flow Systems near Deloraine in Southwestern Manitoba. Derived from Hydraulic Gradients and Hydrochemical Data of the Groundwater.

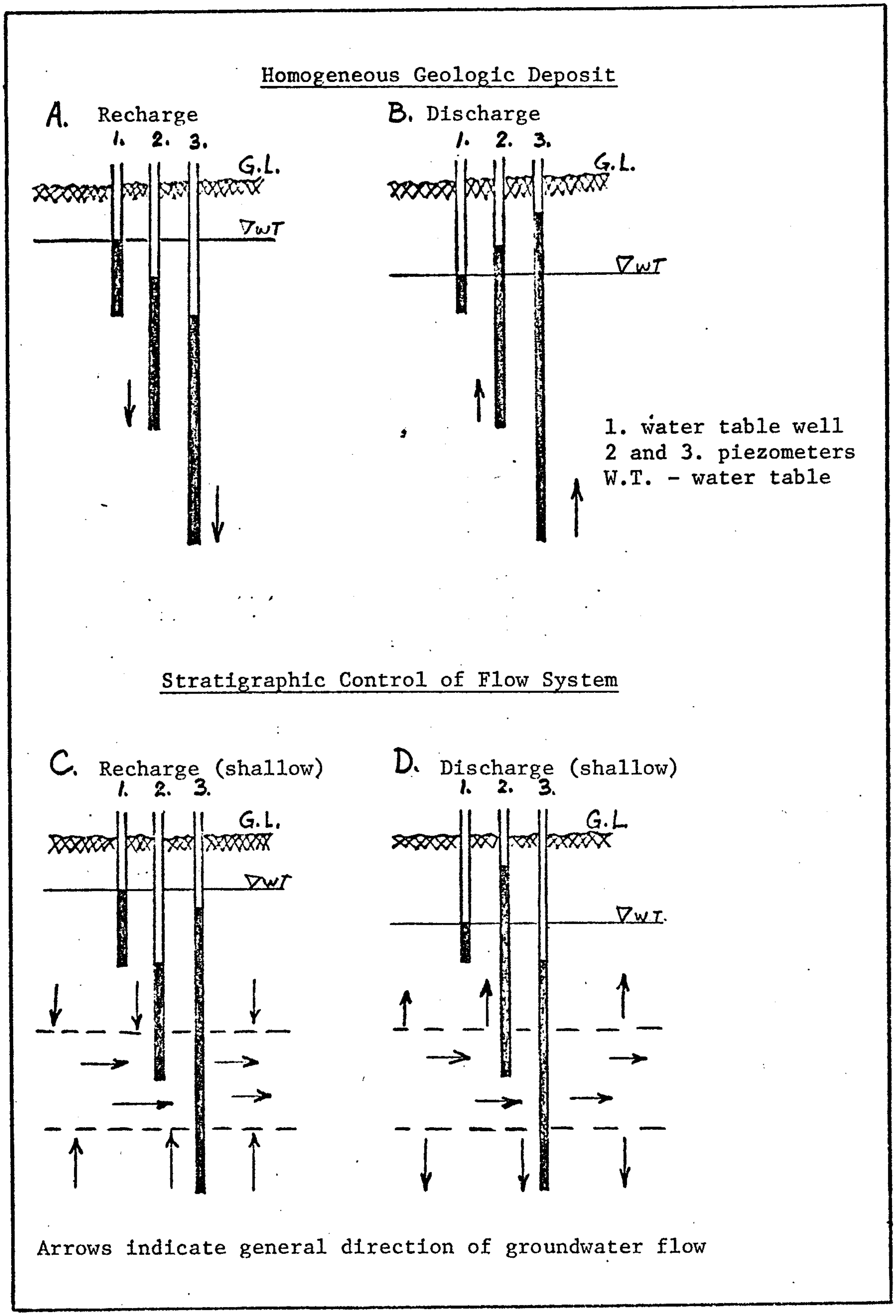


Figure 10. Schematic of piezometer nests to facilitate interpretation of hydraulic head data.

Stratigraphic changes in the geologic deposits may result in alterations to the flow system. These changes may be reflected in the vertical hydraulic heads of piezometers in a single nest. For example, water levels in deep piezometers above water levels in overlying piezometers, but not above the water table level, indicate a positive vertical hydraulic gradient at depth. This means that groundwater movement is towards the area or intake zone of the overlying piezometer (see Figure 10C). The hydraulic head of the overlying piezometer is also below the water table, indicating that groundwater flow is generally downward from the water table. The area of the intake zone of the overlying piezometer is interpreted, therefore, as a zone of dominantly lateral flow.

Conversely, deep piezometers having water levels below the water levels of the overlying piezometers (Figure 10D) are interpreted as having nagative vertical hydraulic gradient. Groundwater zones having negative vertical hydraulic gradients probably have water movement into them. The flow of water in the area of the intake zone of the overlying piezometer is interpreted as dominantly lateral with diverging components.

The concept of positive and negative vertical hydraulic gradient is introduced here to describe groundwater flow conditions in hydrogeologic units below the water table zone.

The terms positive and nagative hydraulic gradients are used instead of discharge and recharge, respectively, because the terms discharge and recharge are most commonly used to refer to the dominant flow conditions near the water table.

The above mentioned variations of hydraulic head were used to interpret the general flow of groundwater in the study area. The actual orientation of the flow arrows in relation to the equipotential lines (Figure 9) was determined according to a method described by van Everdingen (1963). In theory the direction of groundwater flow or stream lines are normal to the lines of equipotential. Van Everdingen (1963), in a computer analysis, showed that when there is an exaggeration of the vertical scale in comparison to the horizontal scale of groundwater flow diagrams, the lines of groundwater flow cross the lines of equipotential at angles less than 90 degrees. This accounts for the distortion of scale and gives a more accurate picture of the natural groundwater flow.

Hydrochemical Data

Hydrochemical data includes the major ion composition, pH and electrical conductivity of groundwater. These data are measurements related to the degree of mineralization of groundwater, and are important parameters used in conjunction with, or to supplement and verify, interpretations based on hydraulic head data.

Since the degree of mineralization of groundwater in a given mineralogical medium is mainly dependent upon the time it has been in contact with minerals, increasing ionic concentrations are interpreted as indicating direction of groundwater flow. Increasing mineralization with increasing flow distance is a relation commonly observed in groundwater studies in Western Canada (Meyboom, 1966 and Cherry *et al.*, 1971). The major ions in groundwater may also indicate the origin or source of the groundwater when compared to the mineralogic composition of the aquifer from which it was obtained (Rozkowski, 1967).

The hydrochemical data for 1971 is shown in Figures 11, 12 and 13. Additional hydrochemical data is included in Appendices D and E. Figures 11, 12 and 13 show the distribution of the major ions, pH and electrical conductivity of the groundwater.

The distribution pattern of the cations as shown in Figure 11, shows the relative concentrations of the various cations to one another and the areas of apparent accumulation.

Calcium. The maximum concentration of Ca^{++} is 30.4 meq./1., the average concentration, however, is generally much less than 20 meq./1. Groundwater recharge areas commonly have concentrations less than 10 meq./1., whereas groundwater discharge areas generally have concentrations of approximately 20 meq./1. The concentration of Ca^{++} is generally very low in comparison to the concentrations of Mg^{++} and Na^{+}, probably due to its dependence on the carbonate equilibrium conditions in the groundwater.

Magnesium. Low Mg^{++} concentrations ranging from 0.9 to 8.1 meq./1. (Figure 11) are common to areas of downward groundwater flow in the study area. The areas of upward water movement typically have much higher Mg^{++} concentrations, ranging from 2.7 to 241 meq./1. Areas with high Mg^{++} concentration generally coincide with those of high Ca^{++} concentrations.

Sodium and Potassium. Analyses showed that the concentration of K^{+} in the groundwater was very small when compared to the concentrations of the other ions (Appendix E-2). Therefore, the concen-

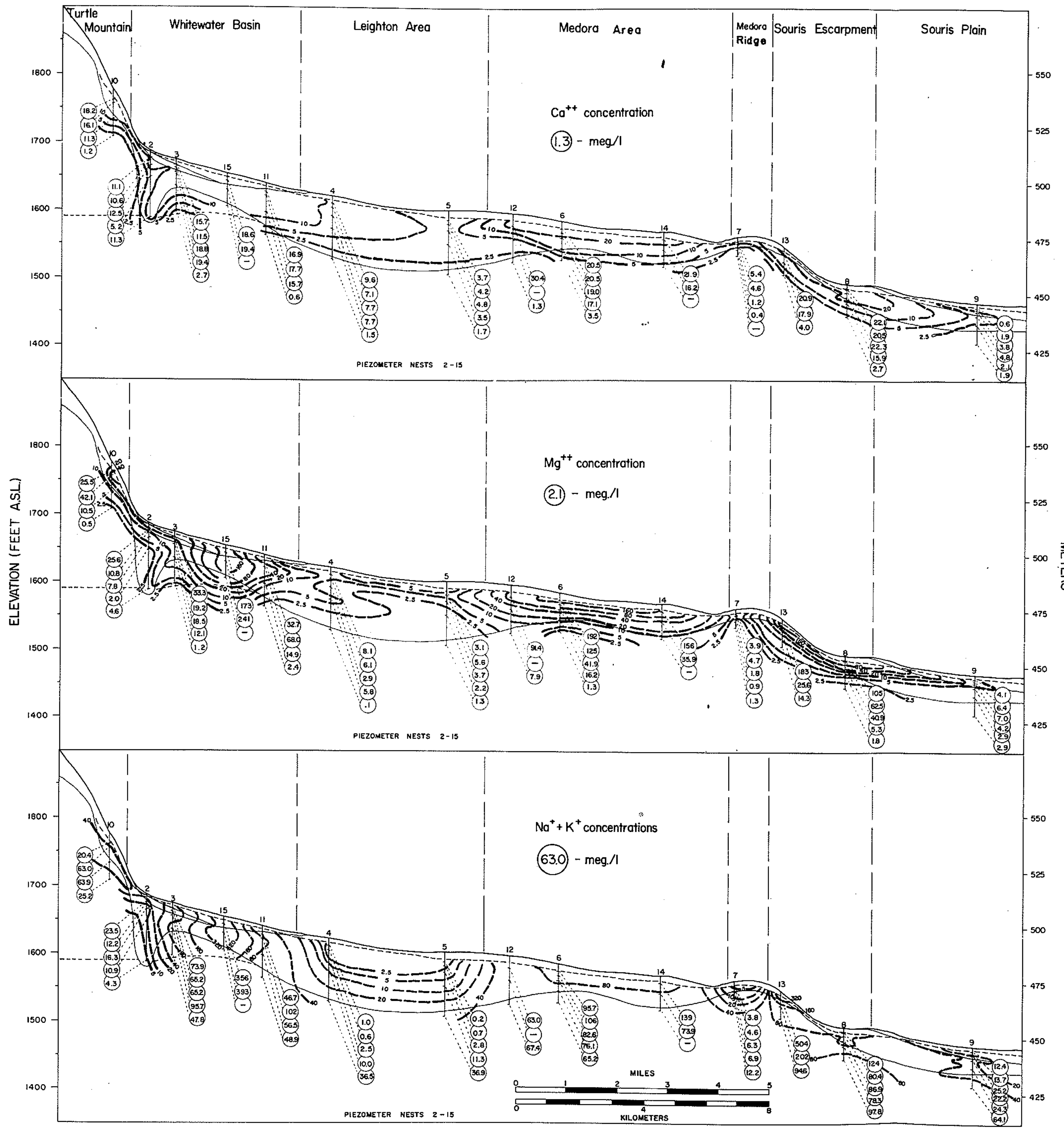


Figure 11. Distribution of Cations in the Groundwater Flow System.

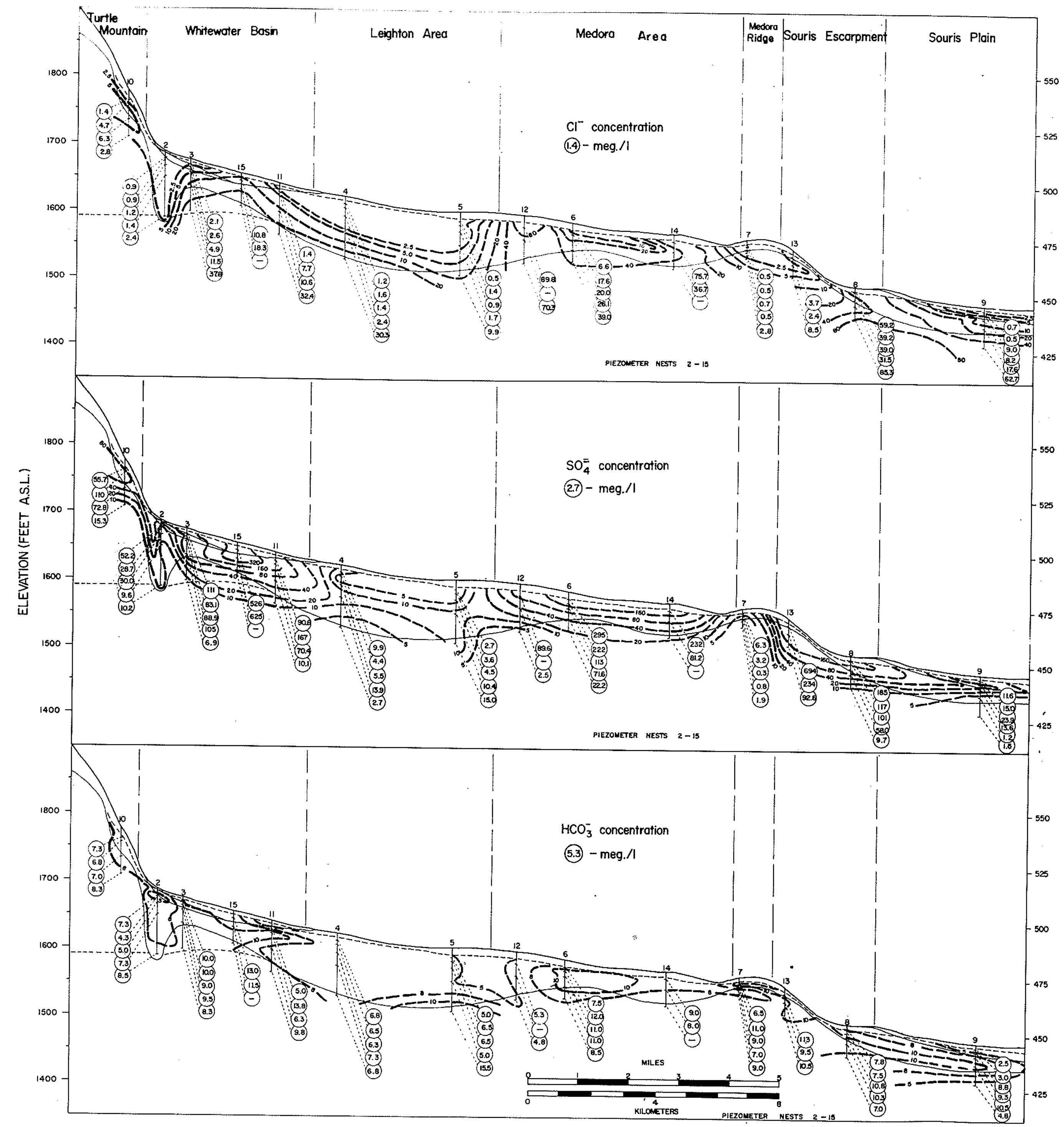


Figure 12. Distribution of Anions in the Groundwater Flow System.

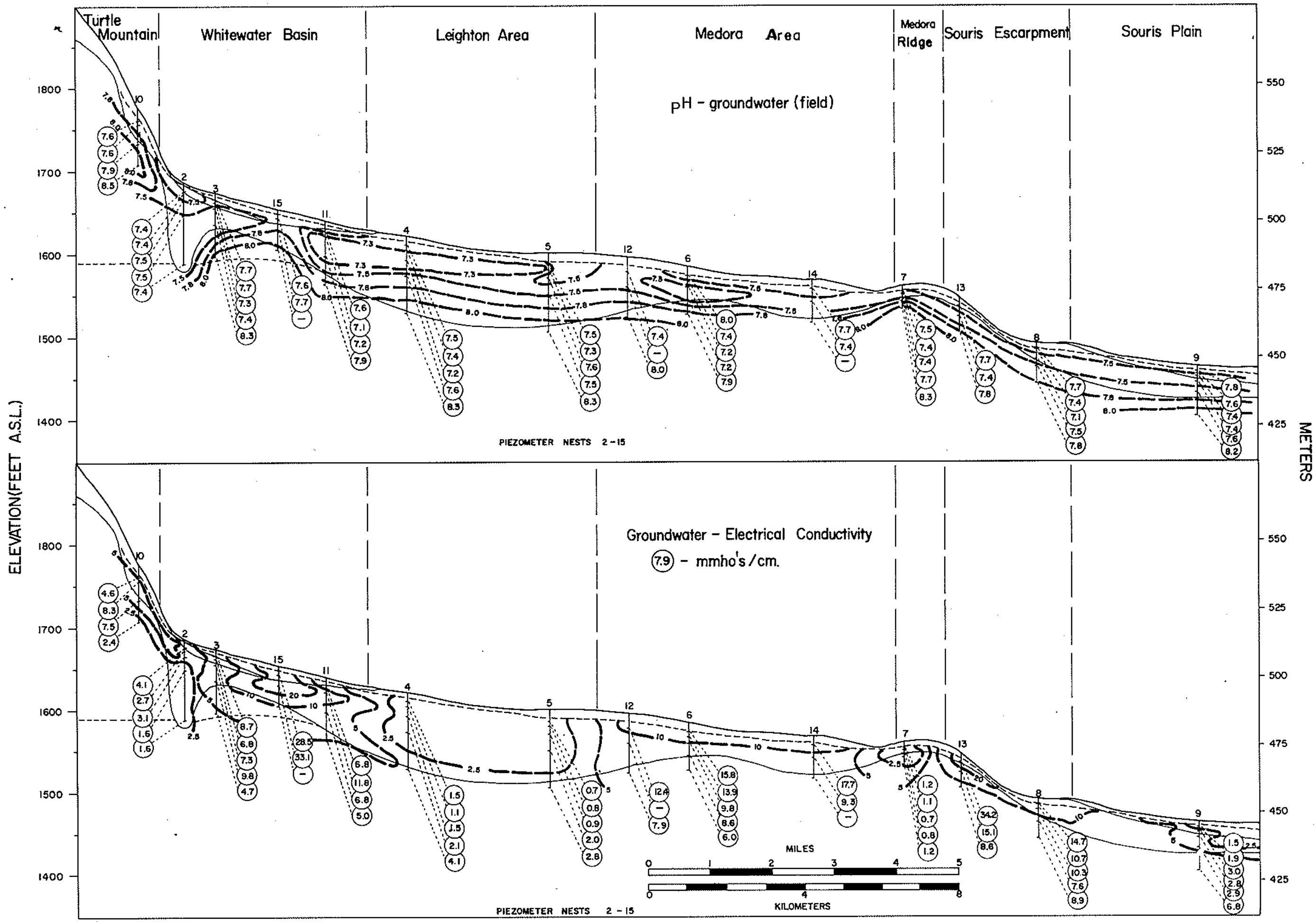


Figure 13. Distribution of pH and electrical conductivities of the Groundwater Flow System.

tration of K^+ is not shown separately in Figure 11, p. 43. The values shown for Na^+ + K^+, therefore, are discussed as the general values for the Na^+ concentration.

The vertical distribution pattern of Na^+ (Figure 11, p. 43) is different from that for Ca^{++} and Mg^{++}, primarily due to the high concentrations of Na^+ in the bedrock shales. On the other hand, the lateral distribution pattern for Na^+ shows that areas of highest Na^+ concentration generally coincide with the areas of high Ca^{++} and Mg^{++} concentrations.

The distribution of major anions Cl^-, $SO_4^=$, and HCO_3^- is shown in Figure 12, p. 44.

Chloride. The highest concentrations of Cl^- are generally found in the marine shales and in the glacial tills of the three major discharge areas (Figure 12, p. 44). In the recharge areas, the tills contain relatively small quantities of Cl^- compared to the underlying shales.

The concentration of Cl^- is generally a good indicator of groundwater flow due to the fact that it does not readily combine with other ions to form a precipitate nor is it affected by exchange mechanisms.

Sulphate. Sulphate is the most abundant anion in the groundwater (Figure 12, p. 44). Concentration of 625 meq./l. and 694 meq./l. occur in Whitewater Basin and the Souris Escarpment, both of which have been designated as areas of groundwater discharge. Recharge areas commonly have much lower $SO_4^=$ concentrations. The lowest concentrations (2.7 meq./l. and 0.3 meq./l.) occur in the

Leighton and Medora Ridge areas, respectively.

Bicarbonate. Although the concentration of HCO_3^- is much lower than the other ions (2.5 to 15.5 meq./1.), the zones of highest concentration generally occur in areas of groundwater discharge.

pH. The distribution of field measured pH (Figure 13) shows a slight differentiation with the direction of groundwater flow. Values of pH in the range of 7.3 to 7.5 are commonly found in groundwater recharge areas, while higher values of pH in the range of 7.5 to 8.5 are characteristic of groundwater discharge areas. Increasing values of pH correlate with decreasing concentrations of HCO_3^-. Cherry (1971) observed a similar correlation in the Holocene and Pleistocene deposits of the Wilson Creek area of Manitoba, where a decrease in the HCO_3^- concentration was associated with an increase in pH.

Electrical Conductivity (EC). EC is a measure of the ability of a cube, one centimeter on a side, to conduct an electrical current. In the case of water, EC is a function of temperature, type of ion present, and concentration of ions. It is, therefore, a very easy method of estimating the chemical quality of water (Davis and De Wiest, 1967, pp. 83-84).

The EC values for the groundwater (Figure 13) reflect the degree of mineralization or quantity of total dissolved solids (TDS) according to

$$TDS = EC \times K \qquad (1)$$

where K = some constant factor.

However, since TDS generally increases in the direction of groundwater flow, EC will also increase in the direction of groundwater flow.

The degree of mineralization, however, depends upon the number of ions in solution. Thus

$$TDS = TC + TA \qquad (2)$$

where TC = Total cations

TA = Total anions.

Therefore, TC + TA will also increase in the direction of groundwater flow. Increasing values of EC, TC, and TA can therefore be used to interpret the direction of groundwater flow within a uniform geologic medium. It should be noted, however, that redox reactions and exchange mechanisms can reverse this trend for some ions. Ca^{++} and Mg^{++}, for example, can be removed from solution by absorption onto the exchange sites of various minerals with the subsequent displacement of Na^{+}. Under exchange conditions, therefore, the concentrations of Ca^{++} and Mg^{++} will decrease as Na^{+} increases in the direction of groundwater flow. This situation commonly occurs as water moves from one geologic unit to another, for example, from a calcareous till to a non-calcareous marine shale.

Geology

The interpretations of the groundwater flow systems (Figure 9, p. 38) were also based, to some extent, on the nature and properties of the surficial and bedrock geology of the study area. The flow of groundwater through any geologic unit is dependent upon the permeability. In turn, permeability is dependent upon texture, bedding, and structure such as joints and fractures of the different geologic units. For example, the flow of water through materials with laminar or horizontal bedding or which have high intergranular permeabilities is generally expected to be in a lateral direction. Geologic materials which are predominantly characterized by a system of vertical fractures and joints are expected to have a generally vertical direction of groundwater flow.

Kohut (1972) suggests that the horizontal component of permeability in the Riding Mountain Formation is greater than the vertical component due to the horizontal bedding and fissility of the shale. It is reasonable, to expect groundwater to move laterally northwestward through the shale with little tendency for vertical circulation. He also suggests that the sandy texture and unconsolidated nature of the various geologic units in the Boissevain Formation results in a relatively high intergranular permeability. This, coupled with the horizontal bedding of the Boissevain Formation, probably results in a larger horizontal than vertical component of hydraulic conductivity, thus causing dominantly lateral groundwater flow.

Kohut (1972) observed, in outcrops of the Turtle Mountain Formation, that the permeability was mainly due to vertical joints and fractures. He concluded from this, that the dominant component of hydraulic conductivity was vertical.

In this study, vertical joints and fractures were also observed in the overlying glacial till at many of the drill sites. It was expected, therefore, that much of the groundwater flow through the till would be vertical. In several instances, however, it was found that textural variations and/or lithological discontinuities in the till interrupted this vertical pattern of flow and in essence created small zones within the till which had dominantly lateral flow. The influence of these textural and stratigraphic differences will be discussed in more detail in the following section dealing with individual flow regimes.

Patterns of Groundwater Flow

The patterns of groundwater flow (Figure 9, p. 38) therefore, based on hydrologic and geologic parameters, show that the study area consists of seven hydrologic areas characterized by specific conditions of groundwater flow. These areas are: Turtle Mountain, Whitewater Basin, Leighton, Medora, Medora Ridge, Souris Escarpment and Souris Plain. Three areas, Turtle Mountain, Leighton, and Medora Ridge, are characterized by recharging groundwater conditions, while three other areas, Whitewater Basin, Medora, and Souris Escarpment are characterized by discharging groundwater conditions. The seventh area, Souris Plain, is generally under the influence of lateral groundwater flow.

PART III

HYDROLOGY AND SOIL CHARACTERISTICS OF THE STUDY AREA

Part III of this chapter is discussed in two sections. Section I is a detailed interpretation of the hydrologic (hydraulic head and hydrochemistry) data and the associated soil profile types for each of the hydrologic area identified. Section II is a detailed discussion of the relations between soil salinity and hydrology.

I HYDROLOGY AND SOIL PROFILE TYPES IN EACH OF THE SEVEN HYDROLOGIC AREAS

The hydrologic and pedologic data are discussed for each of the seven hydrologic areas, in order of decreasing regional elevation. Although soil salinity will be discussed in Section II, some pertinent discussion related to surface and subsurface soil salinity within individual areas will be presented in this section, in order to fully describe the characteristics of each area.

Turtle Mountain

Hydraulic head. Piezometers at Nests 1 and 10 have negative hydraulic gradients indicating downward movement of water. The elevation of Nest 1 relative to the other nests (Figure 8a, p. 32), and the fact that it has a large downward gradient (water level in bottom piezometer is approximately 45 feet below water table), indicates that it is an area of strong groundwater recharge. Nest 1 was purposely located at one of the higher points on Turtle Mountain to determine the magnitude of the hydraulic head and the initial degree of mineralization of the groundwater in the uppermost part of the till. Due to its topographic location and generally vertical permeability, the hydrological data for this site is probably typical of the groundwater characteristics in the upper till of the Turtle Mountain area. The majority of the Turtle Mountain Area, including Nest 1, has been excluded from all cross-section diagrams because of its high elevation. This has resulted in a more useful cross-section scale.

The piezometers at Nest 10, which is situated on a small escarpment at the base of the Turtle Mountain, intersect the Turtle Mountain and Boissevain Formations. The piezometer at 68 feet, which intersects the Boissevain Formation, has a consistently negative hydraulic gradient (water level is approximately 32 feet below water table), indicating a downward flow of groundwater. The piezometer at 43 feet, which intersects the Turtle Mountain Formation, also has a consistently negative hydraulic gradient; however, the magnitude of the gradient is much less (water level is less than 3 feet below water table). The water level in the piezometer at 18 feet in the surface till occasionally coincides with the water table level. However, when the water table fluctuates, because of precipitation, there is a small lag in the piezometer water level response. This results in periods of small positive hydraulic gradients during the fall and small negative hydraulic gradients during the summer.

Hydrochemistry. The hydrochemistry of the Turtle Mountain Area, as determined from the piezometers in Nest 1, indicates a generally increasing degree of mineralization with increasing depth below ground surface (Appendix E). Since the till at Nest 1 appeared to be relatively uniform in texture and mineralogical composition, the hydrochemistry of this site is considered to be representative of groundwater conditions in the Turtle Mountain Upland.

Each of the three different geologic units at Nest 10 have characteristic major ion concentrations. The Boissevain Formation, for example, has very low concentrations of Ca^{++}, Mg^{++}, and $SO_4^{=}$ (Figures 11 and 12, pp. 43 and 44). The Turtle Mountain Formation, situated immediately above the Boissevain Formation, appears to have intermediate values of Ca^{++} and Mg^{++} and lower values of Na^{+} and Cl^{-}, than either the Boissevain Formation or the overlying till. The overlying till has higher concentrations of $SO_4^{=}$, Ca^{++}, and Mg^{++}, than the other two units. The low concentration of Ca^{++}, Mg^{++}, and $SO_4^{=}$ indicates that the Boissevain Formation is non-calcareous and probably has very low quantities of soluble salts.

Soils. The soils on Turtle Mountain are typically leached (of soluble salts) and well drained. These soils, which were mapped as members of the Horton Catena (Figure 14) are developed on moderately calcareous, medium to moderately fine textured till. The majority of the soils are classified as Orthic Dark Grey, and Rego Dark Grey Chernozems. The Dark Grey soils are generally found at elevations above 1800 feet. Below 1800 feet, the soils are predominantly mapped as Orthic and Rego subgroups in the Ryerson Catena (Figure 14). The soils are predominantly well to moderately well drained, with minor areas of imperfect and poorly drained soils in lower slope and depressional positions. The soil profiles are typically non-saline

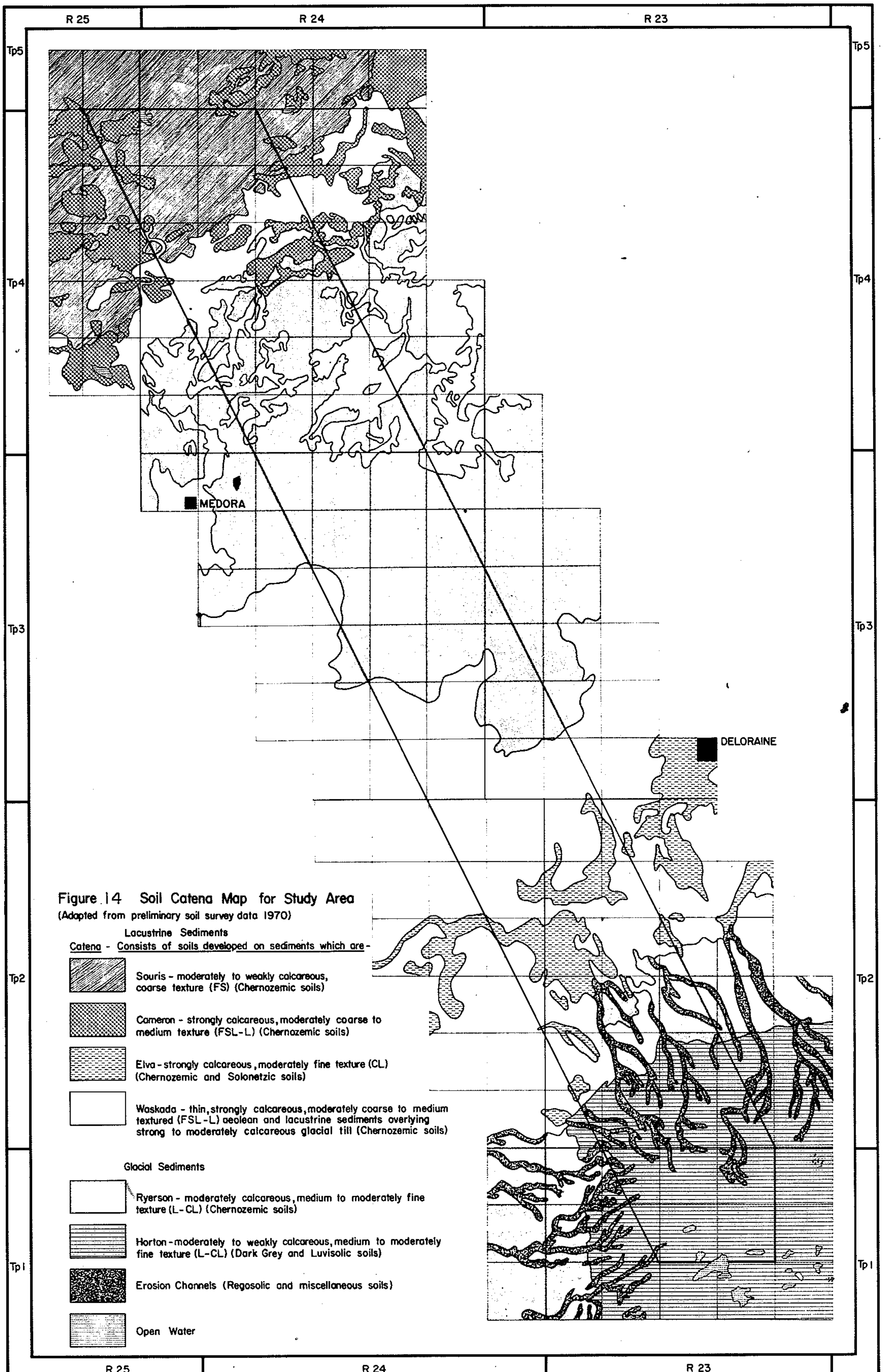


Figure 14 Soil Catena Map for Study Area
(Adapted from preliminary soil survey data 1970)

and weakly to non-calcareous. This indicates that leaching of salts and carbonate minerals has occurred in the soil profile.

The local relief in this area has resulted in some of the soils being moderately to severely eroded as a result of cultivation, rapid surface runoff, and exposure to the wind. Soils which have been severely eroded are not leached and strongly calcareous. These soils are evident in the landscape as light grey colors on the tops of knolls.

Although salinity in the near surface layers of the soils in this area is very uncommon, deeper soil investigations showed that considerable quantities of soluble salts (as indicated by the higher EC values) are present in the lower parts of the 10 foot drill samples (Appendix F-1, sites B1 and 4). Apparently, many of these salts have been leached from the solum of the soil and deposited at these greater depths by infiltrating water. The higher EC values (Appendix F-1) at site Y (Figure 5, p. 22) are considered to be accumulation as a result of leaching and subsequent deposition. The EC values for surface and subsurface soil samples at Nest 1, (Appendix F-2) indicate that the average values for EC of the regional till may be in the range of 3 to 4 mmho's/cm. It appears, therefore, that some redistribution of soluble salts has occurred in the near surface zone of this area of strong groundwater recharge.

In general, the major ion concentrations, the hydraulic head values, and the genetic soil properties of the Turtle Mountain Area indicate a dominantly downward movement of soil water and groundwater causing the majority of the genetic soils to be leached and eluviated.

Whitewater Basin

Hydraulic head. Hydraulic head data from piezometer Nests 2, 3, 15 and 11 were used to interpret the groundwater flow systems of Whitewater Basin. The hydrographs of the piezometers in Nests 3, 15 and 11 show small positive hydraulic gradients, whereas the hydrographs for the piezometers at 98 and 38 feet, in Nest 2, show strong positive hydraulic gradients. The water levels in the latter two piezometers are approximately 12 feet above the water table level. These strong, positive heads at the 98 and 38 foot depths below ground level are probably due to the close proximity of the piezometer intake zones to the vertical contact between the relatively permeable Boissevain Formation and the more compact glacial till (Figure 9, p. 38). The strong vertical flow gradients at Nest 2 are in direct contrast to the lateral flow in the Boissevain Formation. This alteration in direction of groundwater flow may be attributed to the abrupt change in permeability between the Boissevain Formation and the till. This is analogous to the situation of the aquifer pinchout at depth as described by Freeze and Witherspoon (1967) and shown in Figure 4, p. 11. The very low hydraulic gradient between the 38 and 98 foot piezometers is attributed to the influence of the permeable Basal Alluvial Unit and the underlying Riding Mountain shales. The energy of the water being discharged from the Boissevain Formation, in the vicinity of the intake zone of the bottom piezometer, is somewhat dissipated as some of the water moves into the Alluvial Unit and into the underlying shales.

In contrast, the shallow piezometers (18 and 10 foot depths) in Nest 2 have water levels which are similar to the water table as measured in the observation well. Small upward and downward heads in the shallow piezometers were observed at various times during the year. These small changes in head were attributed to water table fluctuations in response to precipitation.

The shallow piezometers in Nest 2 are located in or near a thin coarse gravel lens which is overlain in most cases by lacustrine clay loam sediments. The gravel lens pinches out in the northwestward part of the Whitewater Basin (Figure 9, p. 38). The lens appears to behave as a semi-confined aquifer. Rain causes the water table to rise in the zones where the lens is at or very near the ground surface. This causes the hydraulic head to increase throughout the lens and results in periodic artesian conditions in the shallow piezometers. This is detected by the small positive hydraulic gradients in the shallow piezometers at various times during the year.

At Nest 3, the piezometer at 78 feet is in the Basal Alluvial Unit and has a water level consistently below the level in the overlying piezometer. Since this piezometer is in the southeastern part of the Basal Alluvial Unit, it is probable that the hydraulic head is low because of energy dissipation as water moves out of the Boissevain Formation and crosses the narrow channel of till and enters the Basal Alluvial Unit (Figure 9, p. 38).

The piezometer at 38 feet also has a consistently negative hydraulic head gradient. Since this piezometer is very near the contact of the Basal Alluvial Unit and the overlying till, some energy loss is expected as the water moves into the upper part of the Alluvial Unit. This would result in a low hydraulic head. The general direction of groundwater flow, therefore, as indicated by the hydraulic head at 78 and 38 feet, is probably from the till into the upper part of the Basal Alluvial Unit.

The shallower piezometers at the 18, 10 and 6 foot levels respond similarly to those at Nest 2 and are probably influenced by flow in the semi-confined gravel aquifer.

The piezometer at 45 feet in Nest 15 was installed in a soft shaley alluvial deposit believed to be the lower end of the Basal Alluvial Unit. Although the water level in the piezometer was slow to respond after installation, it eventually attained a level above the water table, thereby indicating an upward component of flow. The upward flow is attributed to the northwestward pinchout of the Basal Alluvial Unit between the overlying till and underlying shale (Figure 9, p. 38). The pinchout of this confined moderately permeable unit causes artesian pressure to occur in the northwestern part of the deposit. This type of deposit would be expected to have a larger horizontal component of permeability than vertical component due to the thin horizontal layering which characterizes this type of deposit (W.A. Meneley, 1972, personal comm). It appears that water enters the southeastern end of this aquifer and flows laterally towards the pinchout zone, where the artesian pressure condition causes some of the flow to be diverted upward, thereby creating a groundwater discharge area in the overlying water table zone at a lower elevation.

The water level in the piezometer at 25 feet is slightly below the general water table level. This indicates a small downward gradient which may be the result of one or both of the following: the downward component of a divergent flow from the pinchout of the thin gravel lens above, or the influence of the downward flow as water enters the underlying Basal Alluvial Unit.

The piezometer in the shale at 75 feet in Nest 11 was installed in 1971, whereas the other piezometers in this nest were installed in 1970. It has water levels which are consistently lower than the overlying piezometer in the till and indicates that the movement of water is downward from the till into the shale.

The piezometer at 44 feet in Nest 11, generally has water levels which are above the water table in the fall and winter and below the water table during the spring and summer. This indicates that the upward gradient in the winter is reduced or reversed by the rise in the water table during the summer. On the other hand, the piezometer at 18 feet generally has a water level above the water table during the summer, and although there is a slight lag in the time of response for the water level in the piezometer, it still indicates an upward flow direction.

It appears, therefore, from the hydraulic head data of Nests 2, 3, 15 and 11, that the groundwater flow systems of the Whitewater Basin are basically controlled by stratigraphic changes in the geologic deposits. Whitewater Basin is characterized by groundwater discharge through the overlying glacial deposits. The pattern of hydraulic head in the four nests of piezometers is analogous to the pattern of groundwater flow through a confined partial aquifer as proposed by Freeze and Witherspoon (1967) (Figure 4, p. 11).

The flow from the Boissevain Formation is analogous to the flow from a semi-confined aquifer which pinches out at some depth below the surface. The flow is consequently diverted to areas of lower hydraulic head, in this case upward to the water table zone and downward into the Basal Alluvial Unit and underlying Riding Mountain shale.

Hydrochemistry. The hydrochemistry of the groundwater in the Whitewater Basin closely reflects the nature of the geologic units in which it occurs. The major ion concentrations in the two lowest piezometers of Nest 2 are similar to the major ion concentration of the bottom piezometer in Nest 10 which is in the Boissevain Formation (Figures 11 and 12, pp. 43 and 44). The EC values for the lowest piezometers in Nest 10 and 2 range from 2.4 to 1.6 mmho's/cm., respectively (Figure 13, p. 45). It appears, therefore, that the groundwater in the lowest piezometers of Nest 2 probably came from the Boissevain Formation. Due to the proximity of Nest 2 to this formation, it is probable that many of the original salts within the till have been leached and carried further along in the flow system. This would account for the present similarity of the major ion concentrations in the groundwater of these two deposits.

As for the shallow piezometers in Nest 2, the EC values (Figure 13, p. 45) are somewhat misleading. The Na^+ and Cl^- distributions (Figures 11 and 12, pp. 43 and 44) suggest that groundwater from the Turtle Mountain Formation probably does not contribute to the shallow groundwaters at Nest 2. It appears that lateral groundwater seepage from the upper part of the Boissevain Formation is the major source of water in the shallow groundwater zone. The concentrations of Ca^{++}, Mg^{++}, and $SO_4^{=}$ are probably the result of local surface water infiltration which subsequently mixes with water from the Boissevain Formation to produce the observed major ion chemistry.

The water chemistry in the upper piezometers at Nest 3 (Figures 11 and 12, pp. 43 and 44) shows a lateral and vertical increase in salt concentration from Nest 2. Water from the bottom piezometer has a much lower salt concentration than that in the overlying piezometers. These lower concentrations of Ca^{++}, Mg^{++} and $SO_4^{=}$ are attributed to the fact that the most probable source of groundwater for the Basal Alluvial Unit is the Boissevain Formation which contains small quantities of these ions. Lower concentrations of Ca^{++}, Mg^{++} and $SO_4^{=}$ might also be due to the small volume of till through which the water moves before it enters this unit. There may not be sufficient minerals present in this narrow channel of till to give high concentration of these ions. It is assumed that the soluble salts, which may have been present initially in the till, have been leached, and since the Basal Alluvial Unit is non-calcareous, low concentration of Ca^{++}, Mg^{++} and $SO_4^{=}$ would be expected at this site.

The large increase in the Na^{+} and Cl^{-} concentrations in water from deep piezometers in shale is attributed to the presence of large quantities of sodium chloride (NaCl) naturally found in these shaley materials.

The Cl^- concentration in the Basal Alluvial Unit is very high compared to values in the overlying till. Very little water therefore, moves upward from the Basal Alluvium through the till. Water in the till at Nest 3 must be derived mainly by lateral flow through the till from the vicinity of Nest 2.

The Mg^{++}, Na^{++}, $SO_4^=$ and Cl^- concentrations in the upper piezometer and well at Nest 15 are much greater than in Nest 3. The piezometer at 45 feet in Nest 15 was chemically contaminated by the cement grout, therefore, useable chemical data such as the major ion concentrations, pH and EC are not available.

Although the Cl^- concentration in the till at Nest 15 has increased from Nest 3, it is still rather low compared to typical Cl^- concentrations in the underlying Basal Alluvium. This suggests that there is no water discharged from the Basal Alluvial Unit into the till in the vicinity of Nest 15. The water in the till is picking up salts but most of the pick up of major ions is probably from the till itself. Ca^{++} and Mg^{++} concentrations are high in the till but very low in the shale and Basal Alluvial Unit. Therefore, probably no water from the till enters the Basal Alluvial Unit at Nest 15. The other possibility is lateral and upward water flow through the till from the area of Nest 3. The till probably contains sufficient soluble salts to account for the distribution of the major ions as shown in Figures 11 and 12, pp. 43 and 44. The concentrations of the major ions, therefore, is increasing along the path of groundwater flow.

The concentration of major ions decreases laterally to Nest 11 (Figures 11, 12, and 13, pp. 43, 44 and 45). The shape of the isopleths for Mg^{++}, $Na^{+} + K^{+}$, $SO_4^{=}$, HCO_3^{-}, and EC suggest that there is lateral water movement within the till. This could be due to a change in permeability resulting from an intertill contact or fracture zone. Although water chemistry at Nest 11 is affected by the constituents picked up from the Basal Alluvial Unit, it probably derives much of its character as it moves upward and laterally from the Basal Alluvial Unit.

Therefore, it appears that the interpretations of the groundwater chemistry data for Whitewater Basin are in agreement with the flow pattern interpretations based on the hydraulic head data.

The chemical composition of the groundwater being discharged from the Boissevain Formation increases in concentration as it moves through the tills and the Basal Alluvial Unit. The presence of the Basal Alluvial Unit extends the discharge area much further downslope than would normally be expected.

The thin, shallow, semi-confined, coarse gravel aquifer in the vicinity of Nests 2 and 3 facilitates lateral groundwater flow in the upper 15 feet of sediments. The pinchout of this gravel aquifer results in artesian water pressures in the pinchout area between Nests 3 and 11. The discharge from this aquifer is evident from the accumulation of soluble salts in the soil profile and on the soil surface.

At some point near midway between Nests 11 and 4 the predominant groundwater flow direction appears to become lateral as would be expected in a transitional area between discharge and recharge areas.

Soils. The majority of soils in Whitewater Basin are developed on stratified, saline, lacustrine sediments. Most of the soils are imperfectly drained and saline. The soils have predominantly Gleyed Orthic Black and saline Gleyed Carbonated Rego Black profiles and are mapped as members of the Elva and Waskada Catenas (Figure 14, p. 54). The occurrence of well developed Solonetzic soils is also common in this area.

A detailed field inspection in the vicinity of Nest 3 revealed that the distribution of salinity was related to hydrologic conditions of the near-surface gravel aquifer and to textural variations inherent in lacustrine sediments. The presence of thin, coarse textured layers appears to halt the upward movement of salts at the contact of these lenses, resulting in a relatively non-saline soil profile above them (Plate 7, Appendix G). Where these coarse textured layers are absent, salt crystals were evident in the solum of the soils and white salt crusts were prevalent on the ground surface. Figure 15 schematically represents observations made in the field. The arrows are interpretations of the most probable direction of water flow through the saturated and unsaturated soil zones. The hydrologic data for Nest 2 and 3, as previously discussed, indicate that Whitewater Basin is characterized by generally lateral and upward groundwater flow, and that there is partially confined lateral flow through the pinched out gravel aquifer. The interpretations of the upward flow of water in the unsaturated soil zone are based on the

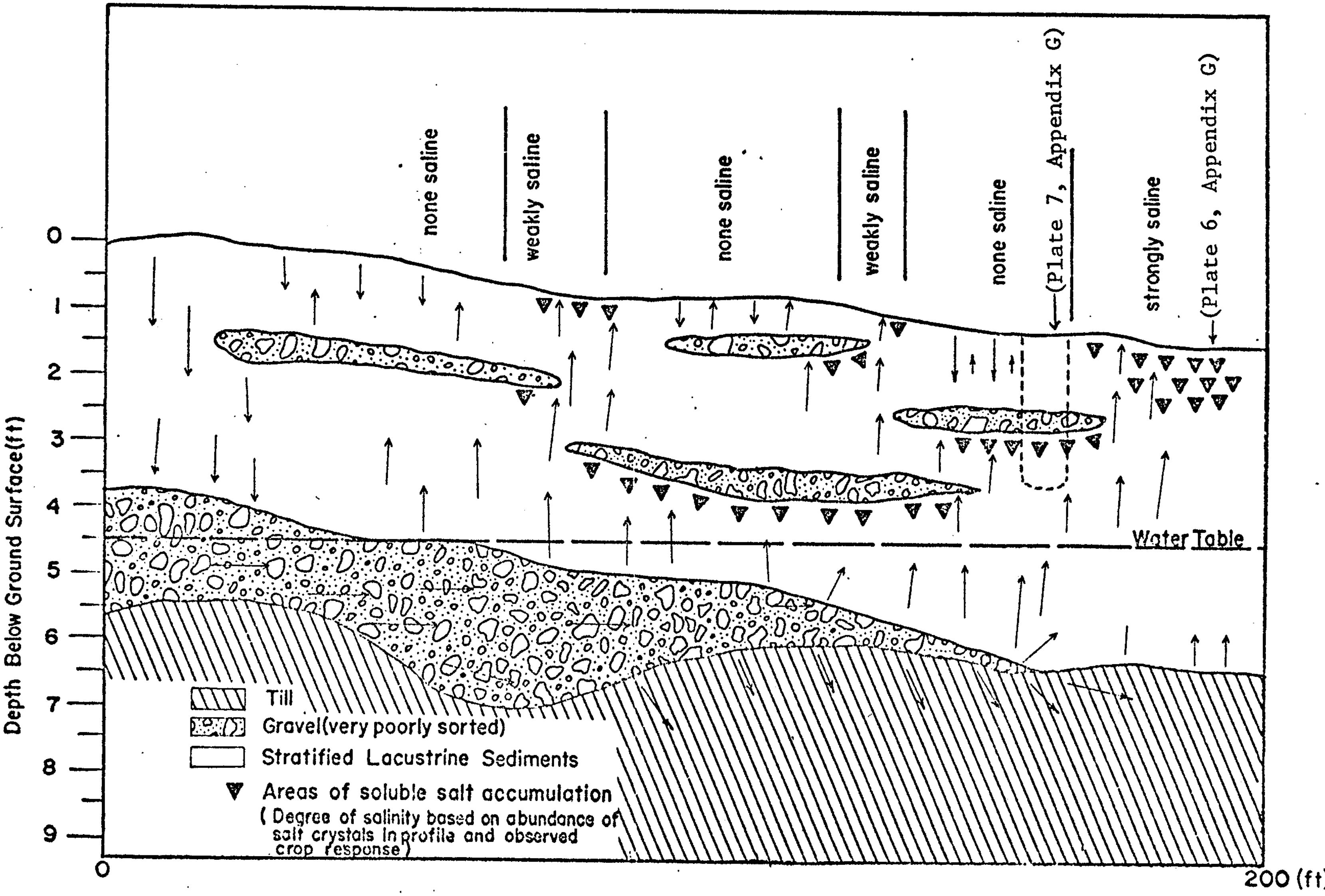


Figure 15. Schematic showing the occurrence of thin, coarse textured (gravelly) lenses in the sediments of Whitewater Basin near piezometer nest 3. Arrows indicate probable direction of water movement.

flow characteristics as discussed in Baver (1963, p. 252) and the principles of capillary movement of water and salt solutions in stratified soils as discussed by Felitsiant (1961).

It was observed in several soil profiles in areas under low artesian pressures, that the presence or absence of thin, coarse, gravelly layers at some point in the unsaturated soil zone, was very significant in determining the occurrence, distribution and the concentration of soluble salts.

It appears, therefore, that large contrasts in the texture of different soil layers determines the position of salt deposition within the soil profile. Coarse gravelly layers tend to act as semi-impermeable boundaries at which point the capillarity is abruptly broken. This results in salts being deposited at the bottom of the coarse textured layers. Areas which had no coarse textured layers commonly had white salt crystals at or near the surface.

On the other hand, soil areas not under small upward flow gradients, and lacking these coarse textured lenses, tend to have no salinity. They are leached and usually have moderately well drained profiles.

The genesis of soils in the Whitewater Basin, therefore, is strongly influenced by surficial geology, in particular, the micro-stratigraphic and textural variations, and the groundwater flow pattern in the upper part of the glacial drift. The geologic and groundwater conditions, to a large extent, control the movement of water and salts in the unsaturated zone above the water table.

Leighton Area

Hydraulic head. The hydraulic head in the Leighton Area was determined at Nests 4 and 5. With the exception of the piezometer at 93 feet, the hydraulic heads in the remaining piezometers at Nest 4 are generally coincident with the water table (Appendix C).

The lack of appreciable vertical hydraulic gradients at this Nest is indicative of a zone of lateral groundwater flow. The piezometer at 93 feet has a consistently downward head indicating that the most probable direction of groundwater movement is downward from the till to the underlying shale.

The hydraulic head at Nest 5 is more typical of groundwater recharge. The piezometer at 93 feet has a very stable head of approximately 6 feet below average water table level. Although the piezometer at 48 feet was initially slow to respond it attained a head of approximately 3 feet below average water table level during 1971. The water levels in piezometers at 28 and 15 feet correspond closely to the water table, generally indicating zero head. This condition of downward head in the deep piezometers and zero head in the shallow piezometers, suggests that water movement is downward in the lower part of the till and lateral in the upper part of the till.

The bedrock shale in the Leighton area has stable piezometer water levels below that in the overlying till. Water therefore, tends to move downward from the till into the shale. Upon entering the shale, the main water flow is probably horizontal towards the northwest.

Hydrochemistry. There is a significant decrease in major ion concentration of the groundwater between Nest 11 and Nest 4, indicating that the flow system must have changed. The hydrochemistry at Nest 4 is probably the result of lateral flow in the transition zone between discharge at Nest 11 and recharge at Nest 5.

Because the water at Nest 4 has larger ion concentrations than Nest 5 (Figures 11 and 12, pp. 43 and 44), water must move downward between 4 and 5, and therefore not reach Nest 5. The water at Nest 5 is recharged in the vicinity of Nest 5 and moves with a significant downward component. The increase in the Na^+ and Cl^- concentration with increasing depth below ground surface is more typical of the values which could be derived by downward flow through the till than from flow through deposits of shale.

The lateral distribution pattern of Ca^{++}, Mg^{++}, and $SO_4^{=}$ indicates that there is a slight irregularity in the normal downward flow of groundwater in this recharge area. This lateral distribution of ions in a zone near the 20 to 30 foot depth between Nests 4 and 5, suggests that the lateral component of groundwater flow is larger than the vertical component of flow. A zone in which the horizontal permeability is greater than the vertical permeability would produce this type of groundwater flow. A change in the nature of the permeability of a zone within the till could occur as a contact zone between two units of till or as the result of glacial thrusting (W.A. Menelley, 1972, personal comm.). Lateral groundwater flow in this zone is also indicated by the lack of vertical hydraulic head in the shallow piezometers of Nest 5.

Soils. The soils in the Leighton Area are mapped primarily as members of the Waskada Catena (Figure 14, p. 54). These soils are developed on a thin, discontinuous, medium textured aeolian and lacustrine deposit overlying medium to moderately fine (loam to clay loam) textured glacial till. These soils are generally found in juxtaposition to the till soils of the Ryerson Catena.

The majority of these soils are well to moderately well drained Orthic Blacks. Most of the surface runoff water collects in shallow closed depressions. There are a few short ephemeral streams which disappear before they leave the area (Figure 6, p. 27). Therefore, most of the surface water in this area is either taken in directly by the soils or is collected in shallow stream beds and depressions. Water is lost from these depressions by evaporation from the water surface, evapotranspiration from the surrounding area, and by infiltration to the groundwater.

A detailed examination of the soils in the vicinity of Nest 5 shows that the shallow depressions in the upper part of the landscape are generally characterized by Gleyed Eluviated Black and Orthic Black profiles; depressions at slightly lower topographic positions by Humic Eluviated Gleysols and Orthic Humic Gleysols; and the lowest depressions by Saline Gleyed Carbonated Rego Black and Saline Carbonated Rego Humic Gleysols (Figure 16). An interpretation of this distribution of soil types suggests that soils in depressional areas in the upper part of the landscape form as a result of considerable leaching by infiltrating water and are indicative of local groundwater recharge conditions. Soils in the lower parts of the

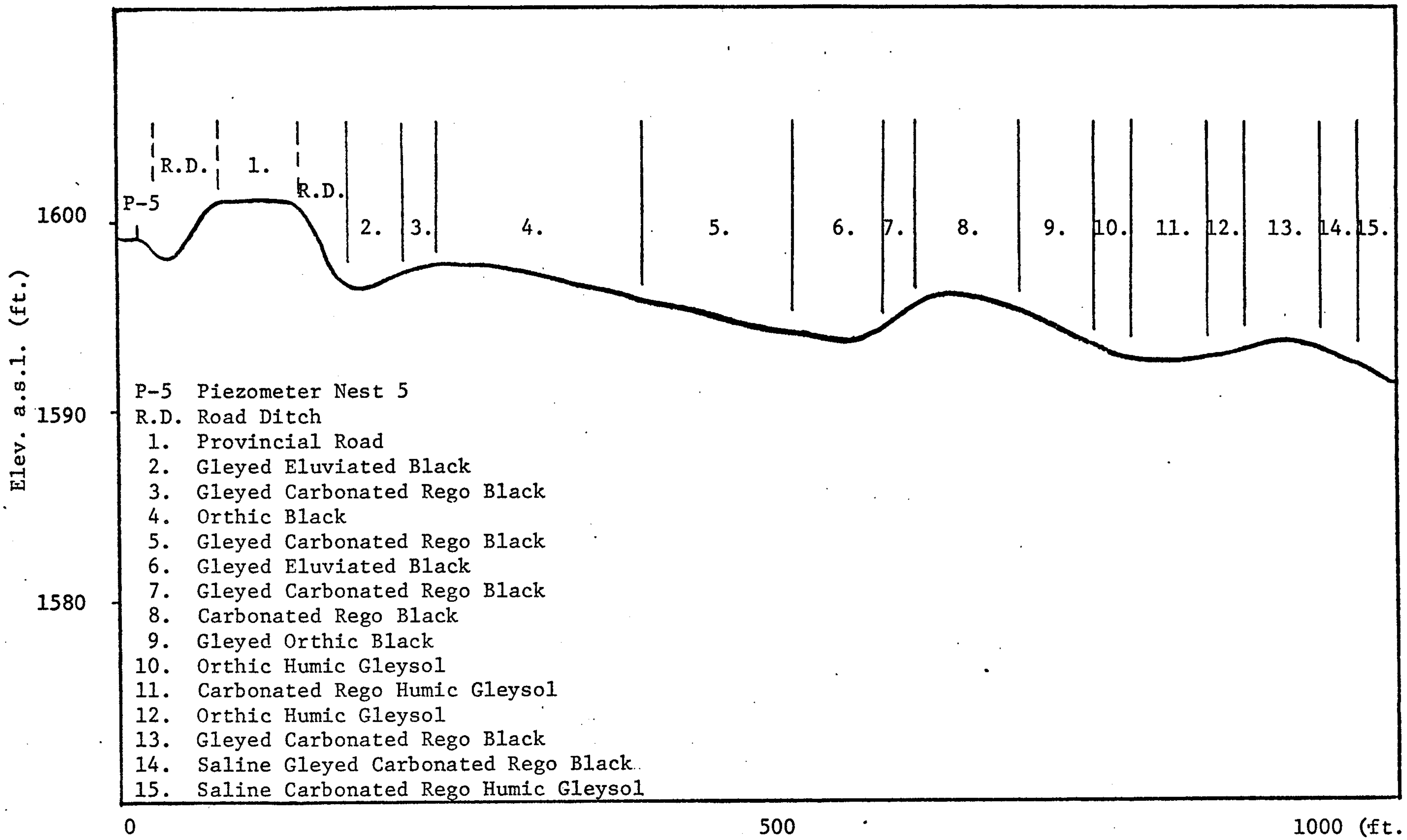


Figure 16. Schematic profile showing observed genetic soil relations in glacial till in a groundwater recharge area.

landscape which are locally more moist or humid are carbonated, saline, and morphologically show no signs of leaching. Much of the soil water loss is attributed to evaporation. These soils are typical of areas with high water tables, saline groundwaters and are indicative of local groundwater discharge conditions.

Many of the soils on the upper slopes and knoll positions are carbonated and appear as greyish white eroded areas in the landscape. These soils are not leached, due to a more rapid surface runoff which leaves very little water for infiltration and leaching. Any infiltration that does occur is likely lost by evapotranspiration. It is probable that very little or no water enters the water table as a result of normal infiltration through the soils on slopes and knolls because of surface runoff.

Thus, while the overall groundwater flow in the Leighton area tends to be lateral and downward, micro-relief creates significant local differences that are reflected in the soil morphology.

Medora Area

The hydrologic segment designated as the Medora Area is interpreted as an area of groundwater discharge from very shallow depths in the glacial till. Below the shallow discharge zone there is lateral flow and downward flow to the bedrock shale. These interpretations are based on the rather complex pattern of hydraulic head and major ion distributions.

The most important evidence supporting the shallow groundwater discharge interpretation is that the concentrations of Na^{+}, Ca^{++}, Mg^{++}, Cl^{-}, and $SO_4^{=}$ are very high in the shallow piezometers at

Nests 6, 12, and 14 (Figures 11 and 12, pp. 43 and 44); in fact, they are among the highest concentrations encountered in the entire study area. The contrast between the dilute shallow groundwater chemistry in the Leighton Recharge Area and the saline discharge segment of the Medora Area is very distinct.

Hydraulic head. The cause of the hydrochemical pattern becomes more clear by considering the hydraulic head distribution. The head in the bedrock shale is consistently much lower than in the overlying till, indicating that flow in the deeper part of the till has a downward component. The discharging conditions in the upper most part of the till must, therefore, be caused by a zone of higher permeability. This causes the flow to be channelled laterally northwestward under confined pressure conditions producing diverging flow upward and downward from the channelling zone or zone of lateral flow. If this condition exists, there must be higher hydraulic head in the lateral flow or channelling zone than at the water table above the zone and in the till below the zone. This situation is confirmed by the hydraulic heads in the piezometers at Nest 6 where the 15 foot piezometer commonly has water levels above the water in the 10 foot water table well and often slightly above the levels in the underlying piezometers at 23 feet and 38 feet. These water level relations indicate that a higher head zone occurs between 15 and 23 feet and, therefore, a higher permeability within this depth interval. Although not detected by obvious changes in sample material obtained during drilling, it is likely that the higher permeability zone is associated with the contact between two different till units. As indicated previously, two tills have been observed in the region to the east of the study area by Kohut (1972).

The shallow discharging gradients are not detected in Nest 12 and 14, presumably because these nests do not have piezometers at the appropriate shallow depth interval below the water table wells.

The shallow lateral groundwater flow in the upper part of the till of the Leighton Recharge Area, therefore, appears to be continuous into the Medora Discharge Area. Due to the decreasing elevation of the water table and the increased volume of water from recharge in the Leighton Area, this lateral groundwater flow becomes a semi-confined divergent flow with part of the water flowing upwards to the water table and part flowing downwards from the lateral flow zone. The dominant trend in the interior of the apparent inter-till zone is probably lateral flow towards the northwest.

Hydrochemistry. The hydrochemistry of the Medora Area (Figures 11 and 12, pp. 43 and 44) shows that the concentration of the major ion chemistry decreases with increasing depth*. This distribution is typical of groundwater discharge areas. However, the distribution of Cl^- between Nest 6 and 14 reflects a zone of significant lateral flow within the upper till. The concentration of Cl^- increases upwards and downwards in the vicinity of the 25 foot depth of Nest 14. The lateral flow is indicated by the horizontal increase from 20.0 meq./l. at 23 feet in Nest 6 to 36.7 meq./l. at 25 feet in Nest 14. The concentration of Cl^- subsequently

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* The groundwater samples from the 35 foot depth in Nest 12 and the 50 foot depth in Nest 14 were contaminated with cement and, therefore, no useable hydrochemical data is available.

increases upward to the water table and downward, away from the 25 foot depth.

The concentrations of the other major ions show significant upward increases at shallow depths near the water table. The lateral flow zone in the till, as indicated by the Cl^- concentrations, is not readily apparent from the Ca^{++}, Mg^{++}, or $SO_4^=$ concentrations; however, the concentration values are much lower below the 25 foot depth than near the water table.

The Cl^- concentrations increase slightly across the till-shale contact suggesting that water probably does move into the shale. The distribution of Cl^-, therefore, is in agreement with the hydraulic head data which showed lower heads in the underlying shale.

The other ions, however, behave differently. The concentrations of Ca^{++}, Mg^{++}, and $SO_4^=$ decrease across the till-shale contact, while Na^+ shows corresponding increases. The lower values of Ca^{++}, Mg^{++}, and $SO_4^=$ in the shale indicate that if water from the till enters the shale, as indicated by the hydraulic gradients near the till-shale contact, large concentrations of these ions must be lost through various mechanisms such as redox reactions and cation exchange.

The Na^+ concentration which is much greater than the Cl^- concentration can be attributed to the exchange mechanisms. As Ca^{++} and Mg^{++} are absorbed onto exchange sites in the shale, Na^+ is displaced. This would account for the abrupt decrease in Ca^{++} and Mg^{++} concentrations within the shale and at the same time account for some of the excess Na^+ ($Na^+ - Cl^- =$ excess Na^+). The accompanying decrease in $SO_4^=$ concentration is probably due to reduction processes within the shale. The odor of hydrogen sulfide (H_2S) gas was very evident in the piezometers in this area, particularly the piezometers in the shale.

It appears, therefore, that the pattern of downward flow which is characteristic of the Leighton Area changes to a more complex pattern of divergent groundwater flow in the Medora Area. Both hydraulic head and hydrochemistry patterns indicate the presence of a more permeable inter-till lateral flow zone with diverging upward flow to the water table and downward flow to the lower tills.

Soils. The majority of soils in the Medora Area which are developed on moderately calcareous, medium to moderately fine textured glacial till are mapped as members of the Ryerson Catena (Figure 14, p. 54). Many of the well drained, upper slope soils have eroded Rego Black and Calcareous Black profiles, while the soils on lower slopes are generally imperfectly drained, carbonated and occasionally saline.

Saline soils commonly occur in rings around sloughs and depressional areas. Areas of higher local relief generally have salts leached out of the solum. However, in these areas salts are quite conspicuous at lower depths in the soil profile.

Due to a slight increase in local relief, the surface runoff is generally more rapid than that of the Leighton Area. Weak dendritic drainage patterns (Figure 7, p. 30) have developed probably as a result of the more rapid runoff. Most of the groundwater that is discharged in this area probably collects in the deeper depressions and drainage channels and forms small, semi-permanent water bodies and sloughs. Saline Carbonated Rego Humic Gleysols are generally typical of the soils in local discharge areas.

In general, it is the microtopography which is the dominant factor influencing surface runoff, soil drainage and soil salinity of the Medora Area.

Medora Ridge

Hydraulic head. The hydraulic head data for this area was obtained at Nest 7. The hydrographs indicate that the water level in the piezometers quickly responds to changes in the overlying water table. This suggests that the groundwater flow system in this area is relatively dynamic.

The piezometer at 28 feet has the largest range in water level fluctuations. Strong positive gradients were measured during the winter and small negative gradients were measured during the summer. The drill log for the piezometer at 28 feet suggests that the piezometer intake may be situated in a zone of slightly different permeability. This could cause the strong positive hydraulic gradient encountered at this site.

A similar pattern with a much smaller range in water level fluctuation was measured in the overlying piezometers. The duration and magnitude of the positive gradients, however, are much less than the underlying piezometer at 28 feet. It appears that during the spring, summer and fall, the dominant flow of water in the upper part of the shale and overlying till is basically downward. However, in the winter, it appears that the most probable direction of water movement is upward from the shale to the contact of the overlying till.

The lack of ponded surface water, the lack of soluble salts in the upper soil, and the slope of the bedrock topography indicate that any upward moving groundwater from the shale probably flows laterally, either towards the Medora Area or to the Souris Escarpment Area, along the till-shale contact zone.

Hydrochemistry. The degree of mineralization of the groundwater in all piezometers is very low as is indicated by EC values of 1.2 mmho's/cm. or less (Figure 13, p. 45). These low EC values are probably indicative of a moderately shallow freshwater flow system.

The hydrochemistry of this site (Figures 11 and 12, pp. 43 and 44) shows that the concentrations of Na^{+} and Cl^{-} increase with depth. The Cl^{-} in particular, shows distinctive increases towards the Souris Escarpment Area and also towards the Medora Area, indicating the probable direction of flow.

As water infiltrates the thin overlying till, some Ca^{++}, Mg^{++}, and $SO_4^{=}$ will be picked up; however, as it moves into the shale in the groundwater zone, cation exchange mechanisms cause a decrease in Ca^{++} and Mg^{++} concentration and results in a corresponding increase in Na^{+} concentration. On the other hand, $SO_4^{=}$ probably undergoes reduction to H_2S gas.

The larger concentrations of ions in the piezometer at 28 feet suggest that it could be a part of a slightly different flow system. This would be in agreement with the trends indicated by the hydraulic head data.

However, on the basis of the hydraulic head and hydrochemistry and the lack of surface soil salinity this area is characteristic of downward moving groundwater, and the area is referred to as the Medora Ridge Recharge Area.

Soils. The soils in the Medora Ridge Area are developed primarily on strongly calcareous, medium to moderately fine textured glacial till. The soils have been mapped as members of the Ryerson Catena (Figure 14, p. 54). Soils of the Waskada Catena commonly occur in depressional areas.

Soils in the immediate vicinity of Nest 7 are Gleyed Eluviated Blacks grading upslope to Orthic Blacks and finally to Rego Blacks on the top of the knoll. The depressional areas at lower elevations in the area are commonly saline, and imperfect to poorly drained. These depressional soils are usually only 1 to 3 feet deep, overlying the Riding Mountain shale. Saline Gleyed Carbonated Rego Black and Saline Carbonated Rego Humic Gleysolic soils are the characteristic profiles of the thin deposits in these depressional areas.

Surface water runoff from this area occurs in small stream meanders which originate in the Medora Area and empty into the Souris Plain.

Souris Escarpment

Hydraulic head. The piezometers at 20 and 40 feet in Nest 13 (Appendix C) generally have negative hydraulic heads. This situation appears to be caused by the occurrence of shale which is relatively permeable, mainly in the horizontal direction. Flow in the shale appears to be channelled laterally to discharge zones along the escarpment face. This would explain the negative hydraulic gradients at Nest 13.

Nest 8 is located near the base of the Souris Escarpment Area (Figure 9, p. 38). The hydraulic head in the shale at this site, as measured by a piezometer at 48 feet, is relatively stable and consistently below the level in the overlying piezometer. The piezometer at 28 feet, however, has a positive gradient during the fall and winter and a small negative gradient during the spring and summer. The hydrograph generally has the same response as the water table which indicates that it is a relatively dynamic system.

The piezometers at 10 and 18 feet generally have positive gradients through most of the year. This condition is the result of lateral groundwater discharge from the shale of the escarpment.

In general, the hydraulic head data for the Souris Escarpment Area indicates that water is being discharged laterally from the shale to the till in the vicinity of Nest 13. The discharged water subsequently flows downslope along the till contact zone and into the till at the bottom of the slope. This downslope flow of water creates small positive gradients in the shallow piezometers at Nest 8 and results in the discharge of saline groundwater through the till.

Hydrochemistry. The distribution patterns of the major ions (Figures 11 and 12, pp. 43 and 44) show that concentrations increase towards the face of the escarpment and downslope into the till. The Na^+ concentration at the water table in Nest 13 is high (504 meq./l.), suggesting that much of the groundwater probably comes from the shales. Assuming that the distribution of Cl^- is indicative of the direction of flow, it appears that water moves downward through the till of the Medora Ridge Recharge Area and enters the shale. The water apparently moves laterally through the shale and is subsequently discharged at the escarpment face. This small scale flow system would explain the higher than average Ca^{++}, Mg^{++}, and $SO_4^{=}$ concentrations in the shale at 20 feet. These ions were picked up in the till and have been moved down into the shale due to the dynamic nature of the flow regime.

The major ion concentration is much larger at Nest 8, however, and appears to be the result of groundwater discharge from the shale due to the high concentrations of Na^+ and Cl^-. Groundwater, moving laterally downslope from the face of the escarpment, has probably introduced and concentrated these soluble salts in the groundwater at Nest 8. In general, the concentration and distribution of the various ions tend to substantiate the interpretation of the hydraulic head data. This area, therefore, is referred to as the Souris Escarpment Lateral Discharge Area.

Soils. The soils in the upper part of the Souris Escarpment Discharge Area are developed on strongly calcareous, medium to moderately fine textured glacial till. The well drained soils in the area have Rego Black and Orthic Black profiles and are mapped as members of the Ryerson Catena (Figure 14, p. 54). There are also thin soils overlying the shale in this area, which occur near the face of the escarpment. Some of these soils have little profile development, probably due to their topographic position, whereas others tend to have accumulations of salts and very little profile development mainly due to laterally discharging groundwater. These soils occupy only a very small portion of the area and therefore, have not been shown on the map (Figure 14, p. 54).

The majority of the soils at the base of the escarpment are developed on strongly calcareous, dominantly medium to moderately coarse textured lacustrine sediments. The medium textured soils are mapped as members of the Waskada and Cameron Catenas, whereas the moderately coarse textured soils are mapped as members of the Souris Catena (Figure 14, p. 54). The dominant subgroups in both of these catenas in this area are the Gleyed Carbonated Rego Blacks, Saline Gleyed Carbonated Rego Blacks and Carbonated Rego Humic Gleysols.

Most of these lacustrine soils have carbonated and calcareous profiles and many are moderately saline. The majority of these soils are imperfectly drained, some are poorly drained, and many have white salt crusts on the surface. In general, these profile characteristics are typical of soils in groundwater discharge areas.

Souris Plain

Hydraulic head. Nest 9 is the only piezometer nest located in the Souris Plain part of the groundwater flow system. The piezometer at 57 feet intersects the Riding Mountain shale and, except in the spring and summer, generally has a positive gradient. A positive gradient in the shale in this area indicates that the most probable direction of flow would be from the underlying shale. This condition could not be confirmed since no piezometers were installed at the shale contact.

The overlying piezometers responded much more quickly to changes in the water table, indicating that the flow regime in the upper 28 feet is very dynamic. The hydrographs for piezometers at 28, 18, 15, and 7 feet (Appendix C) show predominantly zero gradient. This is an indication of lateral groundwater flow.

Hydrochemistry. The hydrochemistry of the Souris Plain Area indicates that the most probable direction of groundwater flow occurs in the direction of decreasing concentration of the major ions (Figures 11 and 12, pp. 43 and 44). This decrease in ion concentration could be due to a dilution of the water as it flows laterally away from the major source of the ions; in this case, the shale and till of the Souris Escarpment. Considerably less soluble salts are expected to occur in the coarse textured surface deposits and also rapid infiltration of rain and fresh surface waters would help to dilute the saline groundwater.

It appears that there is a general tendency for the lateral flow to proceed more rapidly along zones of contact between the various geologic deposits. It is also apparent from the hydrochemical data, that upward seepage from the underlying shale is small compared to the lateral flow in the till and overlying sediments. This part of the flow system, therefore, is referred to as the Souris Plain Lateral Flow Area.

Soils. The majority of the soils in the Souris Plain Area are developed on moderately to weakly calcareous coarse textured lacustrine sand and are mapped as members of the Souris Catena. Other soils which are developed on strongly calcareous, moderately coarse to medium textured lacustrine sediments are mapped as members of the Cameron Catena.

Most of the soils regardless of texture, are imperfectly drained and generally have been mapped as Gleyed Carbonated Rego Black soils. Many of the soils contain soluble salts which are evident as small white crystals in the profile and as thin white crystalline crusts on the surface. Coarse textured sandy soils with solonetzic morphology and chemistry are also common in this area. The presence of the large concentrations of Na^+ in these silica sands is attributed to the flow of groundwater from the shale of the Souris Escarpment.

The high Na^+ in the groundwaters may have been the source of Na^+ that is now found in the solonetzic soils. Soil salinity and water tables may have been much higher at one time; however, lower water tables in more recent times may have initiated the formation of these sandy solonetzic soils.

The well and moderately well drained soils are found associated with areas of higher local relief. The duned areas, in particular, generally have Eroded Rego Black and Regosolic profiles.

The soils in the Souris Plain Area are generally influenced by high water tables (av. 2.9 feet at Nest 9). This can be observed in water table wells, sloughs and road ditches. Many of the sloughs and ditches are deep enough to intercept the water table and as a result they contain water for longer periods during the year. These areas are generally characterized by Saline Carbonated Rego Humic Gleysolic profiles.

General Discussion of the Hydrogeologic Influence on Genetic Soil Distribution

The hydrological investigation has shown that the study area is comprised of seven different hydrologic flow regimes. Each of these seven areas has been characterized in terms of hydraulic head and hydrochemical data, and general soil distribution. The genetic soil profiles found in each of the seven areas can be directly related to the conditions of groundwater flow which in turn are affected by the characteristics of topography and geology.

The genetic and morphologic properties of the soils in the Turtle Mountain Area are a reflection of strong groundwater recharge. Most of the soils in this area in the well and imperfectly drained positions are leached of soluble salts and carbonates and many of them are moderately to strongly eluviated. Poorly drained soils occupying depressional positions which retain free water for only short periods are generally strongly eluviated. In depressions which retain free water most of the year, the soils are generally leached of soluble salts and carbonates but show little or no signs of eluviation. This lack of carbonates and soluble salts in the poorly drained soils of this area is probably the most significant factor when compared to the poorly drained soils in the other hydrologic areas. In the Leighton and Medora Ridge Recharge Areas the majority of the soils are leached and eluviated. However, some of the poorly drained soils in depressions have not been leached of salts or carbonates. This presence of soluble salts and carbonates is probably one of the most notable features of soil profile development in comparison to the Turtle Mountain Area. The lack of leaching in some of the poorly drained depressional soils in the Leighton and Medora Ridge Areas suggests that these areas are not characterized by strong groundwater recharge as is the case in the Turtle Mountain Area. It has been shown that the recharge gradient in the Turtle Mountain Area is much greater than that in the Leighton and Medora Ridge Area.

The distribution of genetic soils in the Leighton and Medora Ridge Recharge and the Medora Discharge Areas is largely dependent upon local topography. The micro-relief in each area has resulted in a complex configuration of the upper part of the larger flow system, producing recurring sequences of small recharge and discharge flow regimes. These local flow systems are reflected in the genetic and morphologic properties of the soil. For example, Gleyed Eluviated Black and Humic Eluviated Gleysols are indicative of local groundwater recharge, whereas the Saline Gleyed Carbonated Rego Black and Carbonated Rego Humic Gleysols are characteristic of local groundwater discharge. The larger hydrologic areas are characterized by the predominance of various profile types. That is, recharge areas always have higher percentages of leached and eluviated soils, whereas discharge areas usually have higher percentages of saline and carbonated soils. Small permanent water bodies are also more common in discharge areas.

The distribution of soil profile types also varies between discharge areas. The Whitewater Basin, Medora, and Souris Escarpment areas are characterized by discharging groundwater but have different types of soil profiles. For example, Solonetzic soils are quite common in the Whitewater Basin, whereas no Solonetzic soils were found in either of the other two areas. A possible reason for the lack of Solonetzic soils in the Medora Area might be the lower quantity of Na^+ salts in the groundwater. Since Na^+ is a major characteristic of Solonetzic soils and since the groundwater being discharged in the area does not encounter any Na^+ rich deposits, it appears unlikely that Solonetzic soils would develop. The groundwater in the Souris Escarpment on the other hand does have high concentrations of Na^+ obtained from lateral flow through the Riding Mountain Shales. However, it appears that Solonetzic soils have not developed in this area either, possibly because it still is a very active discharge area. The Solonetzic soils in the Whitewater Basin on the other hand, are generally found in areas where buried gravel lenses and high water tables result in only very weak discharge or even lateral flow in the upper 6 to 10 feet of sediments. This could account for the Na^+ salts being transported into the soil and also provide an opportunity for some leaching to occur as the water table level decreases.

The Souris Plain is dominantly an area of lateral groundwater flow. A comparison of this area to the other hydrologic areas on the basis of soils suggests that it may have certain groundwater conditions in common with the Whitewater Basin Area with regard to the development of Solonetzic soil profiles. The Na^+ salts in the Souris Plain very likely originated in the Souris Escarpment Area and were transported into the Plain Area by lateral groundwater flow. The subsequent development of the Solonetzic soils in this area, therefore, was likely the result of a fluctuating high water table which contributed the Na^+ salts to the soil zone. In this respect, it is similar to the Whitewater Basin.

In general, it is difficult to compare the genetic soil distribution patterns from one area to the next because the distribution pattern within each area has formed as a result of slightly different hydrogeologic parameters. For example, the nature of the bedrock geology can alter the direction of a large flow system, whereas the micro-stratigraphy and micro-relief can alter the direction of local flow systems.

The establishment of general hydrogeological and pedological relations, such as leached soils indicate recharge and saline soils indicate discharge, is very common. However, on the basis of the genetic and morphological properties of a soil profile, it is usually only the local flow system which can be identified. The extent of larger flow regimes can only be approximated by the areal distribution of soil profile patterns. It should be remembered, therefore, that specific soil subgroups (profiles) are only indicative of local site conditions of groundwater flow and that it is the overall pattern of the subgroup distribution that must be used to describe the larger hydrologic areas.

Another point to be considered is that soils and groundwater exist in a dynamic relationship and that the properties and characteristics of the present soils may not necessarily be indicative of the present groundwater conditions. The evolution and development of soil subgroups, therefore, generally follows a sequence or cycle of events which invariably are directly associated with the hydrogeologic conditions of the area.

II SOIL SALINITY AND HYDROLOGY

It has long been recognized that areas of groundwater discharge are invariably associated with areas of saline soils. Therefore, since this hydrologic study was conducted in an area where the occurrence of saline soil is very common, some attention was devoted to determining the conditions controlling salinity, the degree and distribution of salinity, and the source of the soluble salts responsible for the salinity. To facilitate this discussion, it is first necessary to define the following terms: soil salinity, subsoil salinity, saturated soil salinity and groundwater salinity.

Salinity

The term salinity as used by soil scientists denotes the presence of soluble salts in a medium. The quantity of salt is usually expressed in terms of electrical conductivity. A soil is considered to be saline if a solution extracted from a saturated paste has an electrical conductivity value of 4 mmho's/cm. or more.

The System of Soil Classification for Canada (1970) groups saline soils into the following classes: i) non-saline soils which have an electrical conductivity less than 4 mmho's/cm., ii) weakly saline soils which have an electrical conductivity in the range of 4 to 8 mmho's/cm., iii) moderately saline soils which have an electrical conductivity in the range of 8 to 15 mmhos/cm., and iv) strongly saline soils which have an electrical conductivity greater than 15 mmhos/cm. In addition to the quantity of soluble salt that has to be present, a saline soil must have the salts present in the solum and/or parent material.

The term sub-soil is used here to refer to the zone between the bottom of the soil profile and the top of the water table. The degree of sub-soil salinity as defined here recognizes the same criteria for electrical conductivity as previously stated for the four classes of surface soil salinity: none, weak, moderate and strong.

Saturated soil salinity refers to the salinity of soil samples collected from various depths below the water table during the drilling program. The criteria for determining class of salinity as based on the criteria established in the System of Soil Classification for Canada (1970), is none, weak, moderate and strong as previously defined for soil profile or surface soil salinity.

Groundwater salinity can be defined in terms of the quantity of dissolved mineral constituents which it contains. The following is the classification of groundwater based on the total dissolved mineral constituents which is used by the International Hydrologic Decade and by the United Nations Economic Scientific and Cultural Organization:

Classification	TDS	Approx. EC (mmhos/cm.)
Fresh	less than 1000 mg/litre	<1.4
Slightly Brackish	1000 to 3000 mg/litre	1.4 to 4.3
Brackish	3000 to 10,000 mg/litre	4.3 to 14
Saline	10,000 to 35,000 mg/litre	14 to 50
Brines	more than 35,000 mg/litre	>50

(For comparison, rain has about 15 mg/litre; sea water has 35,000 mg/litre)

Salinity Relations

The standard method of determining soil salinity as described in the USDA Handbook No. 60 is based on electrical conductivity measurements of saturated soil paste extracts. According to the USDA Handbook No. 60, the advantage of the saturation extract method of measuring salinity lies in its direct relationship to the field moisture range. The soluble salt concentration in the saturation extract tends to be about one half of the concentration of the soil solution at the upper end of the field moisture range (approximately field capacity) and about one quarter of the concentration that the soil would have at the lower, dry end of the field moisture range (permanent wilting point). Therefore, EC values obtained by the saturation extract method, on soil samples from the unsaturated soil zone, will generally be one half to one quarter of the EC value of the soil solution in the unsaturated soil. On the other hand, soil below the water table is generally assumed to be saturated and, therefore, the values of EC from soil extracts should be very similar or equivalent to the EC of soil water or groundwater providing that no water was added to the sample and no water was lost during sampling.

In general, measurements of EC for each of the four previously defined zones in an area with a uniform vertical distribution of salinity from the soil surface to the saturated soil zone could be expected to show the following relationship:

$$EC_{(soil\ surf.)} < EC_{(sub\text{-}soil)} < EC_{(sat.\ soil)} \leq EC_{(groundwater)} \quad (3)$$

The EC values for all soil samples discussed herein were all measured according to the saturated paste method. These EC values have not been corrected according to the relationship established by equation 3. Equation 3 indicates that comparisons between EC values of soils become more reliable as the original moisture content of the soil increases. In other words, EC values of soil samples collected at or below the water table are more representative of actual salinity conditions than are EC values for surface soil samples in which the original moisture content is unknown. In the remainder of this discussion, EC values for soil salinity have not been differentiated into the soil, sub-soil or saturated soil intervals unless indicated.

Distribution of Saline Soils

Figure 17 shows the regional distribution of saline soils for the Southwest Map Area of Manitoba. As shown on this map, there are two major areas of saline soils. The first area, referred to as the Souris Plain, occurs between the 1500 and 1400 foot elevation, while the second area, referred to as the Whitewater Basin, occurs immediately below the 1700 foot elevation in the vicinity of Whitewater Lake.

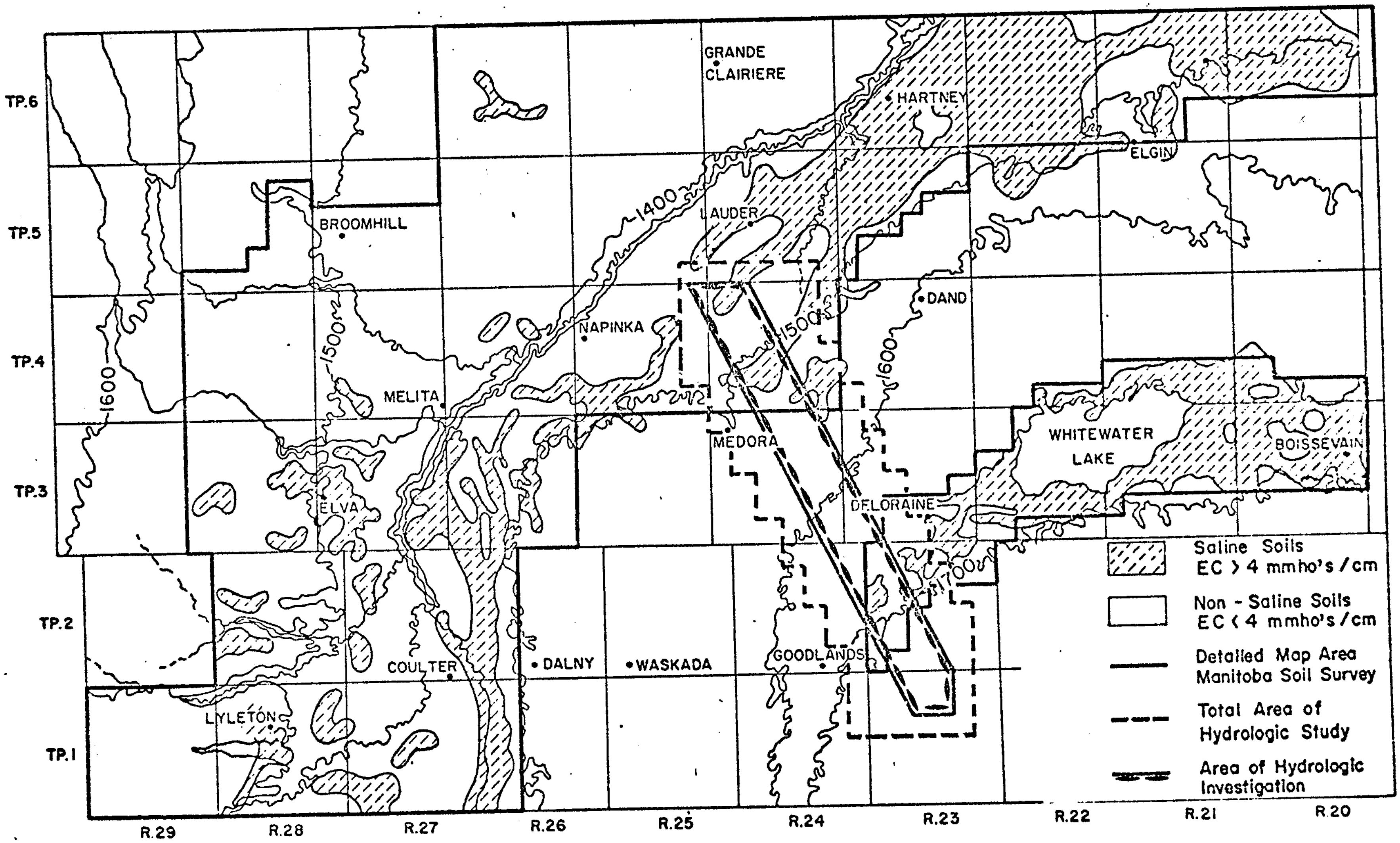

Figure 17. Regional Distribution of Saline Soils for the Southwest Map Area of Manitoba (after Eilers, 1968, 1969).

Figure 18 shows, in more detail, the portions of these two major areas of saline soils which occur in the study area. The first area near the town of Deloraine corresponds to the Whitewater Basin as shown in Figure 9, p. 38. The second area, near the town of Medora, includes part of the Medora Area, the Medora Ridge, the Souris Escarpment and part of the Souris Plain Area. With the exception of the Souris Plain, the areas of saline soils near the town of Medora (Figure 18) could not be separated on the basis of morphologic soil properties alone; therefore, a detailed survey and extensive soil sampling were conducted to determine the saline areas.

Vertical Distribution of Salinity

During the drilling program, samples of soil were collected at one foot intervals from the surface to a depth of 10 feet, at various locations within the study area. Additional samples were collected at greater depths during piezometer installation. The electrical conductivity data obtained from the saturated soil extracts of these samples are shown in Figure 19. The direction of increasing values of EC is indicated by the small vertical arrows immediately above or below each site.

Five distinctive profiles of soluble salt accumulation, as indicated by the magnitude of the EC, were established. These profiles are: (a) increasing accumulation towards the surface, (b) increasing accumulation away from the surface, (c) increasing accumulation from the surface to the water table zone and subsequently decreasing below the water table zone, (d) increasing accumulation upwards from the water table zone to the soil surface and increasing

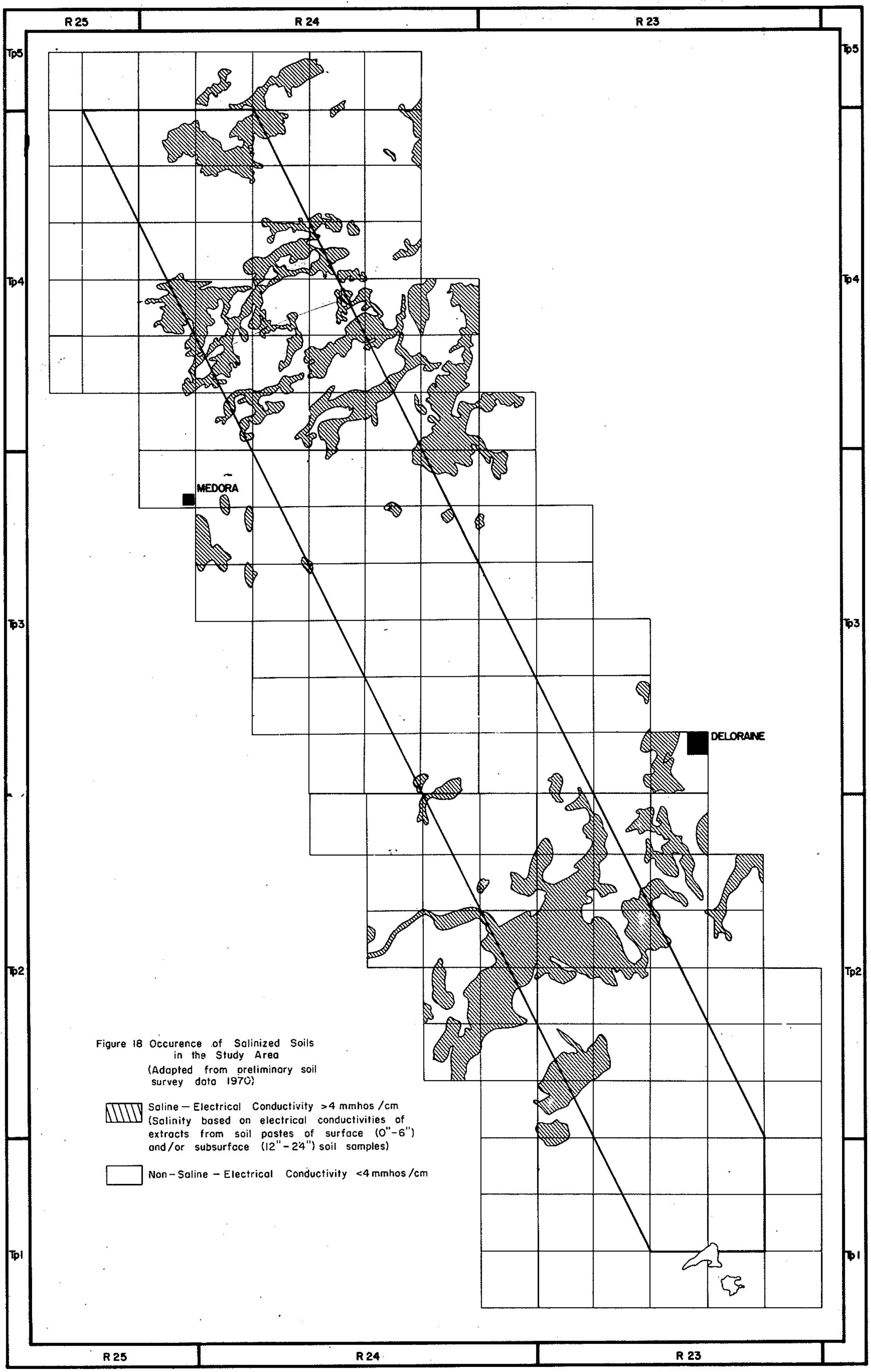

Figure 18 Occurence of Salinized Soils in the Study Area (Adapted from preliminary soil survey data 1970)

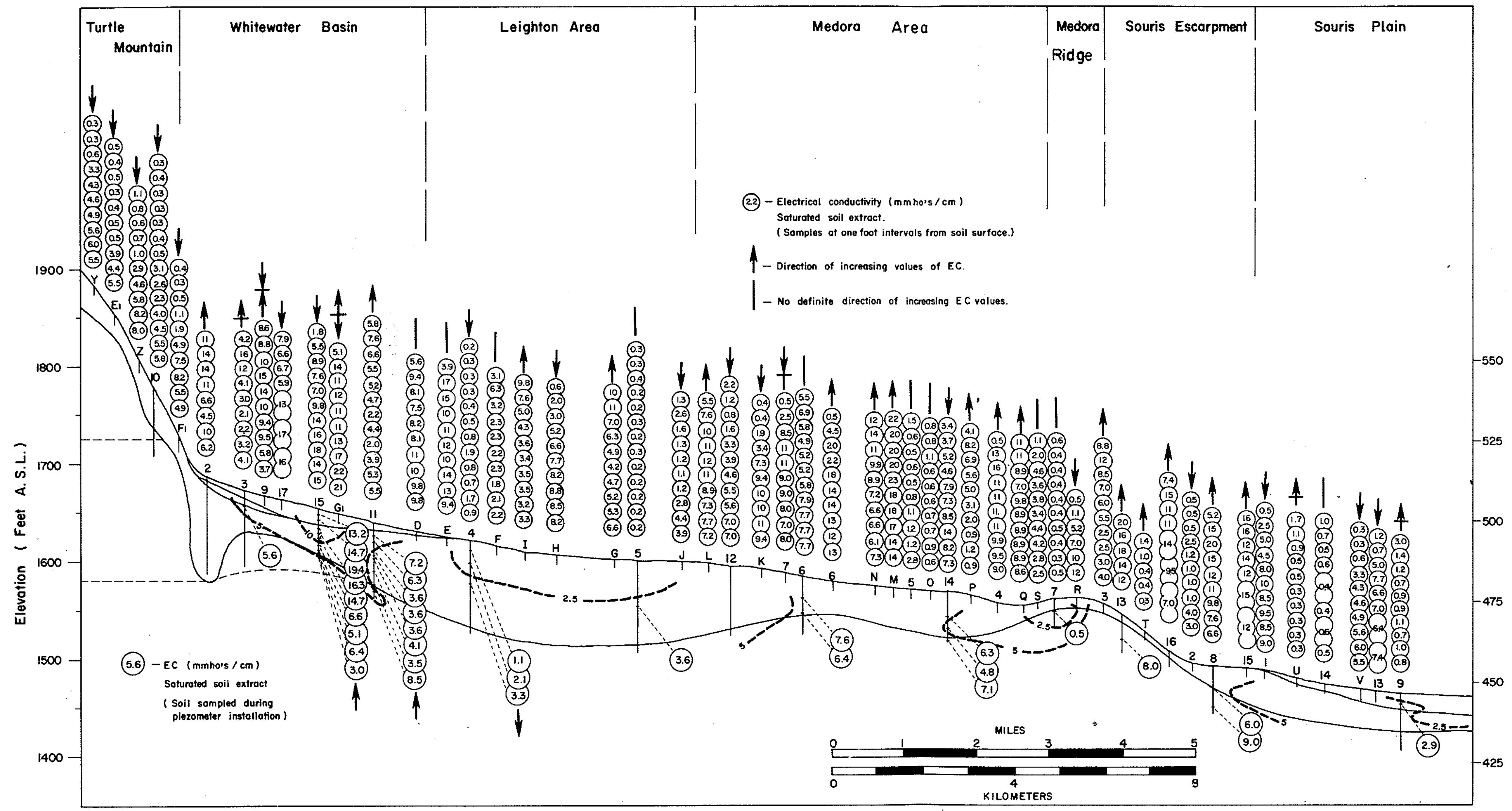

Figure 19. Electrical Conductivities of Soil Samples at Some of the Investigation Sites Along the Hydrologic Cross-section.

downwards from the water table zone, and (e) no vertical increase or decrease throughout the 10 foot profile.

In view of these vertical salt distribution profiles, an attempt was made to relate each of these salinity conditions to the corresponding conditions in the groundwater. In this study, the direction of increasing values of EC was interpreted as indicating the general direction of water movement in both the saturated and unsaturated soil zones. According to the concepts described by Freeze (1967), "water movement in the unsaturated zone is in physical and mathematical continuity with water flow in the saturated soil zone". Therefore, EC values decreasing from the surface to the water table zone were assumed to be the result of evaporation processes which, according to Freeze (1967), would be in physical continuity with discharging groundwater. On the other hand, EC values increasing from the surface downward indicate that surface water infiltration is the most probable method of water movement in the unsaturated soil zone. In this case, infiltration would be in physical continuity with recharging groundwater conditions. The three remaining distribution profiles (Figure 20, c, d, and e) were attributed to transitional and lateral groundwater movement with infiltration and evaporation accounting for the variations in the salt profile.

Using these interpretations, the EC profiles were coded using circles with shading and short vertical arrows corresponding to the five distinctive profiles as shown in Figure 21. The vertical diameter of the circle represents a depth of 10 feet, the shaded area of the circle indicates EC values greater than 4 mmhos/cm, the

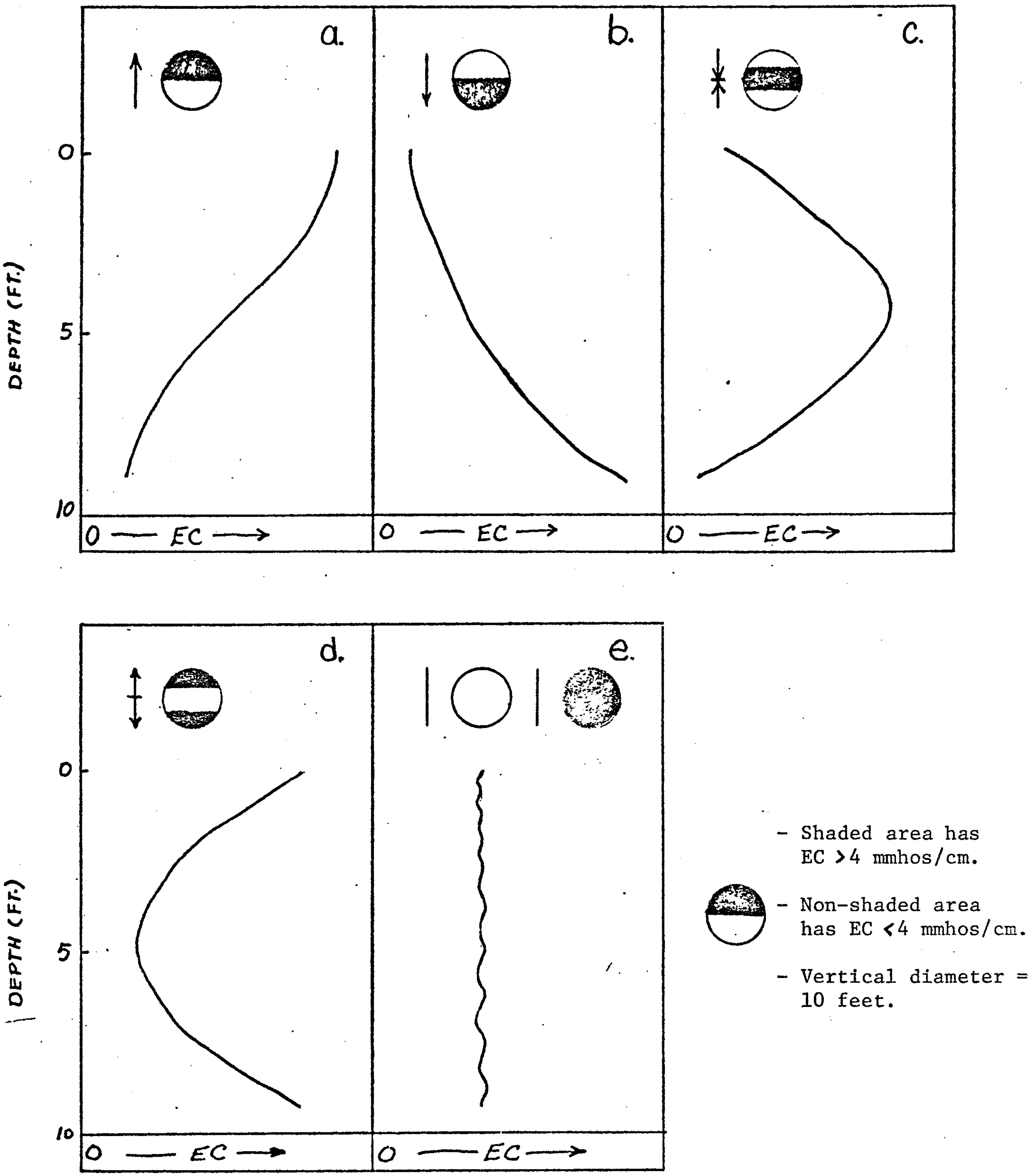

Figure 20. Schematic showing five typical profiles of EC values of soil extracts from samples to depths of 10 feet at the various investigation sites.

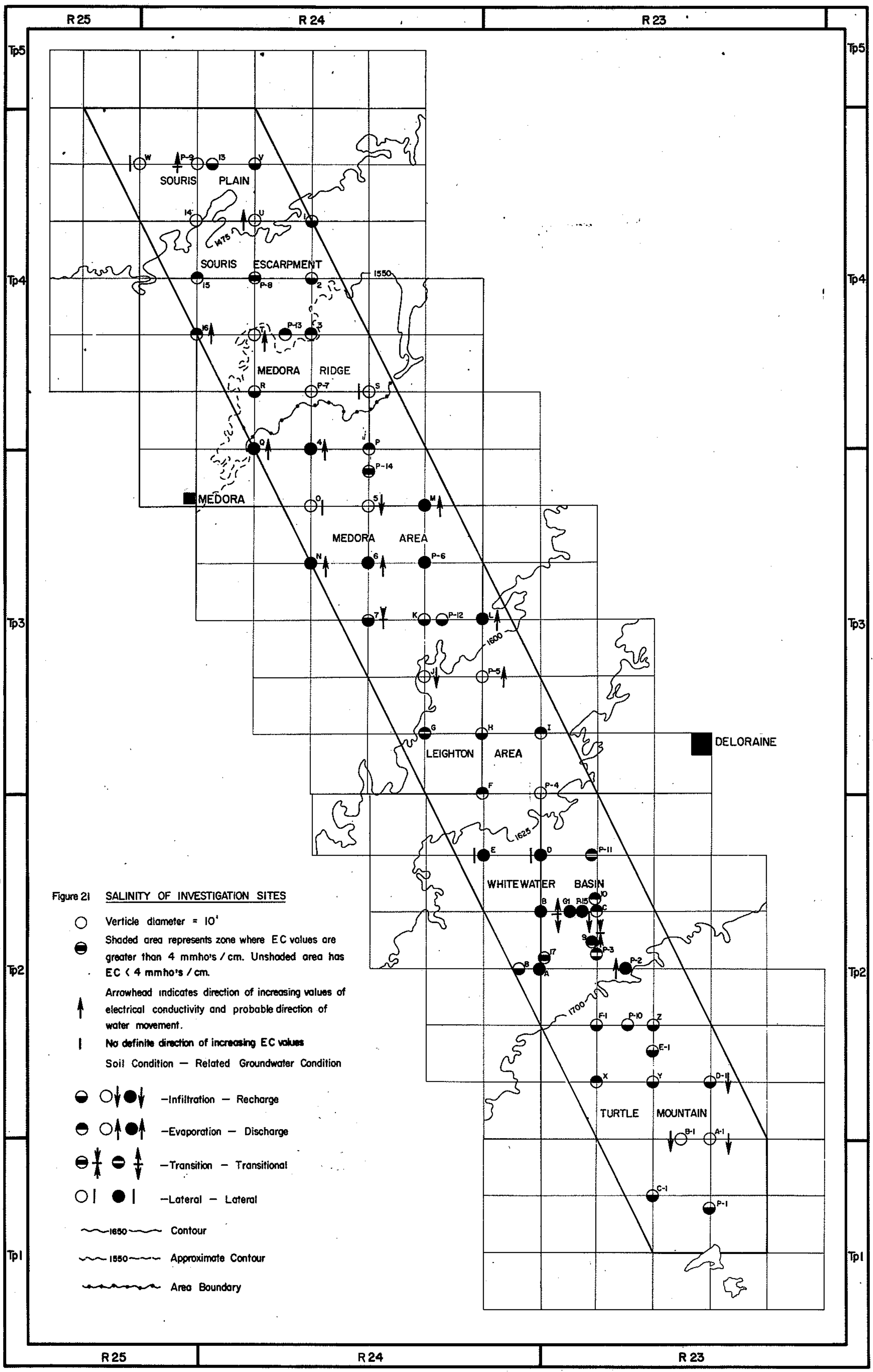

Figure 21 SALINITY OF INVESTIGATION SITES

unshaded area indicates EC values less than 4 mmhos/cm., and the arrows represent the direction of increasing EC. The symbols and arrows were placed at each of the investigation sites as shown in Figure 21.

The boundary lines separating each of the seven hydrologic areas generally approximated the elevational contours as indicated on the relief map (Figure 7, p. 30). However, the boundary which delineates the Medora Ridge Area does not follow any particular contour of elevation due to the dissected nature of the top of the escarpment.

Figure 21 shows that the distribution and degree of salinity in the soils is much more severe in groundwater discharge areas than in recharge areas. It can also be noted that each of the hydrologic areas identified has variable conditions of soil salinity.

Type and class of salinity. To determine the nature of salts in the soils, eight sites were chosen along the cross-section and analyzed for soluble salts. The data is presented in Appendix F-1. The dominant cation and anion were assumed to be the predominant salt present in the soil.

Table II shows the change in type and class of salinity with decreasing elevation throughout the various hydrologic areas. The major ions throughout the study area were Mg^{++} and $SO_4^{=}$. The Whitewater Basin, in addition to containing Mg^{++} and $SO_4^{=}$, also contained significantly higher concentrations of Na^{+} and Cl^{-} than the other hydrologic areas.

Table II also shows the change in distribution of the

TABLE II

TYPE AND CLASS OF SOIL SALINITY WITH DECREASING ELEVATION THROUGH THE VARIOUS HYDROLOGIC AREAS

Site No.	Approx. Elev.	Hydrologic Area	Major Ions	Salinity class	Average EC (mmhos/cm) to 10'
B_1	2200'	Turtle Mountain (Recharge)	Ca^{++}, $SO_4^{=}$	none	0.2
Y	1950'	Turtle Mountain (Recharge)	Mg^{++}, $SO_4^{=}$	none-weak	3.5
G_1	1650'	Whitewater Basin (Discharge)	Na^{+}, $SO_4^{=}$	moderate-strong	13.7
D	1630'	Whitewater Basin (Discharge)	Mg^{++}, $SO_4^{=}$, Na^{+}, Cl^{-}	moderate	8.8
H	1610'	Leighton Area (Recharge)	Mg^{++}, $SO_4^{=}$	weak	5.9
J	1600'	Leighton Area (Recharge)	Mg^{++}, $SO_4^{=}$	none	2.1
K	1590'	Medora Area (Discharge)	Mg^{++}, $SO_4^{=}$	weak	6.3
T	1510'	Medora Ridge (Recharge)	Ca^{++}, $SO_4^{=}$	none	0.8

major ions in the soil with decreasing elevation. Since the dominant anion throughout the study area is $SO_4^=$, the only noticeable change occurs in the concentrations of the major cations. This change occurs between the top of Turtle Mountain and the Whitewater Basin, where the sequence of cations changes from Ca^{++} to Mg^{++} to Na^+, respectively. In general, the major ions in the soils range from Ca^{++} and $SO_4^=$ to Mg^{++} and $SO_4^=$ in the recharge areas, whereas in discharge areas the major ions range from Mg^{++} and $SO_4^=$ to Na^+ and $SO_4^=$ with some sites having appreciable concentrations of Na^+ and Cl^-. This sequence is somewhat similar to that described by Rozkowski (1967) in the Moose Mountain area of Saskatchewan where he found a salt sequence of $CaCO_3$ - $CaSO_4$ - (Recharge Area) to $MgSO_4$ - Na_2SO_4 (Discharge Area) in a hydrologic system with increasing length of flow path, that is, decreasing elevation.

Distribution of Salinity in the Saturated Soil Zone

From the widespread distribution of salinity, the range of soluble salt concentrations, and the relative positions of soluble salt accumulation in the soil, it is apparent that the flow of groundwater is responsible for the movement and deposition of soluble salts.

By comparing the EC values of groundwater in piezometers (Figure 13, p. 45) to the EC values of soil extracts taken from approximately equivalent depths below ground level (Figure 19, p. 95), it is apparent that some redistribution of soluble salts must have occurred below the water table level to account for the higher EC values in the groundwater than in the saturation extracts. These differences range from 2 to 16 mmhos/cm.

Figures 22 and 23 show the vertical distribution of the major ions in soil extracts from below the water table. A comparison of these results to the salt concentrations of the groundwater (Figures 11 and 12, pp. 43 and 44) shows that the basic patterns of high concentrations in discharge areas and low concentrations in recharge areas are similar. In many cases, however, the salt concentrations of the groundwater are two to three times larger than the salt concentrations of the soil. This situation occurs predominantly in groundwater discharge areas as shown in piezometer nests P-15, P-11, P-6 and P-14. On the other hand, the groundwater in recharge areas was found to have equivalent or lower salt concentrations than the soil sample extracts from equivalent depths as shown by piezometer nest P-4, P-5, and P-7. It appears, therefore, that soluble salts are redistributed from recharge to discharge areas along the groundwater flow path.

Distribution of Soluble Salts in the Till

The glacial till in the study area can be described as a strong to moderately calcareous, loam to clay loam textured glacial till composed of mixed materials derived from shale, limestone and granitic rock. Since the till was found to be quite uniform in composition, it is reasonable to assume that, at the time of deposition, the soluble salt minerals were also uniformly distributed throughout the till. However, the present distribution of soluble salts (Figure 19, p. 95) reveals that there are some areas of high salinity and other areas of lower salinity. It is probable

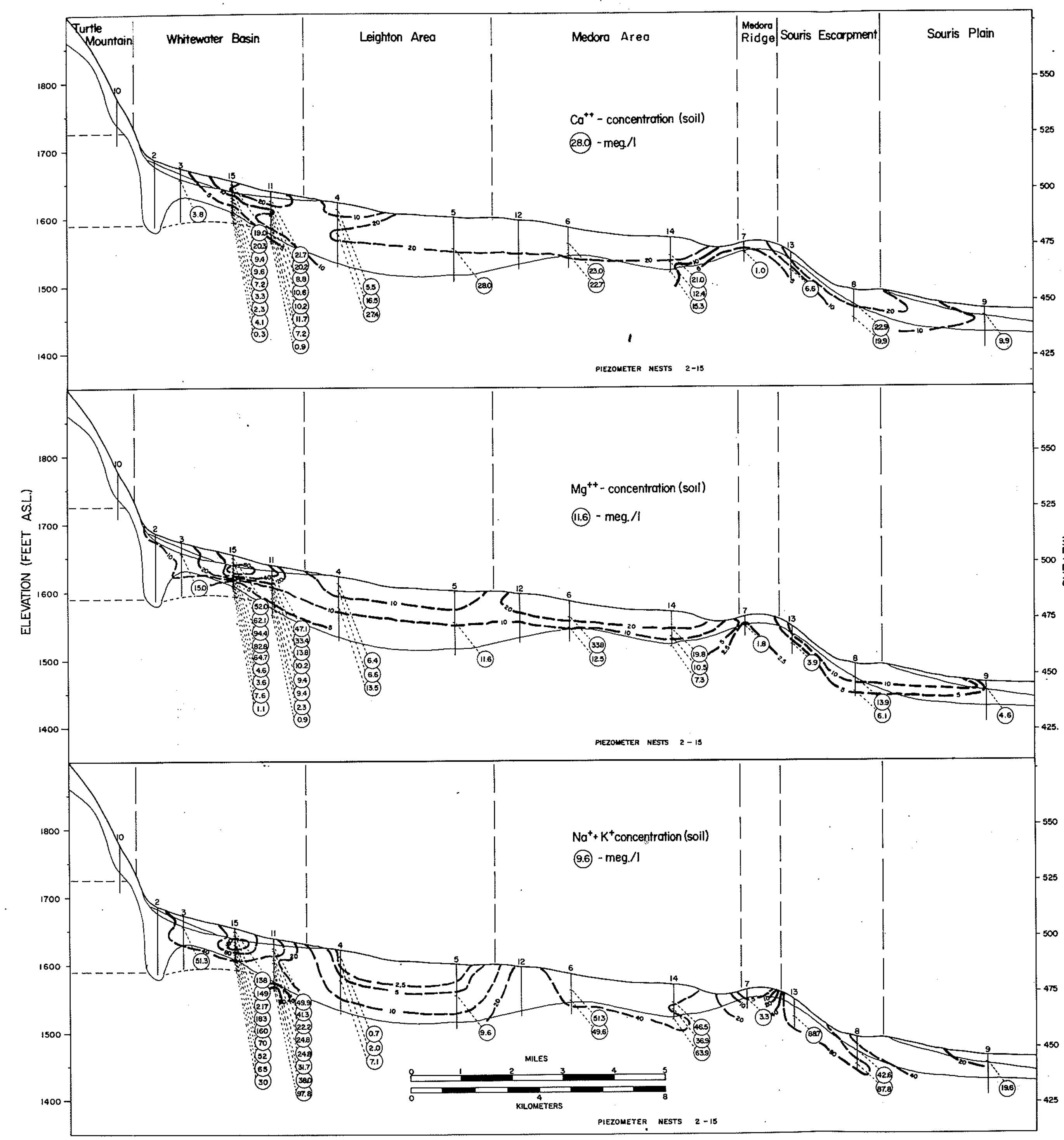

Figure 22. Distribution of Major Cations in Soil Extracts from Various Depths Below the Water Table.

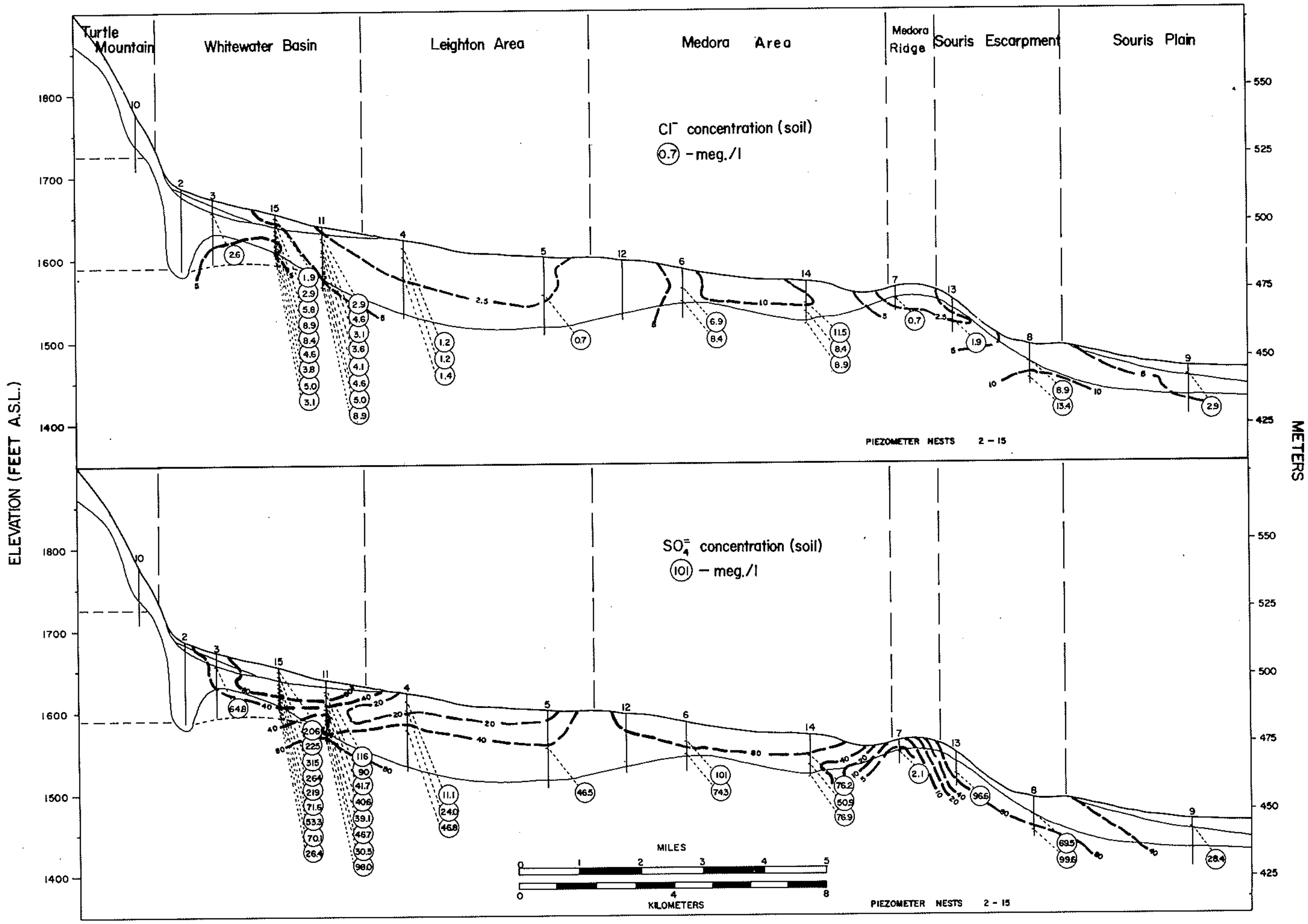

Figure 23. Distribution of the Major Soluble Anions in Soil Extracts from Various Depths Below the Water Table.

therefore, that these soluble salts have been dissolved, transported, concentrated and redeposited by the mechanisms of groundwater flow.

Mechanisms of groundwater flow. The flow of groundwater through any deposit is dependent upon its permeability. The degree of permeability is generally dependent upon the size and shape of pores, and the extent, size, and shape of their interconnections. The degree of permeability of glacial till, therefore, is essentially dependent upon structure. In this study the glacial till was found to have a generally blocky structure. The degree of permeability is determined by the rather intricate system of fractures and joints which result in the blocky structure. The mechanism of groundwater flow, therefore, through the till, can be described in simplified terms as a 'block and channel' flow system (Figure 24).

The channel flow system is basically a free flow system where water flows directly through the openings or fractures in the till. Salts can be dissolved from or deposited directly on the surfaces or interfaces of the fractures, depending upon the chemical saturation status of the groundwater.

The mechanism of water movement within the blocks is referred to as diffuse flow. Diffuse flow is responsible for the transport of soluble salts from within the soil block to the surface or interface of the fracture zones.

Diffuse flow would help to maintain a more consistent groundwater chemistry by continually replenishing the soluble salts which are removed by the fracture flow system. Although no permeability measurements were conducted in this study, it is assumed

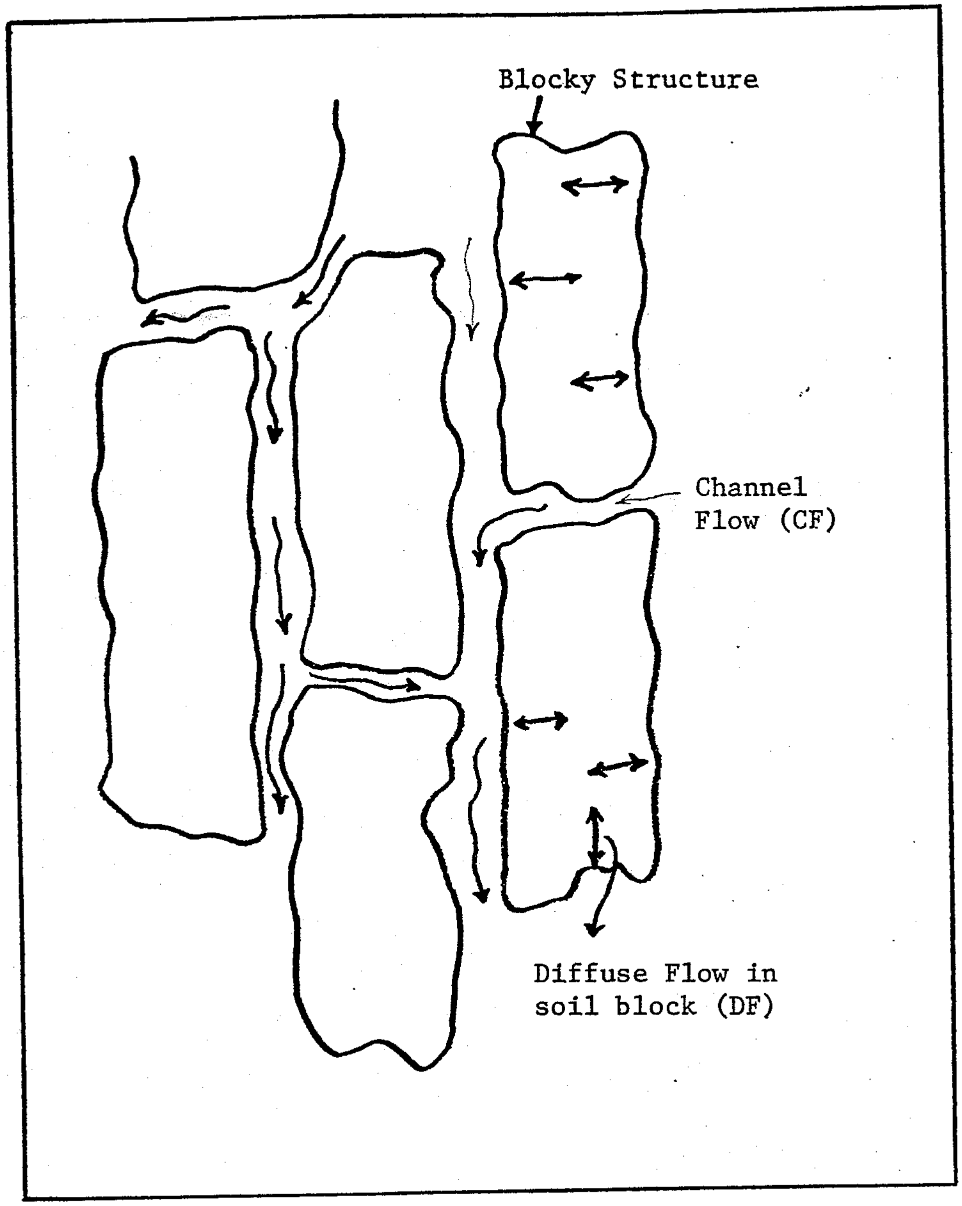

Figure 24. Simplified 'block and channel' groundwater flow systems of glacial till (CF > DF).

that water movement in the fracture flow system occurs at a faster rate than water movement in the diffuse flow system. If this is the case, the chemical composition and concentration of a groundwater sample, which is basically from the fracture flow system, would be expected to be different from the chemical composition and concentration of the extract of a soil sample collected from the same depth vicinity in the till. Therefore, water samples in recharge areas would be less mineralized than the soil extracts taken from equivalent depths (Figures 13 and 19, pp. 45 and 95 and P-4, P-5). Conversely, water samples typical to discharge areas would be more mineralized than the soil extracts from equivalent depths (Figures 13 and 19, pp. 45 and 95 and P-15, P-11, P-6, P-14).

The difference in rate of flow between channel flow and diffuse flow may also help explain some of the variation in the salt profiles of the unsaturated soil zone. As the water table fluctuates with seasonal changes of precipitation the majority of the groundwater flow is assumed to occur in the network of fractures or channels. If all flow occurred at the rate of water table movement the range of distribution of soluble salts should closely correspond to the range of water table fluctuation.

However, due to the slower rate of diffuse flow, there is a lag effect which allows soluble salts to be moved to the fracture planes or block edges. Subsequent water loss due to evaporation causes the salts to precipitate long after the water table has receded.

Sources of Salts in Soils and Groundwater

Each of the major geologic deposits within the study area has a characteristic groundwater chemistry. The groundwater in the till contains moderate to high concentrations of Ca^{++}, Mg^{++}, Na^{+}, and $SO_4^{=}$, and generally low concentrations of Cl^{-}. The concentrations of HCO_3^{-} range from 2.5 to 13.0 meq./1. and pH values range from 7.1 to 8.0. The Boissevain Formation has very low concentrations of Ca^{++}, Mg^{++}, and Cl^{-}. The concentrations of Na^{+}, $SO_4^{=}$ and HCO_3^{-} are generally low to moderate. The pH is about 8.5. The hydrochemistry of the Boissevain Formation was obtained from the piezometer at 68 feet in Nest 10. The hydrochemistry of the Riding Mountain Formation is characterized by high concentrations of Na^{+} and Cl^{-}, moderate to high concentrations of $SO_4^{=}$ and very low values of Ca^{++} and Mg^{++}. The concentration of HCO_3^{-} ranges from 4.8 to 15.5 meq./1. and pH ranges from 7.8 to 8.3. The hydrochemistry for these geologic units is presented in Appendix E-1.

It is apparent from the discussion of the hydrologic flow systems in Part III of this chapter that, with the exception of the Souris Escarpment and the Souris Plain Areas, the Riding Mountain Formation does not contribute significant groundwater to the overlying deposits of the study area. Therefore, the hydrochemistry of the other five hydrologic areas may be attributed to the physical and chemical weathering processes in the glacial tills.

The hydrochemistry of the glacial tills is controlled largely by the presence of calcite and dolomite. Consider first a sample groundwater recharge area in the till near piezometer Nest 5 which has low TDS. If dissolution of dolomite or calcite occurred according to:

$$CaMg(CO_3)_2 + 2H_2CO_3 \longrightarrow Ca^{++} + Mg^{++} + 4HCO_3^- \quad (4)$$

$$CaCO_3 + H_2CO_3 \longrightarrow Ca^{++} + 2HCO_3^- \quad (5)$$

during infiltration, either simultaneously or in sequence, the molar ratio of Ca^{++}/Mg^{++} in dilute recharge groundwater would be greater than 1. Summating the products of equations 4 and 5 indicates that 61 mg/l HCO_3 are produced with 15 mg/l Ca^{++} and 3 mg/l Mg^{++}. Since all of the HCO_3^- is produced from calcite and dolomite the field values of HCO_3^- can be used to determine the quantity of Ca^{++} and Mg^{++} that would be expected in the groundwater.

The observation well at 10 feet at Nest 5 has 305 mg/l HCO_3^- which corresponds to 75 mg/l Ca^{++} and 15 mg/l Mg^{++}. However, the total Ca^{++} and Mg^{++} in the groundwater is 73.2 mg/l and 37.3 mg/l, respectively. In this case, all of the Ca^{++} ions can be accounted for but there is a significant excess of Mg^{++}. In areas of more saline groundwaters there is large excesses of both Ca^{++} and Mg^{++} and much higher concentrations of Na^+, Cl^- and $SO_4^=$. It can be concluded, therefore, that there must be other sources to supply the excess Ca^{++}, Mg^{++} and all of the Na^+, Cl^- and $SO_4^=$. The two most common sources for Ca^{++}, $SO_4^=$, Na^+, and Cl^- are gypsum and halite. This, however, still leaves excess quantities of Mg^{++} and Na^+. Three other possibilities could account for these excesses: 1) all of the excess could be due to cation exchange mechanisms, 2) all of the excess could be due to the presence of other sulphate minerals, or 3) all of the excess could be due to a combination of the above two processes.

As the hydrochemistry of the Boissevain Formation is quite different from that of the overlying glacial till, this causes some doubt as to whether groundwater from the glacial till actually enters this formation. On the basis of the hydrochemistry from only one piezometer installed in this formation, it is difficult to characterize this groundwater. However, the hydrochemistry of the water sample from the piezometer at 68 feet in Nest 10 indicates that very little Ca^{++} and Mg^{++} are present and that the predominant ions are Na^{+} and $SO_4^{=}$.

Hydrochemistry of the Riding Mountain Formation. The groundwater of the Riding Mountain Formation generally has higher concentrations of Na^{+} and Cl^{-} and considerably lower concentrations of Ca^{++}, Mg^{++}, and $SO_4^{=}$ than the overlying glacial tills. Since this formation is composed of non-calcareous marine shales the most probable source for the Na^{+} and Cl^{-} concentrations is halite (NaCl). These shales would also have Na^{+} as the predominant ion on the exchange sites. Cation exchange, therefore, could produce some of the excess Na^{+} which is not accounted for by the dissolution of halite. Cation exchange could also account for the very low values of Ca^{++} and Mg^{++} which occur in areas where groundwater from the overlying till moves into the shale.

The $SO_4^{=}$ concentration is also much lower in the shales than in the overlying tills. Sulfate reduction processes probably result in the production of hydrogen sulfide gas which was evident in nearly all the piezometers in the shale. Sulfate reduction processes in shale have been reported by Schwartz (1970).

In summarizing soil salinity, it is apparent that the degree of salinity is dependent upon the elevation and position of the soil in the landscape, the lithology of the surface deposits, the depth to water table, the quality of the groundwater and the direction and mechanism of groundwater flow.

PART IV

APPLICATIONS OF SOIL-GROUNDWATER RELATIONSHIPS

Hydrological and pedological relations as investigated in this study have many practical applications. The present concern about pollution of soils and shallow groundwater flow systems emphasizes the importance of detailed knowledge of the relationships which exist between pedological processes and groundwater flow phenomenon. Such studies would have application to: waste disposal programs, soil fertility programs, irrigation programs, soil drainage programs, water management programs related to natural and man-made water bodies such as sloughs, dugouts, small dams and lakes, etc.

Many groundwater conditions such as: range of water table fluctuation, degree of salinity, direction, and method of groundwater flow are reflected in the soil by pedological conditions such as: staining and mottling, color, presence or absence of carbonates and soluble salts, and degree and type of soil drainage. Since there is this close relationship between soil and groundwater, any major change or alteration to one, will invariably result in a corresponding change or alteration to the other.

By knowing specific soil-groundwater relationships one can arrive at a better understanding of the dominant soil forming processes from which the present soils have evolved. It must be remembered, however, that in these types of studies, the systems as presently described, exist in a dynamic equilibrium and are subject to changes either natural or artificially induced.

SUMMARY

The main objective of the study was to describe the hydrogeology of a representative area of soils for the purpose of determining the relations between groundwater flow systems and the general distribution of genetic soil profiles.

In order to characterize the groundwater flow system, fifteen nests of piezometers were installed using a power driven auger. Each nest consisted of 5 to 6 piezometers placed at different depths below ground level. Depth to water level measurements and samples of the groundwater were taken from each piezometer. Soil samples were collected from various depths below the ground level during the installation of the piezometers. All samples were analyzed for salinity. Some of the soil samples and all of the groundwater samples were analyzed for the major ion concentrations.

The hydraulic head and hydrochemical data of the groundwater indicate a complex flow system controlled largely by topography and geology. This complex flow system is composed of seven distinctive hydrologic areas. They are as follows: 1) Turtle Mountain (Recharge), 2) Whitewater Basin (Discharge), 3) Leighton (Transitional to Recharge), 4) Medora (Discharge), 5) Medora Ridge (Recharge), 6) Souris Escarpment (Lateral Discharge), and 7) Souris Plain (Lateral Flow). Each of these seven areas is characterized by a different groundwater flow regime.

The dominant direction of water movement in each of the seven hydrologic areas is reflected in the genetic and morphologic properties of the soil. The soils in recharge areas are predominantly

leached and eluviated with good internal drainage. The soils in discharge areas are commonly carbonated and saline with poor to imperfect internal drainage.

The predominant factor affecting water movement through the soil in the areas of lacustrine sediments is the textural variation of the micro-stratigraphy. In the Whitewater Basin, thin, coarse textured, discontinuous gravel lenses occur above and below the water table zone. Below the water table zone these gravel lenses tend to channel the groundwater laterally, creating small positive hydraulic pressures in the lower end of these deposits. Above the water table zone they tend to behave as impermeable boundaries through which capillary water does not move. This causes soluble salts to be deposited below the lens and results in a generally salt free soil above. Where the coarse textured lens is absent, soluble salts are deposited at the soil surface. The textural variation of the micro-stratigraphy, therefore, plays a major role in determining the genetic soil distribution in the Whitewater Basin Area.

Local topography is a prominent factor in areas of glacial till and affects the distribution of genetic soils. Topography determines the direction and rate of surface runoff and thereby the quantity of water infiltrating into the soil. The volume of water and the rate of infiltration are generally reflected in the soil by the degree of profile development and leaching. Due to the influence of micro-relief, areas of glacial till generally have a larger number of different genetic profiles in a given area than an area of lacustrine sediments with uniform topography.

The hydrochemistry of the groundwater indicates that, with the exception of the Souris Escarpment area, the majority of the soluble salts in the soil and groundwater have been derived from the glacial till. Their present concentrations and distributions are the result of a complex system of groundwater flow. The major ion chemistry of the soils and groundwater in areas of glacial till shows that Ca^{++} and $SO_4^{=}$ are the most common ions in recharge areas, while Mg^{++} and $SO_4^{=}$ are the most common ions in discharge areas. The most common ions in thin lacustrine sediments with discharging groundwaters are Na^{+} and $SO_4^{=}$. The bedrock or Riding Mountain Formation does not appear to contribute soluble salts to the overlying tills with the exception of the Souris Escarpment where significantly larger concentrations of Na^{+} and Cl^{-} in the soil have probably originated from the shale at the face of the escarpment.

CONCLUSIONS

From this study it can be concluded that:

1. The study area is characterized by a complex hydrogeological flow system consisting of seven distinct groundwater flow regimes; three recharge, three discharge and one area of lateral flow.
2. The geochemical data of the groundwater in addition to hydraulic head, proved to be a very useful parameter for interpreting the groundwater flow systems.
3. The nature of the geologic deposits is a major factor determining the direction and rate of groundwater flow.
4. The terminology of local, intermediate, and regional, in reference to groundwater flow systems as defined in hydrogeology, is vague and needs to be defined in terms of each hydrogeological study. These terms cannot be readily used or defined by interpretations based on soil profile characteristics.
5. The micro-stratigraphy, texture, and local topography of the surface deposits are important site parameters which affect soil profile development due to their influence on infiltrating and upward capillary movement of soil water.
6. There is a definite relationship between groundwater flow and soil genesis. Leached and eluviated soils are typical of groundwater recharge areas, while saline and carbonated soils are typical of discharge areas.
7. The soluble salts in the soil and groundwater in the area above

the Souris Escarpment are derived for the most part from the glacial till. The soils below the Souris Escarpment are affected by sodium salts from the underlying Riding Mountain Formation.

8. Soils can be used to make interpretations of local groundwater flow conditions; however, some deep drilling should be done to gather information on the groundwater, depth and composition of the surface deposits, and the nature of the bedrock to facilitate a more comprehensive interpretation of the groundwater flow systems.

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APPENDIX A

Field Procedures Employed During the Hydrogeological Investigation

APPENDIX A

Field Procedures Employed During the Hydrogeological Investigation

To facilitate the interpretation of groundwater hydrology, 15 nests of piezometers were installed in a cross-section extending from the Turtle Mountain to the Souris Plain. Each nest consists of 5 to 6 piezometers set at various depths ranging from 10 to 100 feet below ground level. Each nest also has a shallow water table well slotted from 3 to 10 feet below ground level for observation of local groundwater table fluctuations.

The design and installation of the piezometers has been previously described in the Methods and Materials. Table A-I, however, presents a comparison of the hollow stemmed auger versus the solid stemmed auger for the installation of plastic piezometers.

After installation all piezometers were cut off at a uniform elevation which was subsequently determined for each nest by P.F.R.A. surveyors. Each piezometer nest was numbered consecutively and each piezometer within the nest was labeled with a number corresponding to its depth below ground level.

Maintenance

During the course of the hydrologic investigation, it was found that the plastic construction of the piezometers necessitated periodic maintenance and repairs. At several locations adjacent to major public roads, the piezometers were broken off and smashed by vandals and some were damaged by farm machinery. Some of this damage likely could have been reduced by making their presence less obvious

TABLE A-I

COMPARISON OF THE HOLLOW STEMMED AUGER vs. THE SOLID STEMMED AUGER FOR THE INSTALLATION OF PLASTIC PIEZOMETERS

Work Function	Hollow Stem	Solid Stem
Soil sampling	poor ± 10 feet	excellent ± 1 foot
Speed of drilling	average	average +
Positioning of piezometers	excellent	danger of caving and sloughing
Placing of sand pack	excellent	poor - sand sticks to wet edges of bore hole and does not reach intake zone
Placing of cement grout	moderate	moderate
Probability of water contamination	low - sand pack properly installed	moderate - sand pack did not always cover intake zone
Sensitivity to changes in permeability	low	moderately high
Versatility	one directional rotation	two directional rotation - forward and reverse
Appraisal of job accomplishment	superior for piezometer installation	superior for soil sampling and stratigraphy differentiation

from the public road.

Depth to Water Level (Hydraulic Head) Measurements

Depth to water level measurements were determined by three different methods: 1) canvass tape, 2) electrical tape, and 3) a length of stiff Tygon tubing.

The canvass tape method consisted of lowering the tape, weighted at the end, into the piezometer to a sufficient depth to ensure water contact. This depth was noted and the tape was removed. The depth to which the bottom end of the tape was wetted was then subtracted from the initial reading. The difference was determined to be the actual depth to water level. This method was found to have several disadvantages: 1) once the bottom of the tape became wet, each subsequent reading was more difficult to read unless the tape was completely dried between readings, 2) the depth to water level is not a direct reading since it involves a calculation which, due to its tediousness, can be a source of error, and 3) when the tape and weight are lowered into the water some displacement of water occurs due to the narrow diameter of the piezometer. The amount of displacement must be determined and the proper adjustments made.

The second method used was the electrical tape. This instrument is essentially two disconnected electrodes which are lowered into the piezometer to the water contact. The electrolytic properties of the water complete the circuit between the two electrodes. The water contact is observed as a needle deflection on a small resistance meter. The depth to water level can then be read directly from the color coded footage tags which have been used to calibrate the length of the electrode cable. This instrument was found to have the following disadvantages: 1) once the electrode became wet, it had to be dried before taking the next reading. The water film on the electrode was often sufficient to give a slight reading, which caused some difficulty in determining the water level of slightly mineralized groundwater. 2) It was found that after repeated use, cracks developed in the wire insulation and allowed moisture to enter and short circuit the electrode.

The third method used to read water levels was a 1/4 inch diameter stiff Tygon tube calibrated in units of 0.1 feet. The tube was inserted into the wells and piezometers while compressed air was forced through the tube. Detection of a bubbling noise indicated that water contact had been made. The tube was adjusted so that it just touched the water surface; the depth was then read directly at the top of the piezometer. No major disadvantages were found using this method. Occasionally the tubing caught on the construction joints of the walls of the piezometers but due to its rigidity it was twisted and easily manipulated to the desired position. Due to the narrow diameter of the piezometer there was no appreciable distortion in depth due to folding and binding on the piezometer walls. Several aspects of this method were found to be superior to the two previous methods: 1) depth to water level readings could be read directly, 2) it is simple to use and gives consistent results, and 3) it could be used for water sampling and thereby reduce the amount of equipment required for servicing the piezometers.

Methods of Collecting Water Samples from Piezometers

Water samples from each well and piezometer were collected in 1970 and 1971. Two methods were used to obtain water samples from the small diameter piezometer tubes. The first method consisted of three types of metal balers while the second method employed a vacuum pump connected to a vacuum bottle which in turn is connected to a 100 foot length of stiff Tygon tubing.

In the first method, three types of metal balers (1/2 inch in diameter and 24 inches in length) were used. The first type had the bottom sealed and the top open. It was lowered into the piezometer by means of a thin strong cable. As it was lowered into the water, the water flowed upwards between the walls of the baler and the piezometer and entered the baler from the top. It was then removed and empitied by pouring the water out of the top into a collection bottle. This method was found to have the following disadvantages: 1) it caused considerable mixing and aeration during the filling and emptying processes, 2) the water sample could be collected only from the upper waters in the piezometer, and 3) there had to be a minimum of 2 feet of water in the piezometer before a sample could be collected.

The second type of baler which was a slightly modified version of the first, had the bottom sealed and the top fitted with a spring loaded plunger, which was activated by a separate cable. The baler was lowered to the bottom of the piezometer with one cable; the second cable was then pulled to raise the plunger and allow the water to enter. After removal from the piezometer the top portion of the sampler was unscrewed and the water poured into a collection bottle. This had basically the same disadvantages as the first with the addition of the tangling of the two cables.

The third sampler was a further modification of the first two types. This sampler which was open at the top, also had an opening in the bottom which was covered by three small metal balls. As the sampler was being lowered into the piezometer water entered the bottom opening past the metal balls and out the top of the baler. After reaching the bottom of the piezometer the metal balls closed the opening thus retaining the water sample from the bottom of the piezometer. Although this sampler worked better than the first two, there was no way of knowing whether the water actually flowed through the sampler as expected.

Considerable difficulty was encountered in getting all three samplers to pass through the joins in the piezometer tubing which had become constricted with plastic cement used to construct the piezometers. A second problem hindering the movement of these balers in the piezometer was the spirallation of the plastic piezometer tube as it was installed in the drill hole. This phenomena created a twisting tortuous path for the samplers to follow.

As a result of the problems encountered in 1970 with the above mentioned three samplers, a fourth method was developed and used in 1971 which proved to be a more satisfactory for collecting water samples. This method consisted of using a stiff Tygon tube, 1/4 inch in diameter and 100 feet in length which was calibrated in 0.1 foot intervals. This was the same tube used to take water level readings.

The tube, open at both ends, was inserted into the piezometer. Water entered the bottom and rose in the tube. When the tube had reached the intake zone of the piezometer a vacuum was applied to the top end of the tube. At first this vacuum was applied manually, later a vacuum pump was obtained and used. A sufficient vacuum was applied to raise the level of water in the tube 10 to 15 feet above the initial water level in the piezometer. The tube was then removed from the piezometer while carefully maintaining the vacuum. The bottom 10 to 15 feet of water in the tube was collected as a relatively undistrubed sample. The sampling apparatus is shown in Plate 3, Appendix G.

This method was found to be superior to the other methods for the following reasons: 1) the tube was easily lowered to any desired depth in the piezometer, 2) it reduced the mixing and aeration of the water sample to a minimum, 3) an adequate sample could be collected in one operation, whereas the baler methods required several repetitions to collect a sufficient volume of water, and 4) this method proved to be an excellent procedure for flushing the piezometers, since most of the water could be removed by vacuum and, therefore, eliminated the necessity to add foreign water to the piezometer.

APPENDIX B

Drill Logs For Geologic Cross-section

APPENDIX B

Drill Logs For Geologic Cross-section

Piezometer nest no. 1 Date: July 21, 1970

Location: NW 27-1-23W (1/2 mile north of Flossie Lake)

Elevation: 2296.5 feet A.S.L.

Depth (feet)	Description
0 - 2	Clay loam soil (profile destroyed by road construction).
2 - 76	Till, clayey loam, mixed pebble composition, carbonates and very abundant shale fragments. Stiff, no free water, very dry, crumbly, moisture content gradually increases with depth, oxidized colors in the 5Y (olives) range gradually, darkening with depth, becoming unoxidized (dark grey) at 30 to 35 feet.

Piezometer nest no. 2 Date: July 20, 1970

Location: SC 20-2-23W

Elevation: 1687.3 feet A.S.L.

Depth (feet)	Description
0 - 1.5	Clay loam (Saline Gleyed Carbonated Rego Black profile).
1.5 - 6	Light clay loam, clayey, silty and sandy, massive; not typical lacustrine appearance.
6 - 10	Gravel: pebbly, sandy and cobbly, rounded frag-

Depth (feet)	Description
	ments, very oxidized, perhaps somewhat silty, water saturated layer, very permeable.
10 - 98	Till, very dark grey (5Y 3/1), clay loam to clay, mixed pebble composition, limestones, shale, and Boissevain Sandstone chips, unoxidized, stiff, very homogeneous.

Piezometer nest no. 3 Date: July 20, 1970

Location: SW 20-2-23W

Elevation: 1675.3 feet A.S.L.

Depth (feet)	Description
0 - 2	Loamy sand, part of depositional blow bank (Regosolic Profile).
2 - 8	Sandy clay loam, lacustrine, slightly pebbly with tiny granules, oxidized (olives 5Y).
8 - 10	Gravel, very coarse, very poorly sorted sand, water saturated.
10 - 60	Till, clay loam, (very clayey) unoxidized, very dark grey (5Y 3/1) mixed pebble composition, predominantly limestone and shale pebbles, moderately stiff.
60 - 78	Shale, very dark grey (5Y 3/1), no white carbonate specks, slightly sandy, slightly silty and comes off the auger as soft chips (shale conglomerate),

Depth (feet)	Description
	drills moderately easily indicating soft loose shales, shale chips are rounded and appear to have been eroded.

Piezometer nest no. 4   Date: July 17, 1970

Location: NE 36-2-24W

Elevation: 1622.3 feet A.S.L.

Depth (feet)	Description
0 - 2	Loam to clay loam, lacustrine (profile destroyed by road construction).
2 - 25	Till, stiff clayey loam, mixed pebble composition, predominantly limestones, massive, hard, breaks along well defined very irregular surfaces, occasionally appears wet on outside, interior is moist. Grades from olive (5Y 5/4 and 5Y 4/4) oxidized to very dark grey and dark grey (5Y 3.5/1) unoxidized.
25 - 38	Unoxidized, same as above.
38 - 50	Lighter texture, loam, clay approximately 10 to 15 per cent, more moist, dark grey.
50 - 82	Stiff clayey loam till, very dark grey.
82 - 93	Shale, very dark grey, (5Y 3/1), comes up on the auger as chips (shale conglomerated), massive no calcareous specks.

Piezometer nest no. 5 Date: July 18, 1970

Location: NE 12-3-24W

Elevation: 1600.6 feet A.S.L.

Depth (feet)	Description
0 - 2	Clay loam topsoil (Orthic Black Profile).
2 - 23	Till, stiff clay loam, oxidized, olives (5Y 5/3), grading to dark grey (5Y 3/1) unoxidized.
23 - 85	Till, stiff clayey loam, homogeneous, mixed pebbly composition, moist, breaks along very irregular well defined surfaces.
85 - 93	Shale, very dark grey (5Y 3/1), massive, no calcareous specks, moderately soft drilling, very wet, water probably coming in near bedrock contact.

Piezometer nest no. 6 Date: July 18, 1970

Location: NW 24-3-24W

Elevation: 1583.9 feet A.S.L.

Depth (feet)	Description
0 - 2	Clay loam topsoil (Carbonated Rego Profile).
2 - 20	Till, clay loam, pebbly, becomes slightly unoxidized from olives (5Y 5/3) grading to
20 - 25	dark grey with increasing depth to
25 - 30	where it becomes very dark grey (5Y 3/1) and unoxidized.

Depth (feet)	Description
30 - 40	Till, stiff, clay loam, mixed pebble composition breaking along well-defined, very irregular surfaces.
40 - 56	Shale, very dark grey, massive, no white calcareous specks, first five feet very hard, becomes softer and wet between 45 and 56 feet.

Piezometer nest no. 7 Date: July 18, 1970

Location: NE 4-4-24W

Elevation: 1562.8 feet A.S.L.

Depth (feet)	Description
0 - 2	Clay loam topsoil (Gleyed Eluviated Black Profile).
2 - 9	Till, clay loam, oxidized, olive (5Y 5/4 to 5/6) mixed pebbly composition, mainly shale and limestone fragments, moist soft, saturated below 4 feet.
9 - 28	Shale, very dark grey, (5Y 3/1) massive, no white specks, very hard below 22 feet. Upper 10 feet very fractured, drills easily, chips very hard, 20 to 22 feet is a very soft zone, some soft bentonite, 22 to 28 feet comes up as small moist chips, samples are interbedded. Hole is wet below 20 feet, it contained several feet of water by the time the auger was removed. Samples from the 9 to 20 foot zone came up as 1 1/2 - 2 inch very hard chips. Upper few feet drilled somewhat like gravel or bouldery till because of fractured, very hard characteristics.

Depth (feet)	Description
7 - 22	Till, calcareous, olive in color, clay loam texture, mixed pebbles primarily limestones and shales, very oxidized in the upper 10 feet, gypsum crystals abundant at 10 to 20 feet.
22 - 45	Till, calcareous, clay loam, dark grey (5Y 4/1), many of the pebbles are rounded.
45 - 50	Shale, grey and dark grey (5Y 4/1), soft, contact appears gradational, non-calcareous, crumbly, dry.

Piezometer nest no. 8 Date: July 19, 1970

Location: NW 16-4-24W

Elevation: 1493.4 feet A.S.L.

Depth (feet)	Description
0 - 2	Clay loam topsoil (Saline Gleyed Carbonated Rego Black Profile).
2 - 24	Till, clay loam, mixed pebble composition predominantly shale and limestone fragments, soft moist, saturated oxidized, olive color, grading to slightly darker colors at 20 to 24 feet.
24 - 48	Shale, very dark grey, (5Y 3/1) shale is much softer than at sites 4 to 7. Easy drilling at 48 feet, moist, occasional free water.

Piezometer nest no. 9 Date: July 19, 1970

Location: NE 30-4-24W

Elevation: 1464.1 feet A.S.L.

Depth (feet)	Description
0 - 2	Sandy topsoil (Saline Gleyed Carbonated Rego Black).
2 - 15	Sand, medium to fine, well sorted, oxidized, very uniform, no pebbles, most probably lacustrine.
15 - 36	Till, clayey loam (very clayey), very dark grey (5Y 2/1), stiff, mixed pebble composition of limestone and shale.

Depth (feet)	Description
36 - 59	Shale, very dark grey (5Y 3/1), soft, drills fairly easily in upper 15 feet, no white specks of lime, drilling becoming moderately slow at 59 feet.

Piezometer nest no. 10   Date: July 21, 1970

Location: NC 8-2-23W

Elevation: 1776.3 feet A.S.L.

Depth (feet)	Description
0 - 2	Clay loam soil (Orthic Black Profile).
2 - 36	Till, very clayey loam, mixed pebble composition mostly carbonates, shale and coal, stiff oxidized to 36 feet, unoxidized below, (very dark grey, 5Y 3/1).
36 - 50	Turtle Mountain Formation, shale, soft, carbonaceous, with coal fragments, very dark grey and black (5Y 3/1 and 2/1) occasional lime specks (very small).
50 - 68	Boissevain Formation, sand, unconsolidated, very fine grained, laminated, light grey to medium grey somewhat silty and clayey in some samples.

Piezometer nest no. 11   Date: July 21, 1970

Location: NE 30-2-23W

Elevation: 1641.3 feet A.S.L.

Depth (feet)	Description
0 - 2	Saline, clay loam topsoil, gypsum crystals present, (Saline Gleyed Black Profile).
2 - 7	Clayey silt, lacustrine, slightly laminated oxidized, occasional pebble, no sand or gravel.
7 - 62	Till, very clayey loam, mixed pebble composition predominantly limestones and shale fragments, stiff, no free water apparent, oxidized (olive colors) to 25 feet, gradual transition to very dark grey (5Y 3/1) appears to be reduced.
62 - 75	Shale, soft, non-calcareous, dark grey (5Y 4/1) crumbly, dry.

Piezometer nest no. 12 Date: June 30, 1971

Location: SC 24-3-24W

Elevation: 1595.7 feet A.S.L.

Depth (feet)	Description
0 - 3	Loam topsoil, (thin Orthic Black Profile).
3 - 30	Till, clay loam, pebbly, calcareous, mixed pebble composition (limestones and shales), olive (5Y) colors, grades darker with depth to
30 - 64	Till, as described above but unoxidized, very dark grey (5Y 3/1), calcareous pebbles much more frequent than silicates in all samples, gypsum crystals 1/4 inches in length were noted at 35 feet, till is damp but no free water present.

Depth (feet)	Description
64 - 70	Shale, very dark grey (5Y 3/1), non-calcareous crumbly, massive, drills very hard, distinct contact was evident.

Piezometer nest no. 13 Date: June 30, 1971

Location: NC 9-4-24W

Elevation: 1546.9 feet A.S.L.

Depth (feet)	Description
0 - 1	Topsoil has been removed by road cut, (Saline Gleyed Carbonated Rego Black profiles in adjacent areas).
1 - 9	Till, clay loam, oxidized, calcareous, pebbly, olive in color, limestone and shale pebbles predominant, damp, no free water.
9 - 40	Shale, dark grey (5Y 3/1), non-calcareous, interior portions of shale fragments are light grey, interbedded soft and hard units, some zones appear to be saturated.

Piezometer nest no. 14 Date: July 1, 1971

Location: NW 35-3-24W

Elevation 1569.9 feet A.S.L.

Depth (feet)	Description
0 - 1	Topsoil has been removed by road cut (thin Orthic

Depth (feet)	Description
	Black Profile in adjacent areas).
1 - 3	Silt, olive in color, slightly laminated, calcareous, some salt crystals and gypsum present.
3 - 27	Till, calcareous clay loam, olive in color, mixed pebble composition of carbonates and shales, precambrian pebbles rare, grades to dark olive at 25 feet, slightly oxidized and gypsum crystals common at 20 to 25 feet.
27 - 45	Unoxidized, dark grey (5Y 4/1), apparent boulder layer at 25 to 26 feet, large enough to obstruct drilling, till below 27 feet becomes more shaly, seems to grade gradually into shale bedrock.
45 - 60	Shale, relatively soft, crumbly, dark grey (5Y 4/1 to 3/1), non-calcareous.

Piezometer nest no. 15 Date: July 1, 1971

Location: NE 19-2-23W

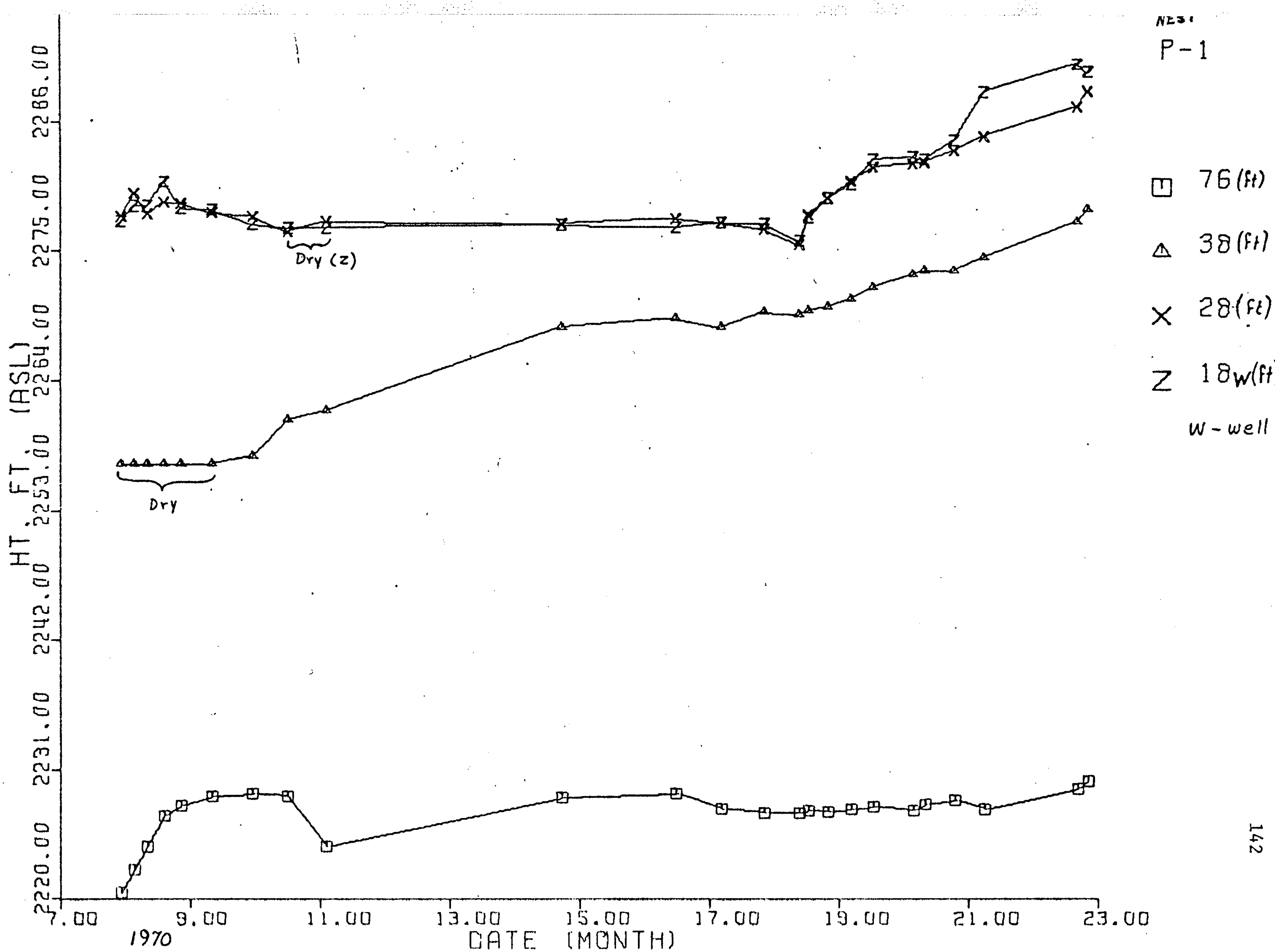
Elevation: 1656.4 feet A.S.L.

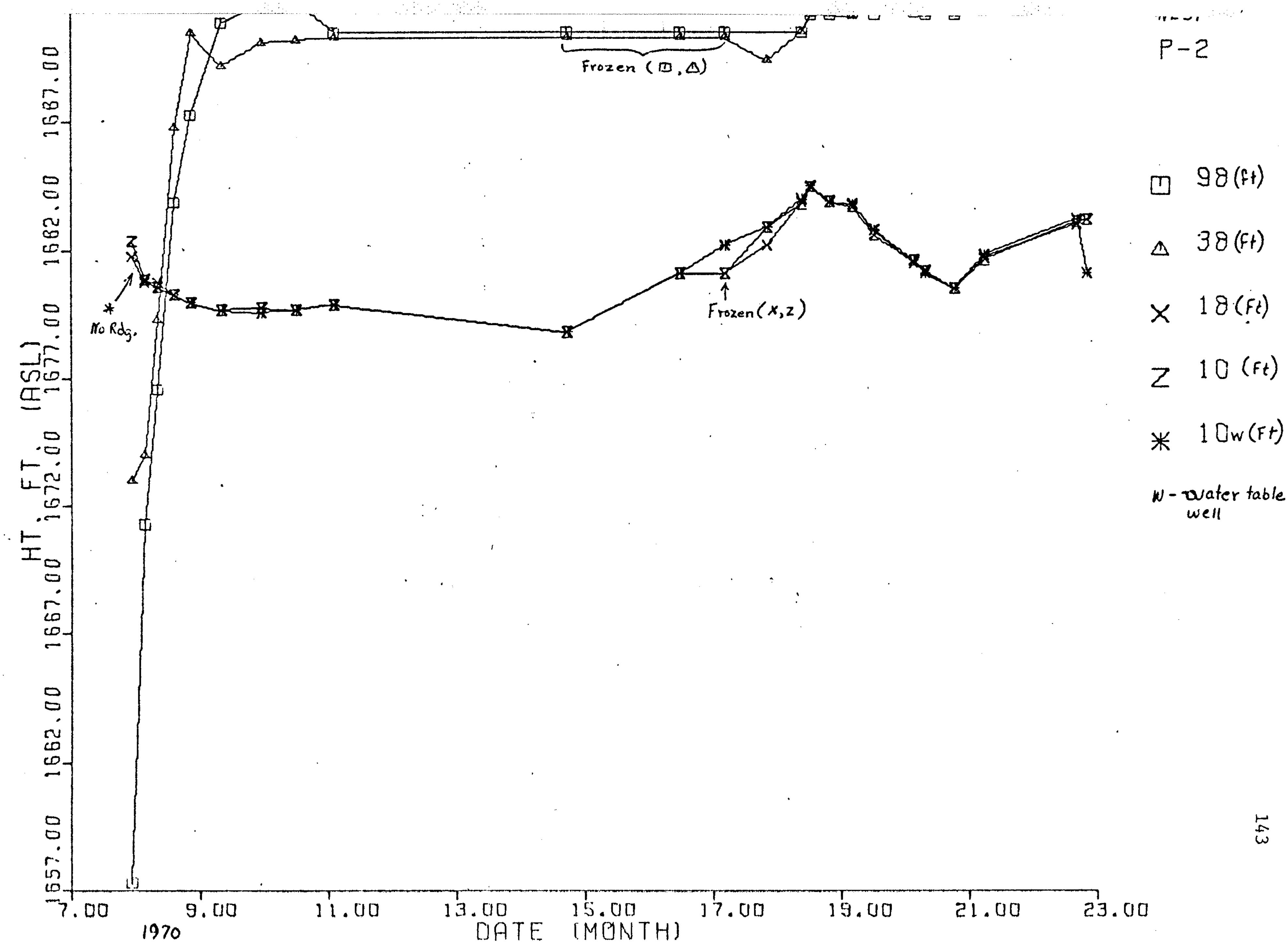
Depth (feet)	Description
0 - 2	Road fill, gypsum and salt crystals very evident, (Saline Gleyed Carbonated Rego Black Profiles in adjacent areas).
2 - 7	Grades into a pebbly, silty lacustrine clay, irregularly laminated, salt crystals prominent.

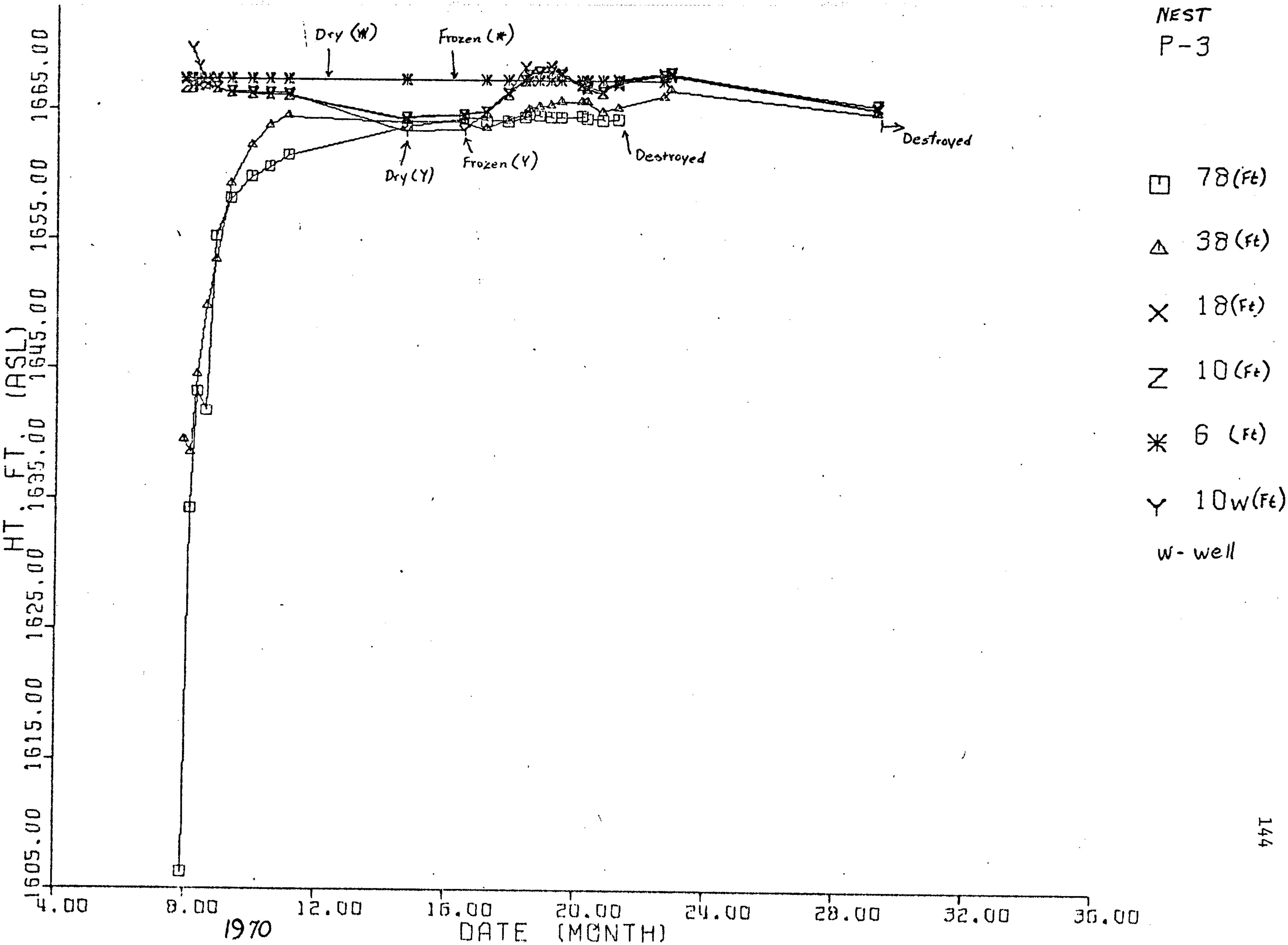
APPENDIX C

Hydrographs of Piezometers and Wells

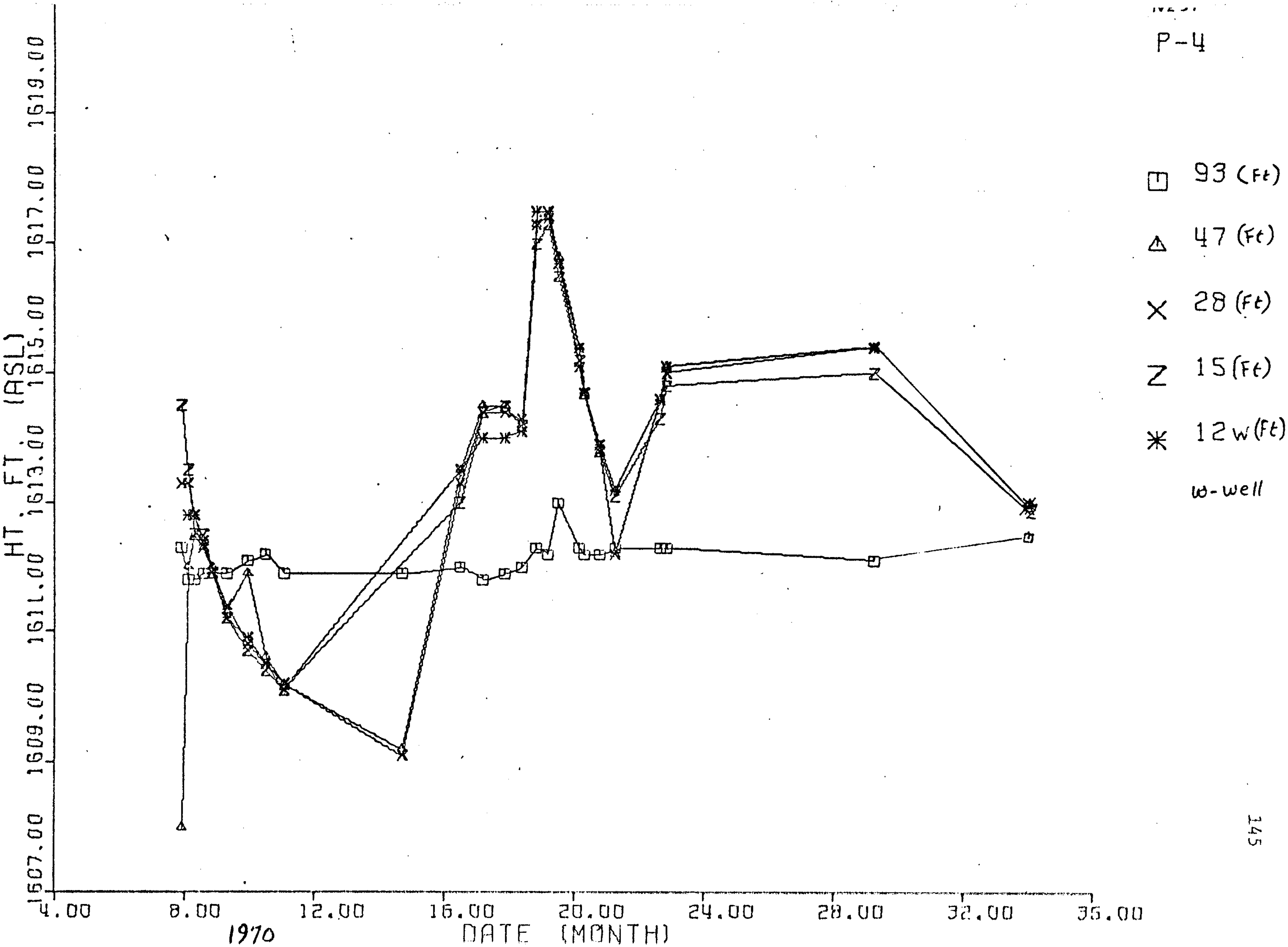
Nests 1 to 15


NEST
P-1
76 (ft)
38 (ft)
28 (ft)
18w (ft)
W - well
HT. FT. (ASL)
2220.00
2231.00
2242.00
2253.00
2264.00
2275.00
2286.00
Dry
Dry (z)
7.00
9.00
11.00
13.00
15.00
17.00
19.00
21.00
23.00
1970
DATE (MONTH)

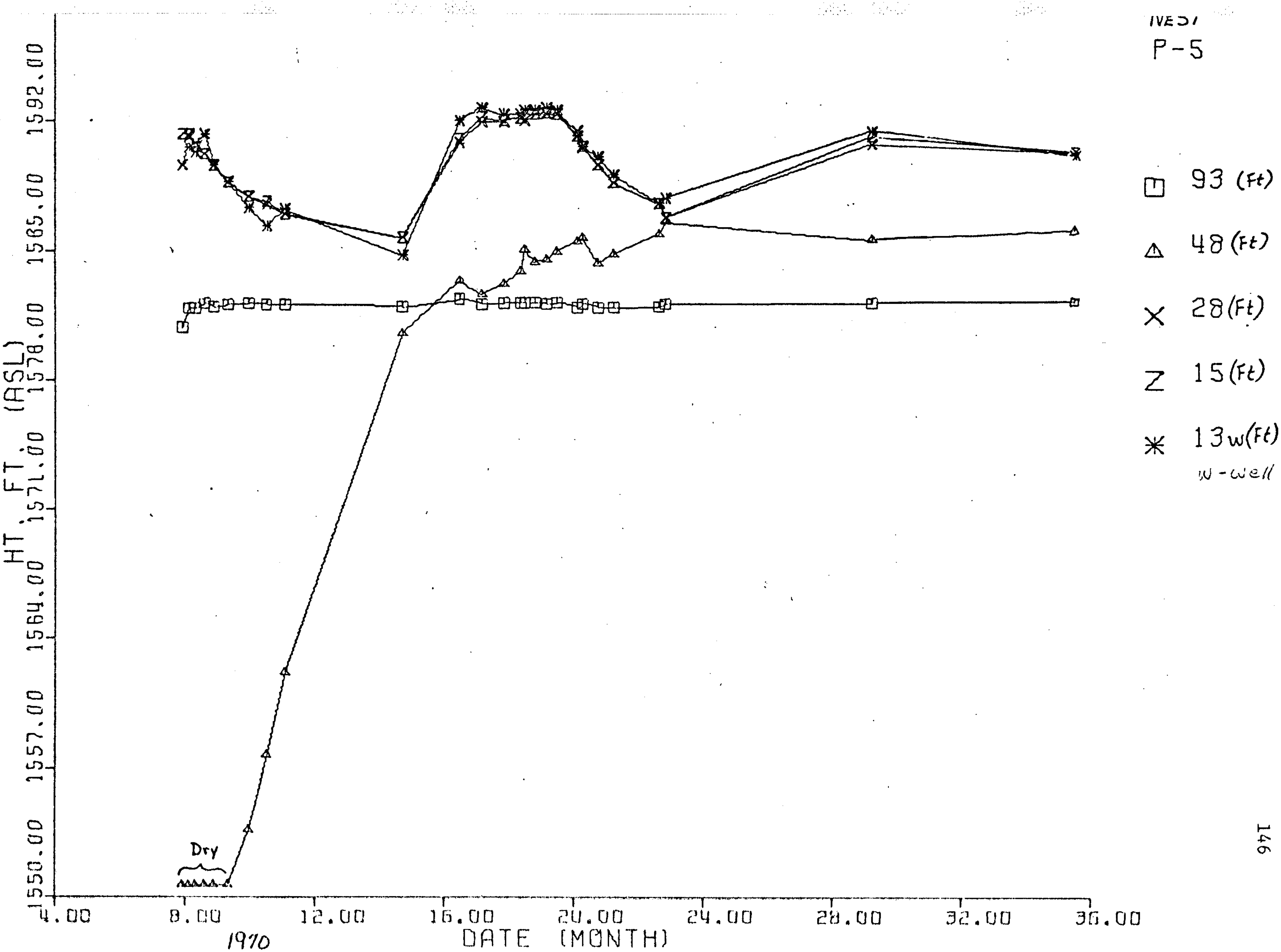

P-2
Frozen (□, △)
Frozen (x, z)
No Rdg.
□ 98 (ft)
△ 38 (ft)
X 18 (ft)
Z 10 (ft)
✳ 10w (ft)
W - water table well
HT. FT. (ASL)
1657.00
1662.00
1667.00
1672.00
1677.00
1682.00
1687.00
7.00
9.00
11.00
13.00
15.00
17.00
19.00
21.00
23.00
1970
DATE (MONTH)

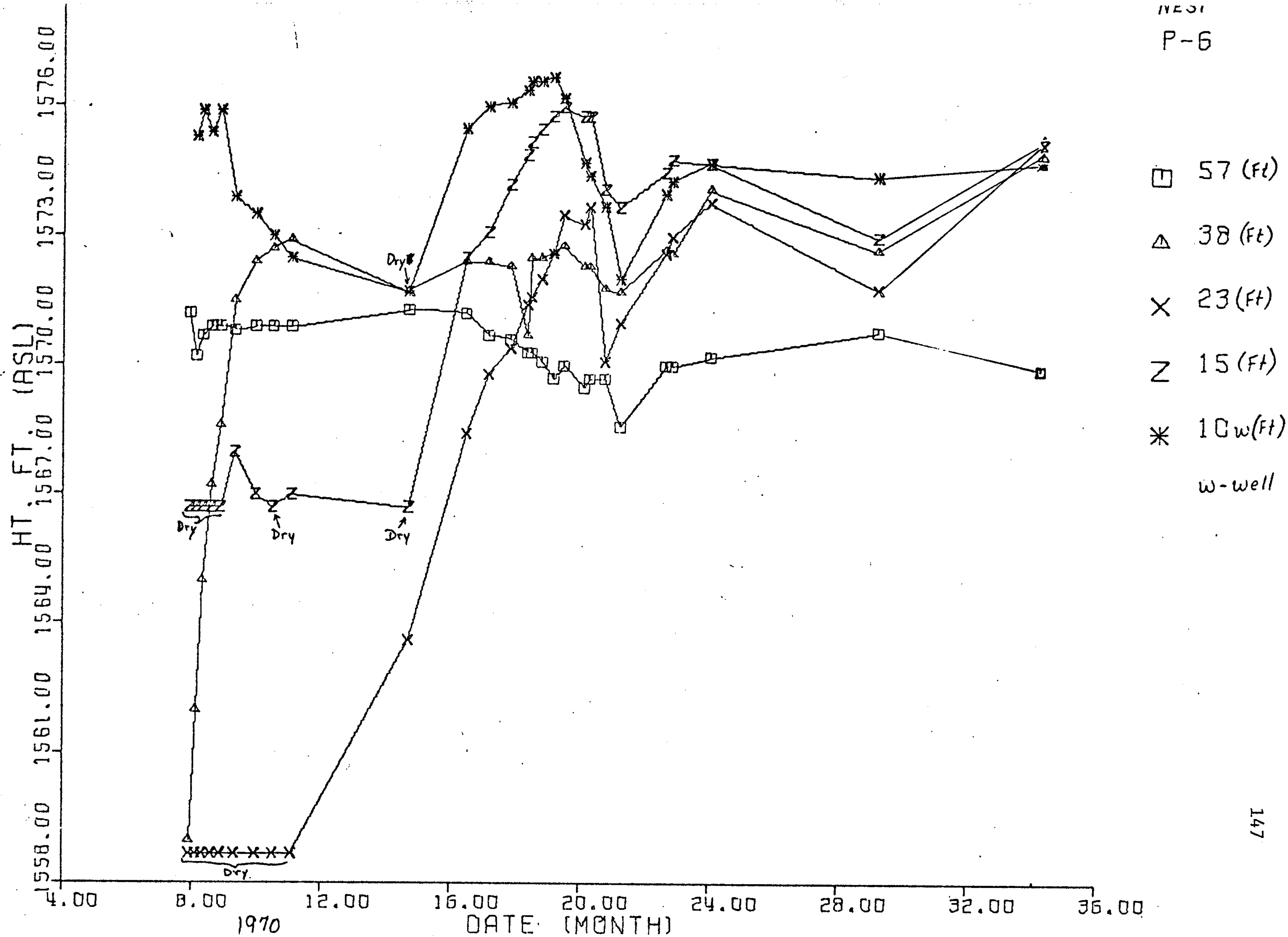


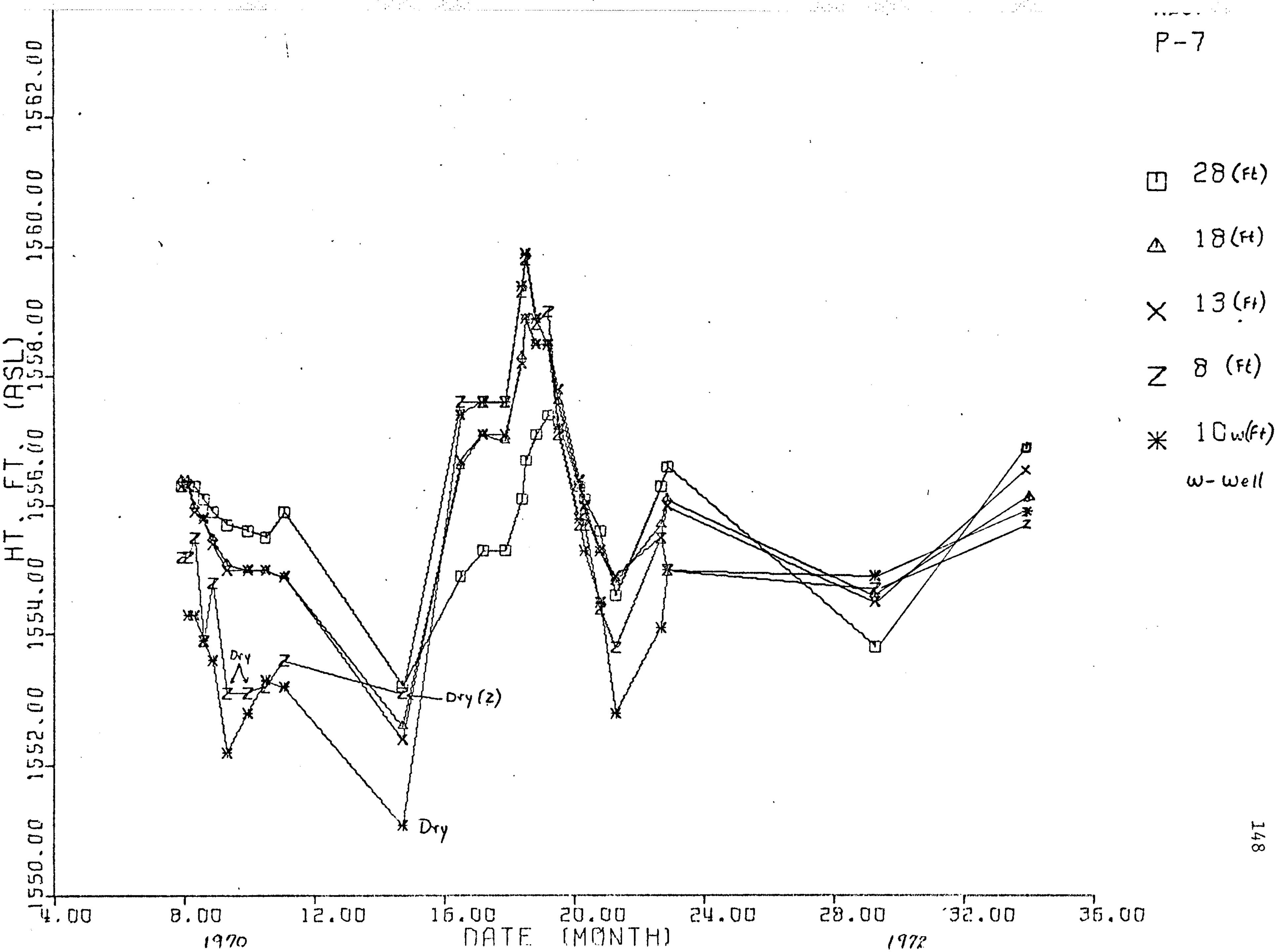
NEST
P-3
Dry (W)
Frozen (*)
Dry (Y)
Frozen (Y)
Destroyed
Destroyed
78 (Ft)
38 (Ft)
18 (Ft)
10 (Ft)
6 (Ft)
10w (Ft)
w - well
HT. FT. (ASL)
1605.00
1615.00
1625.00
1635.00
1645.00
1655.00
1665.00
4.00
8.00
12.00
16.00
20.00
24.00
28.00
32.00
36.00
1970
DATE (MONTH)

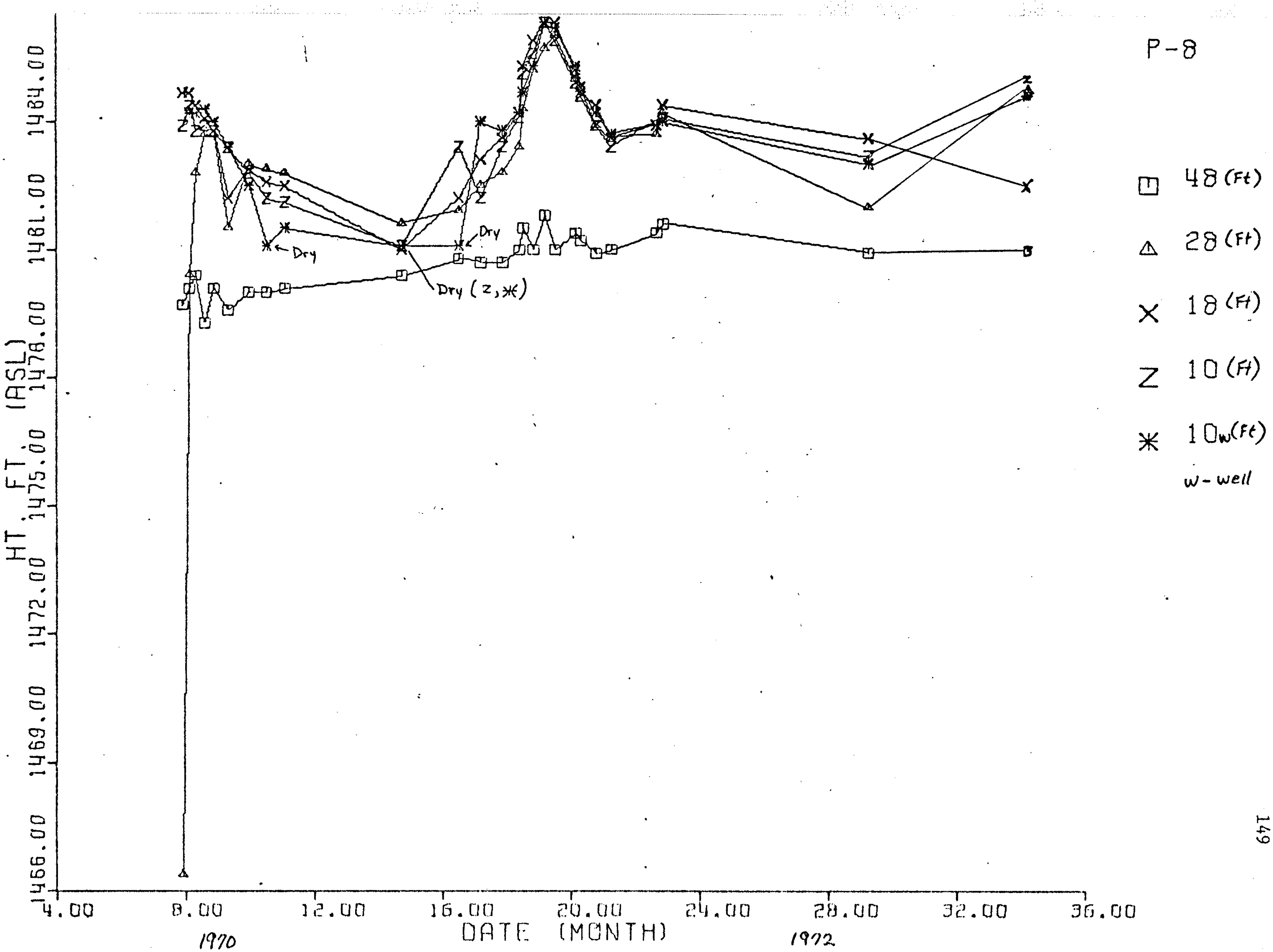


P-4
1619.00
1617.00
1615.00
1613.00
1611.00
1609.00
1607.00
HT. FT. (ASL)
4.00
8.00
12.00
16.00
20.00
24.00
28.00
32.00
35.00
1970
DATE (MONTH)
93 (Ft)
47 (Ft)
28 (Ft)
15 (Ft)
12 w (Ft)
w-well

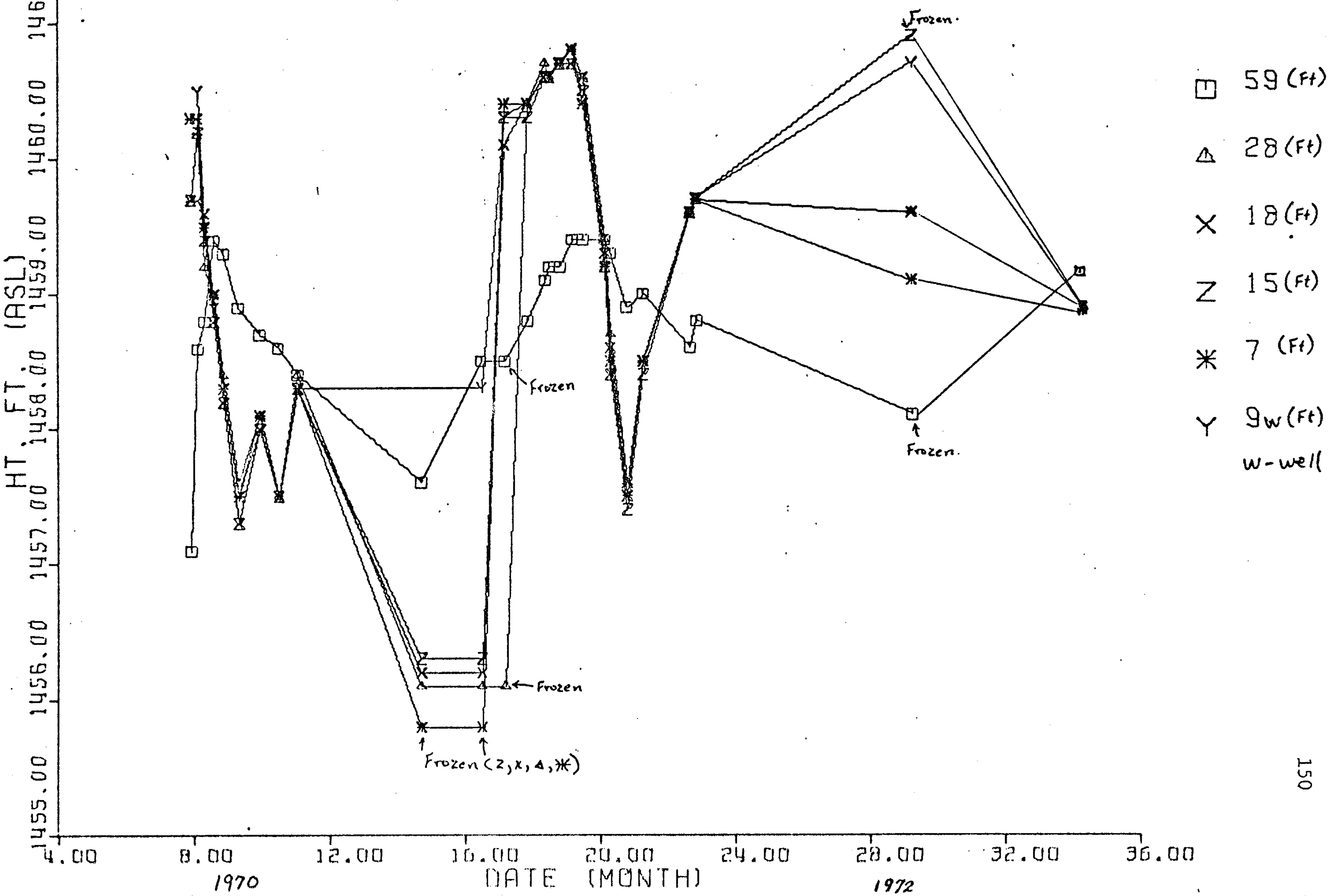

P-5
HT. FT. (ASL)
1592.00
1585.00
1578.00
1571.00
1564.00
1557.00
1550.00
4.00
8.00
12.00
16.00
20.00
24.00
28.00
32.00
36.00
DATE (MONTH)
1970
Dry
93 (Ft)
48 (Ft)
28 (Ft)
15 (Ft)
13w (Ft)
w-well


P-6
HT. FT. (ASL)
1558.00
1561.00
1564.00
1567.00
1570.00
1573.00
1576.00
4.00
8.00
12.00
16.00
20.00
24.00
28.00
32.00
36.00
DATE (MONTH)
1970
Dry
Dry
Dry
Dry
Dry
57 (Ft)
38 (Ft)
23 (Ft)
15 (Ft)
10 w (Ft)
w-well

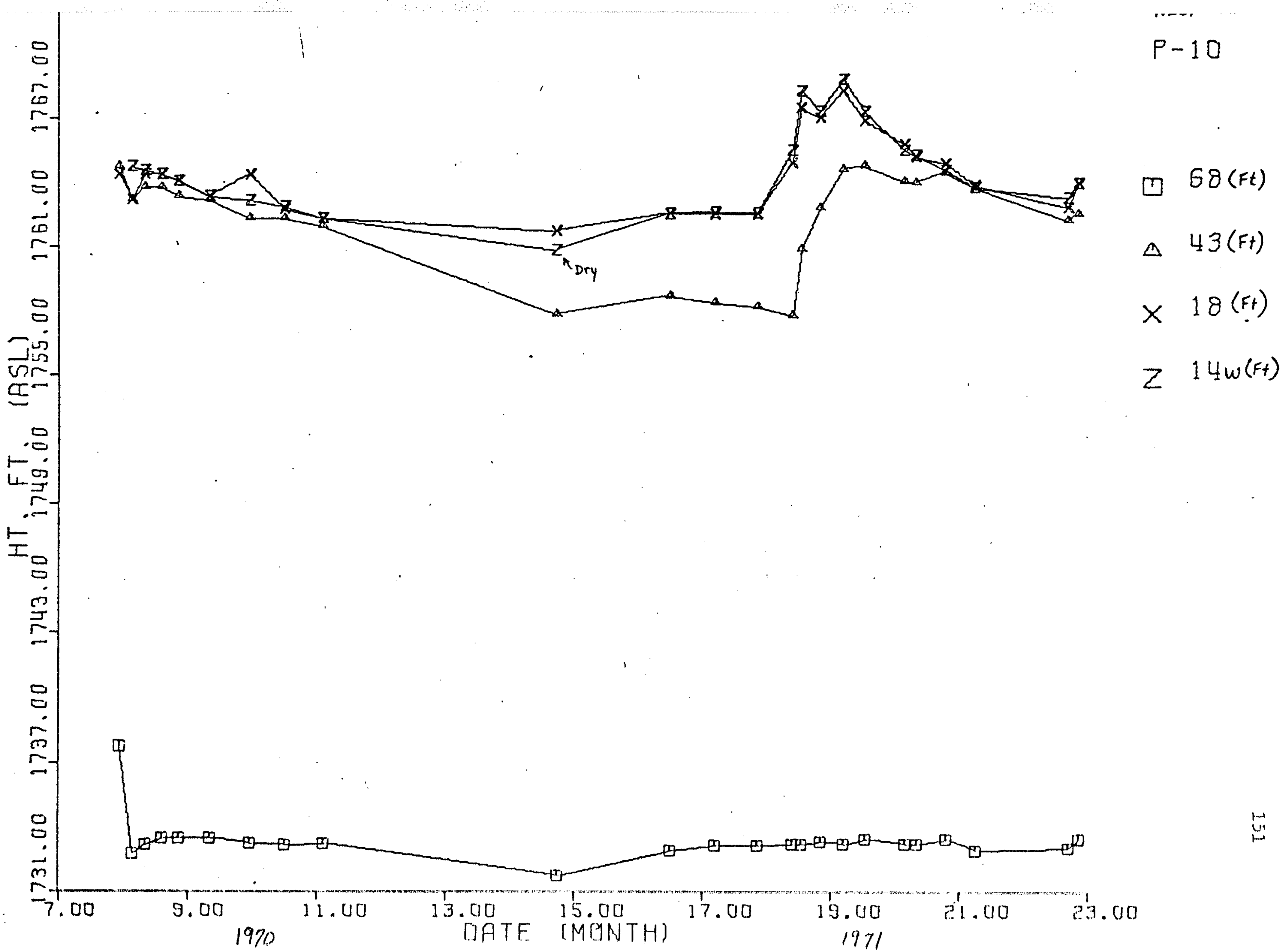

P-7
28 (Ft)
18 (Ft)
13 (Ft)
8 (Ft)
10 w(Ft)
w- well
HT. FT. (ASL)
1550.00
1552.00
1554.00
1556.00
1558.00
1560.00
1562.00
4.00
8.00
12.00
16.00
20.00
24.00
28.00
32.00
36.00
DATE (MONTH)
1970
1972
Dry
Dry (Z)
Dry


P-8
HT. FT. (ASL)
1484.00
1481.00
1478.00
1475.00
1472.00
1469.00
1466.00
4.00
8.00
12.00
16.00
20.00
24.00
28.00
32.00
36.00
DATE (MONTH)
1970
1972
Dry
Dry
Dry (z, ✳)
48 (Ft)
28 (Ft)
18 (Ft)
10 (Ft)
10w (Ft)
w - well

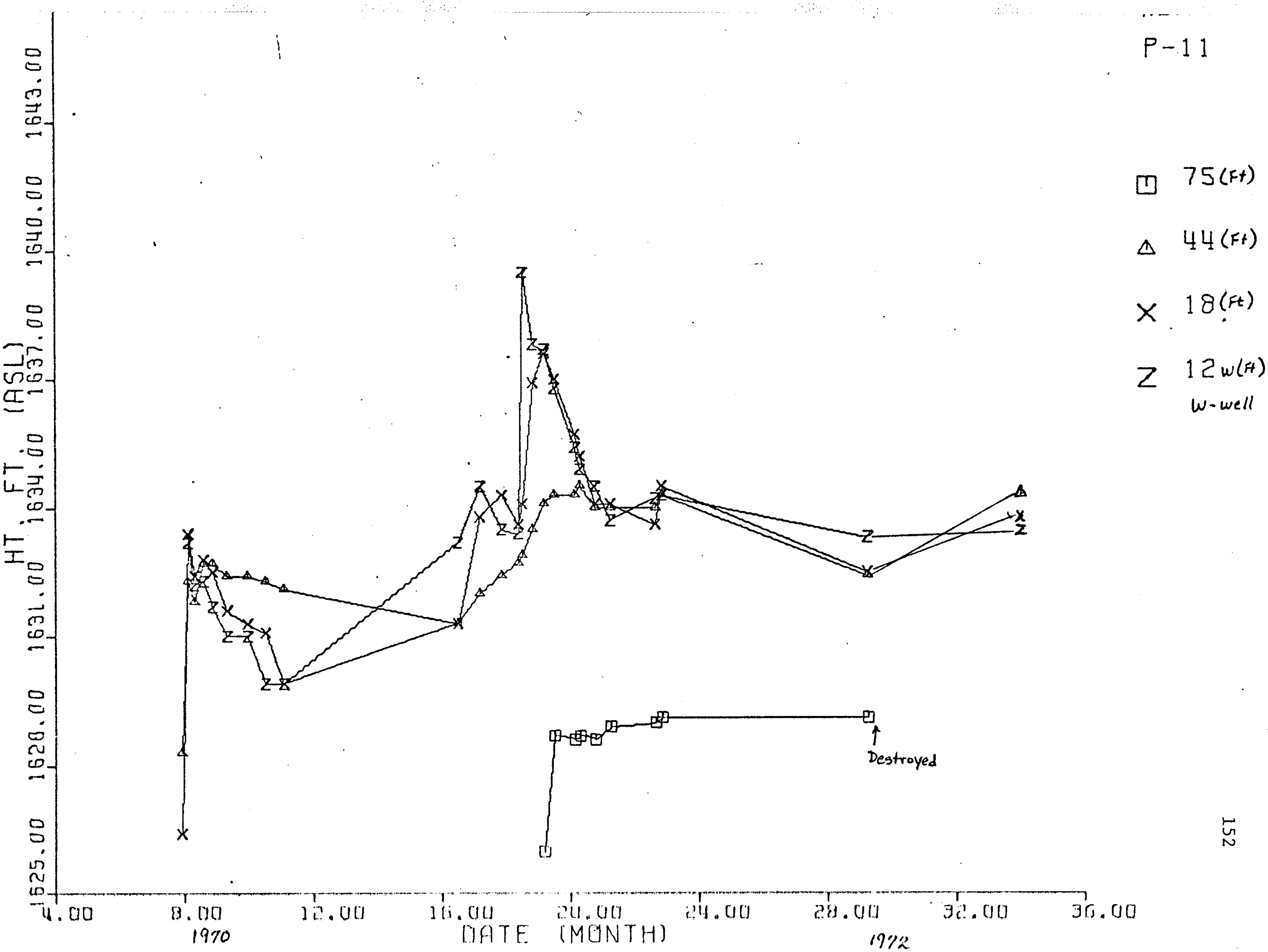
P-9



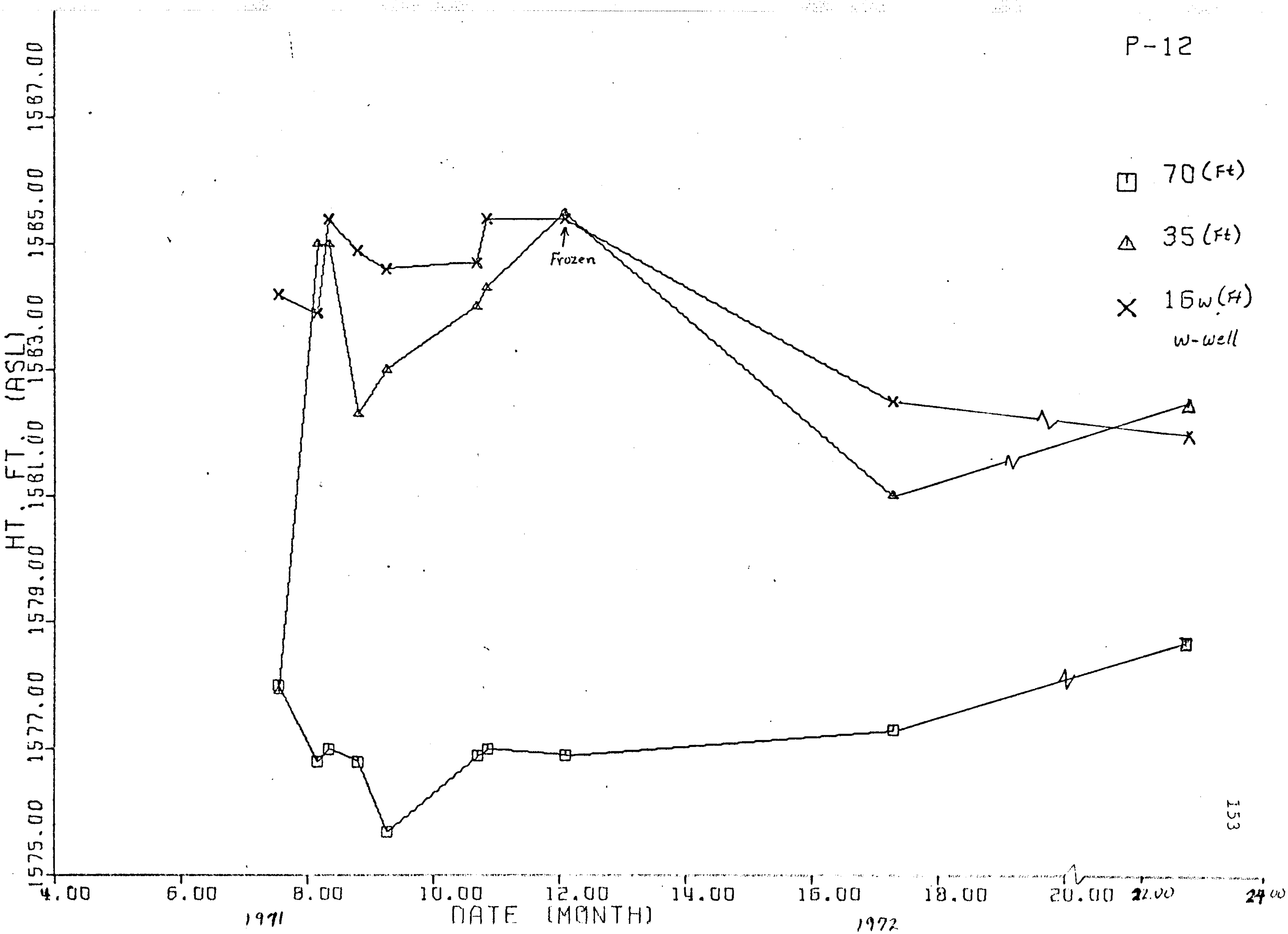
HT. FT. (ASL)
1455.00
1456.00
1457.00
1458.00
1459.00
1460.00
1461.00
4.00
8.00
12.00
16.00
20.00
24.00
28.00
32.00
36.00
DATE (MONTH)
1970
1972
59 (Ft)
28 (Ft)
18 (Ft)
15 (Ft)
7 (Ft)
9w (Ft)
w-well
Frozen
Frozen
Frozen
Frozen
Frozen (z, x, Δ, ✳)

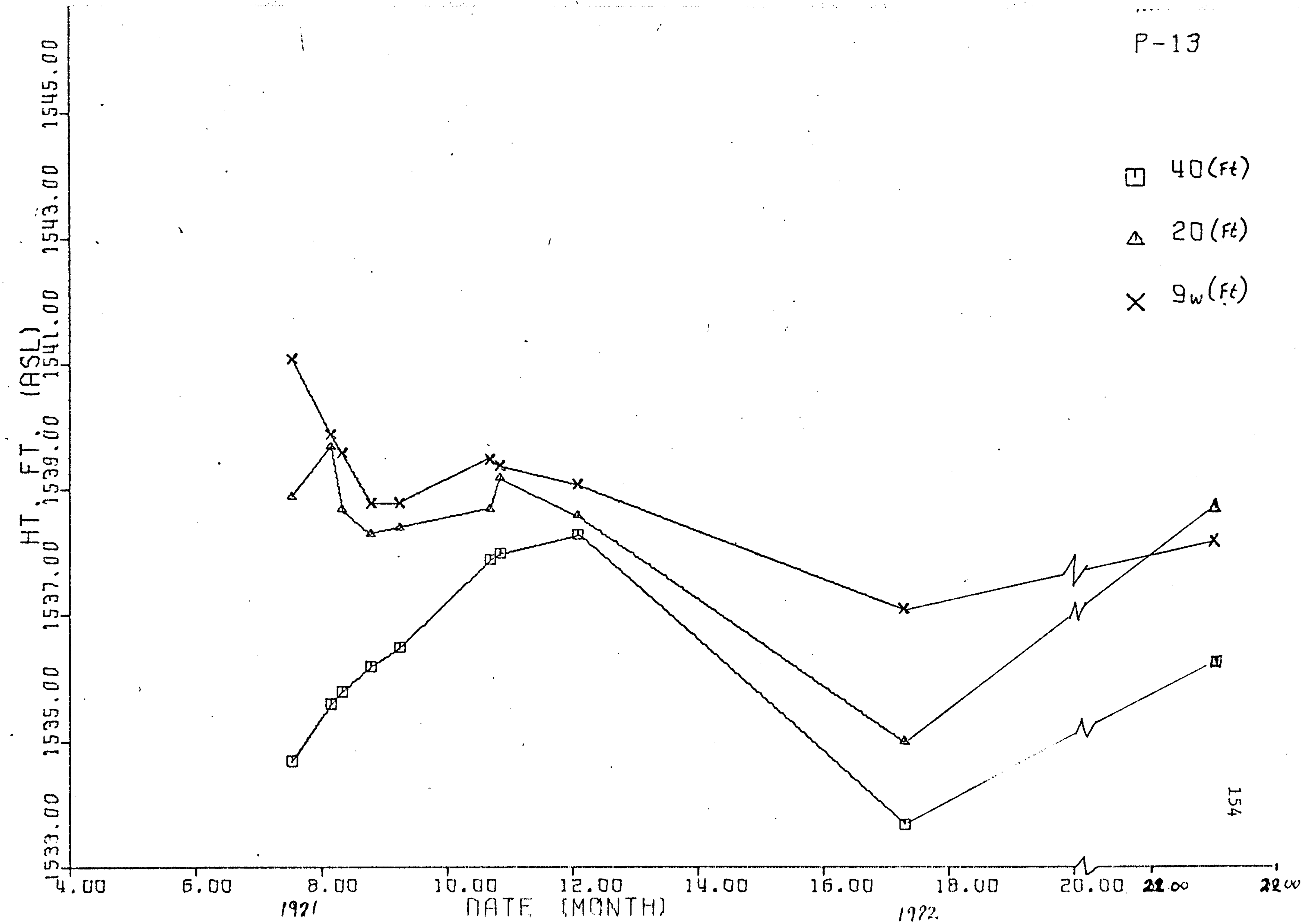

P-10
68 (Ft)
43 (Ft)
18 (Ft)
14w (Ft)
HT. FT. (ASL)
1731.00
1737.00
1743.00
1749.00
1755.00
1761.00
1767.00
Dry
7.00
9.00
11.00
13.00
15.00
17.00
19.00
21.00
23.00
DATE (MONTH)
1970
1971

P-11

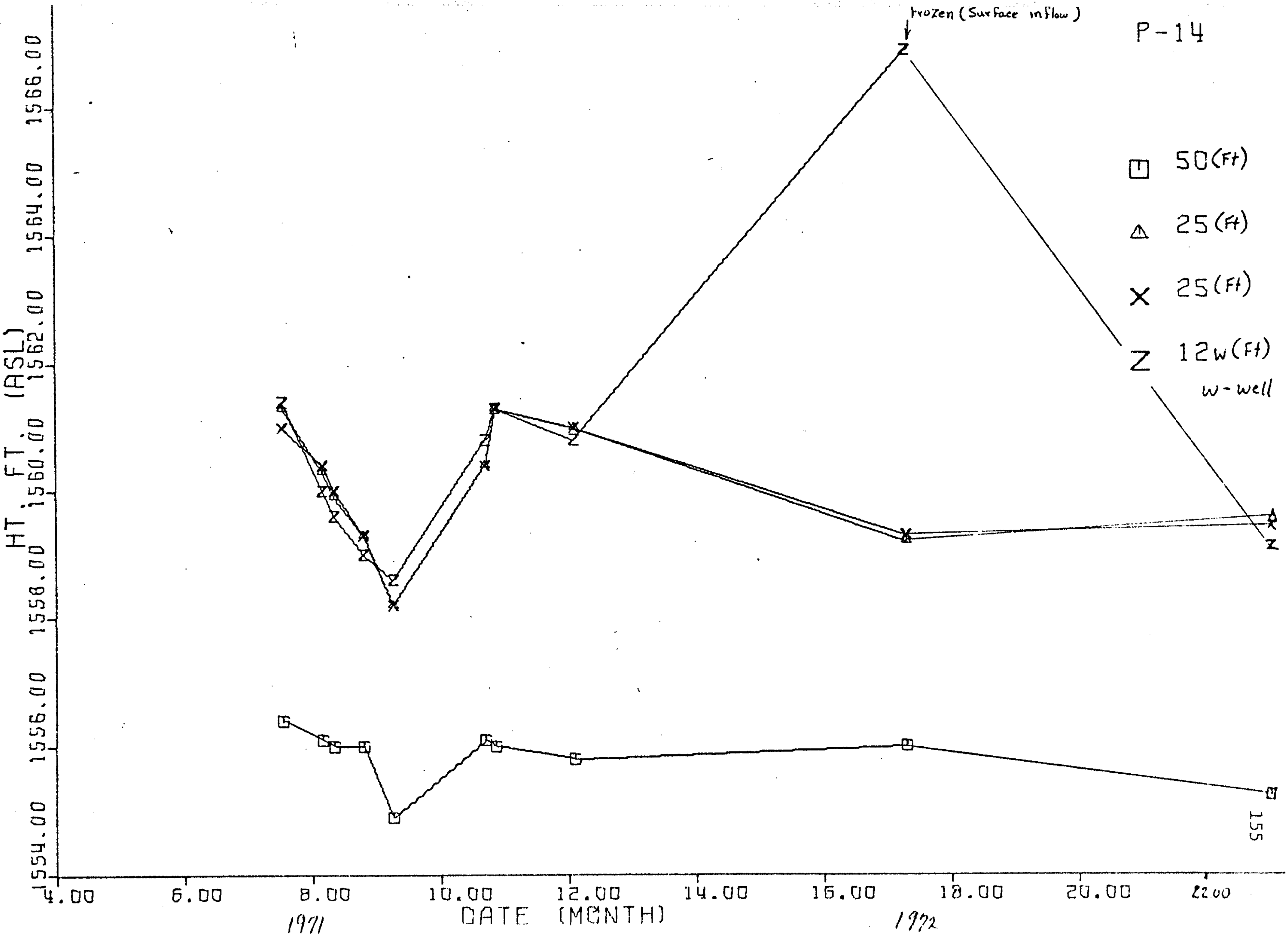


75(Ft)
44(Ft)
18(Ft)
12w(Ft)
W-well
HT. FT. (ASL)
1625.00
1628.00
1631.00
1634.00
1637.00
1640.00
1643.00
4.00
8.00
12.00
16.00
20.00
24.00
28.00
32.00
36.00
1970
DATE (MONTH)
1972
Destroyed


P-12
70 (Ft)
35 (Ft)
16w (Ft)
w-well
Frozen
HT. FT. (ASL)
1575.00
1577.00
1579.00
1581.00
1583.00
1585.00
1587.00
4.00
6.00
8.00
10.00
12.00
14.00
16.00
18.00
20.00
22.00
24.00
DATE (MONTH)
1971
1972
153

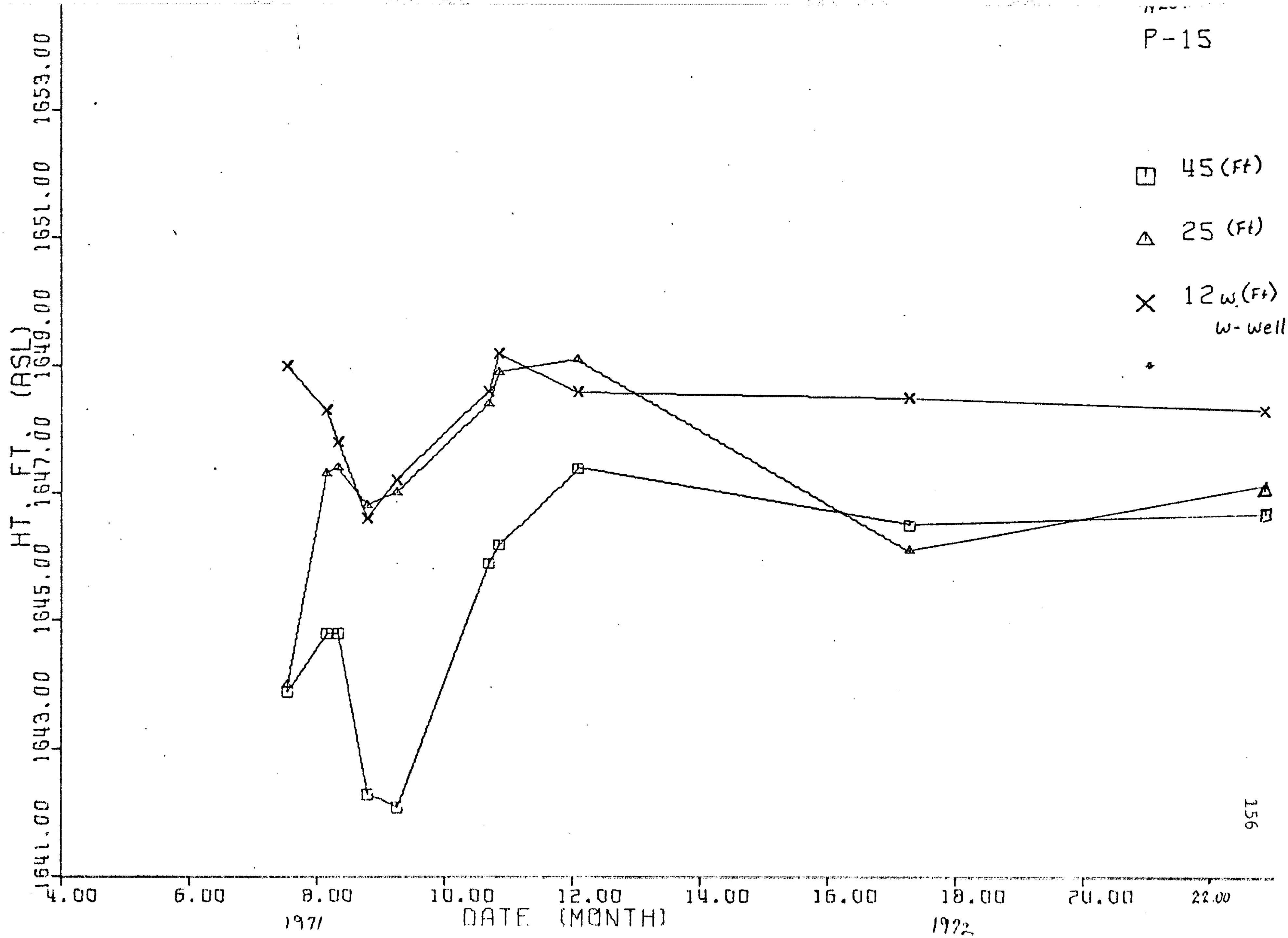


P-13
40(Ft)
20(Ft)
9w(Ft)
HT. FT. (ASL)
1545.00
1543.00
1541.00
1539.00
1537.00
1535.00
1533.00
4.00
6.00
8.00
10.00
12.00
14.00
16.00
18.00
20.00
DATE (MONTH)
1921
1922
154



Frozen (Surface inflow)
P-14
50 (Ft)
25 (Ft)
25 (Ft)
12w (Ft)
w - well
HT. FT. (ASL)
1554.00
1556.00
1558.00
1560.00
1562.00
1564.00
1566.00
4.00
6.00
8.00
10.00
12.00
14.00
16.00
18.00
20.00
22.00
DATE (MONTH)
1971
1972

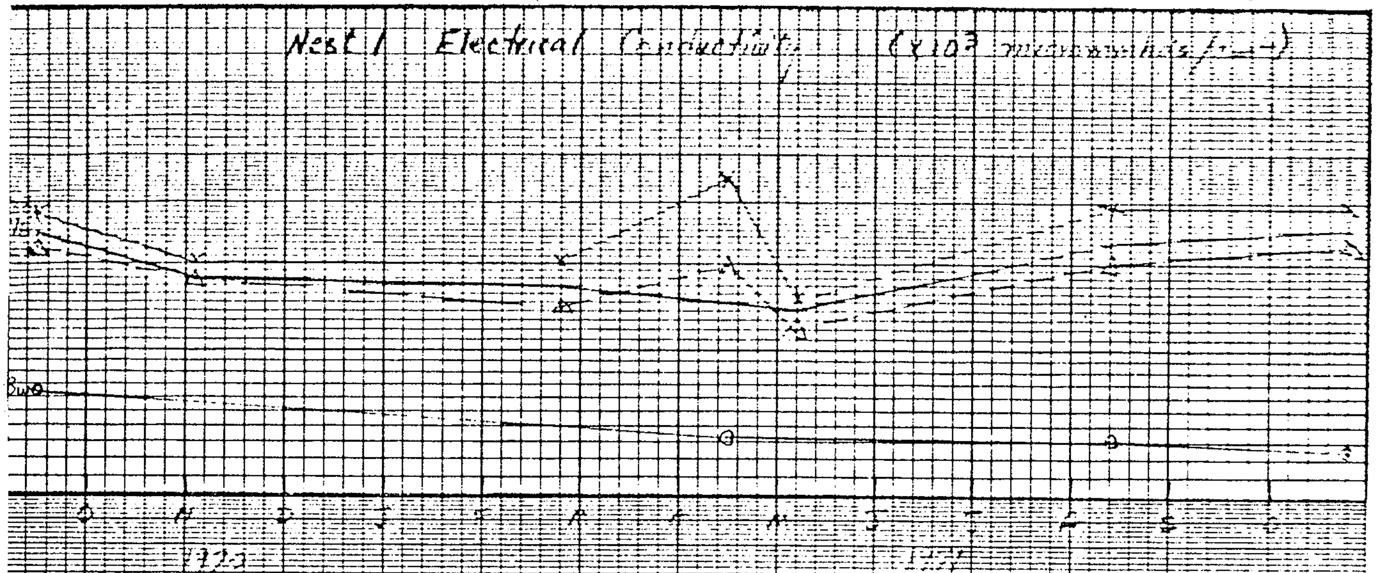
155

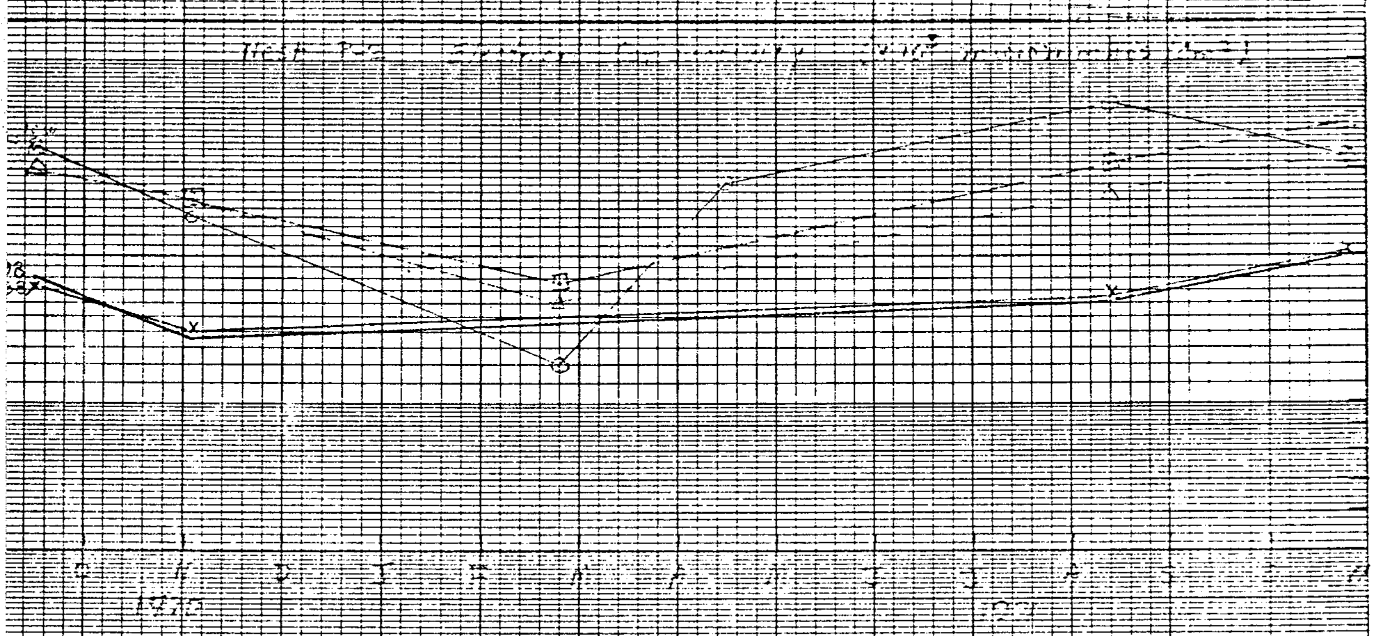

P-15
45 (Ft)
25 (Ft)
12 w (Ft)
w - well
HT. FT. (ASL)
1653.00
1651.00
1649.00
1647.00
1645.00
1643.00
1641.00
4.00
6.00
8.00
10.00
12.00
14.00
16.00
18.00
20.00
22.00
DATE (MONTH)
1971
1972
156

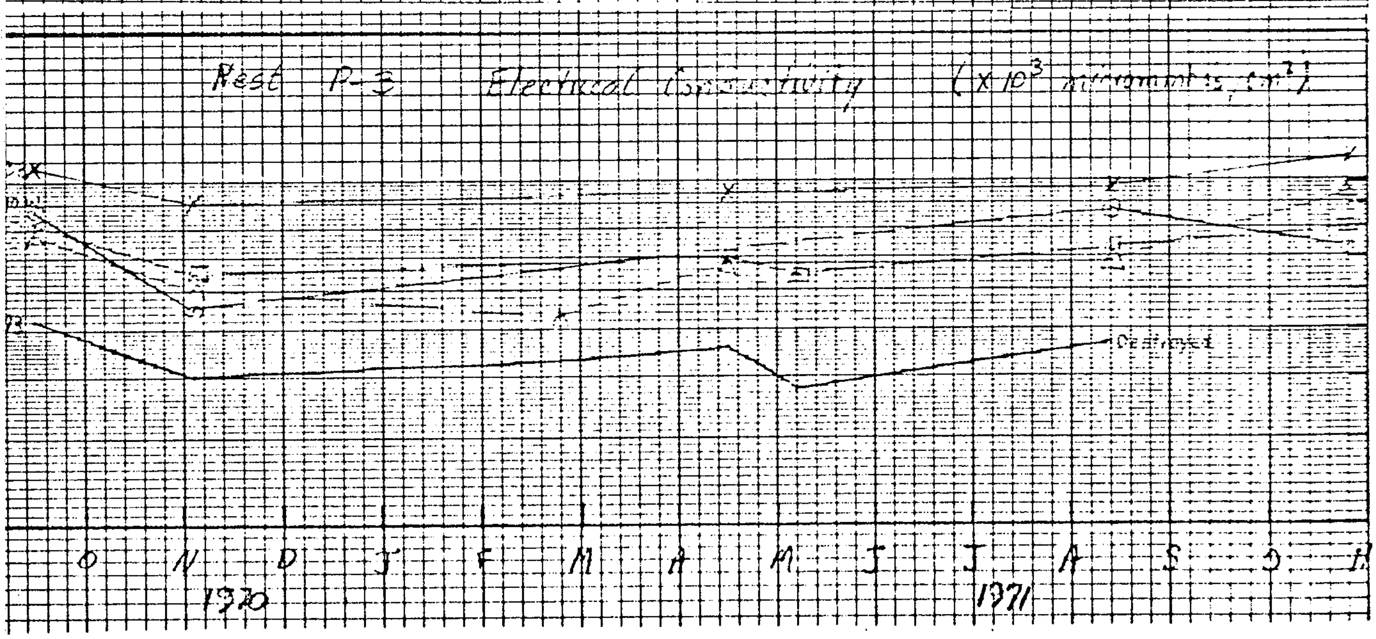
APPENDIX D

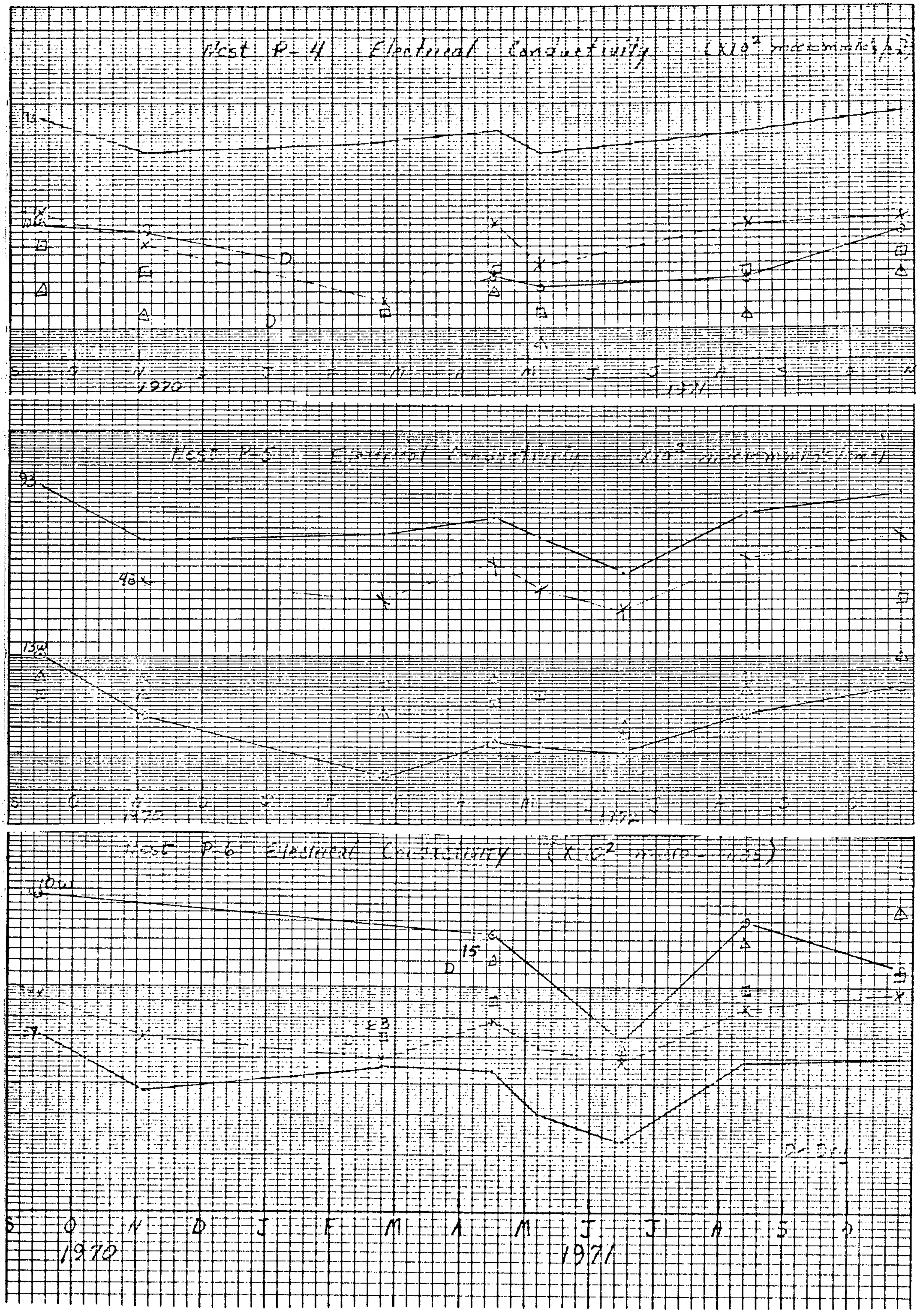
Field Measurements of Electrical Conductivities of Groundwater

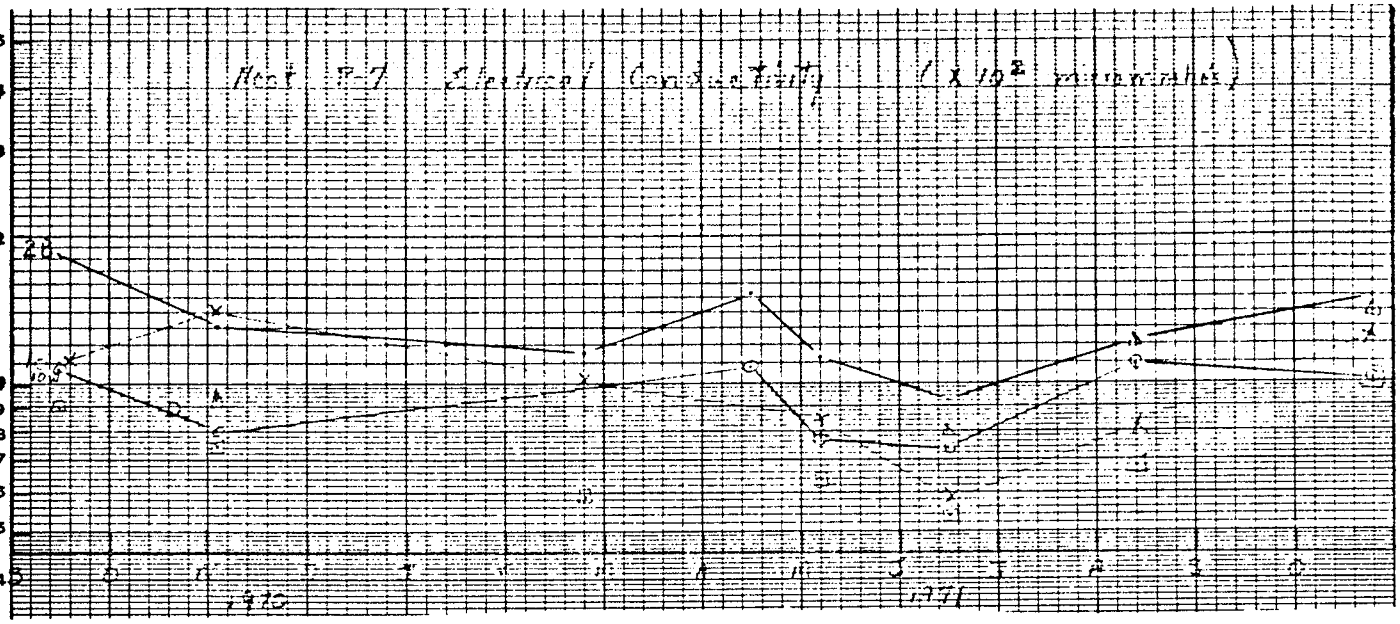
Nests 1 to 11

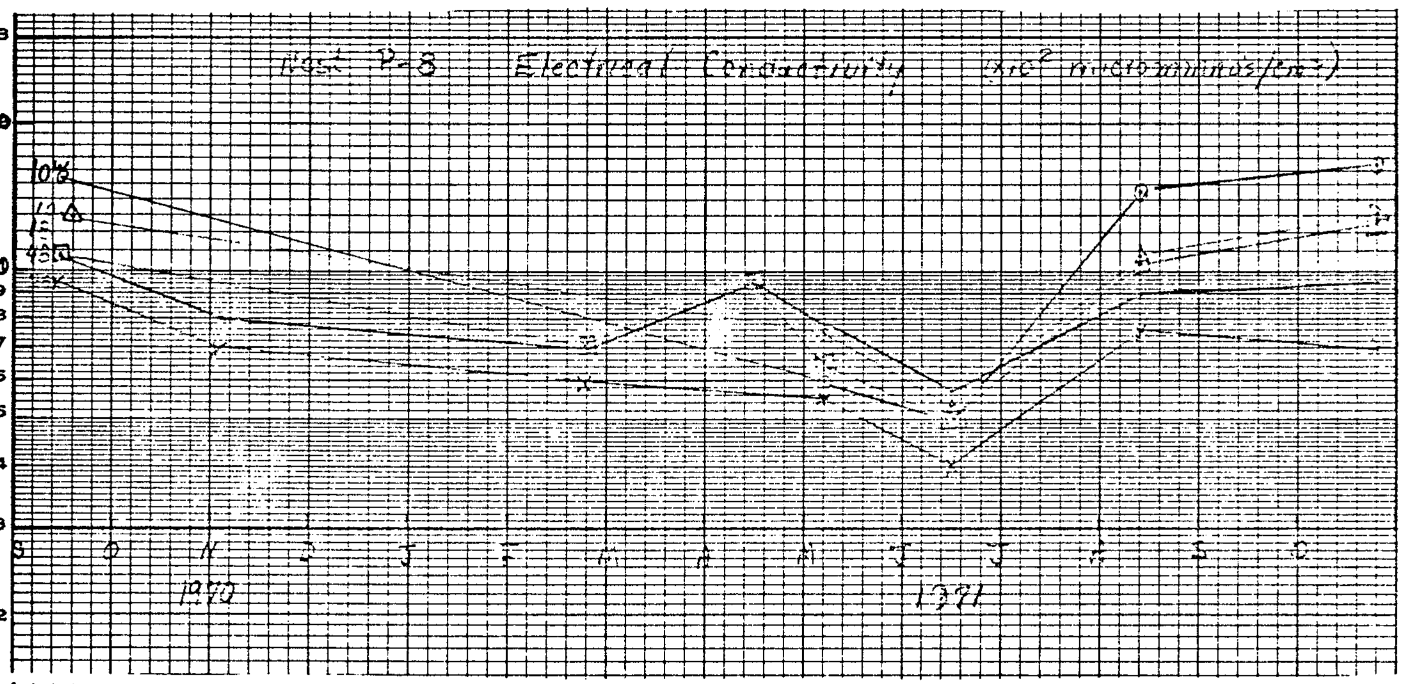

Nest 1 Electrical
O
N
D
J
F
M
A
M
J
J
A
S
O

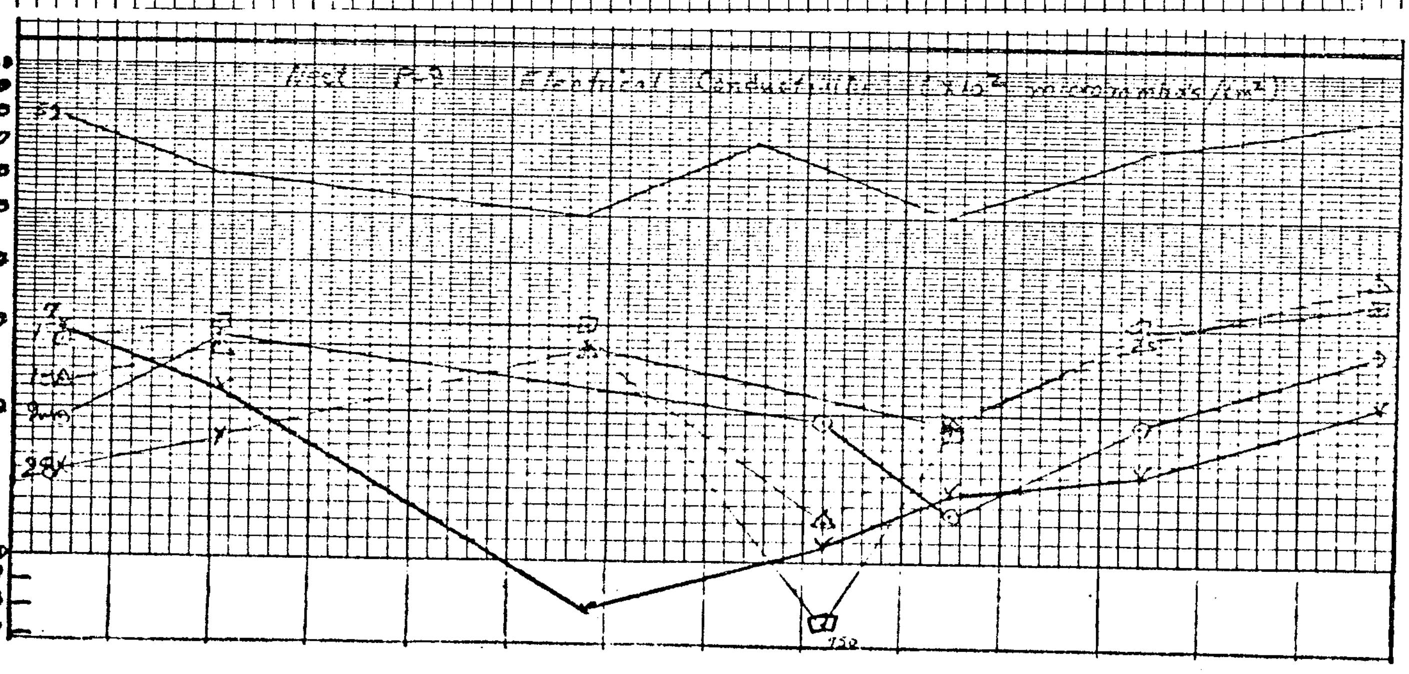

O
N
D
J
F
M
A
M
J
J
A
S
O
N

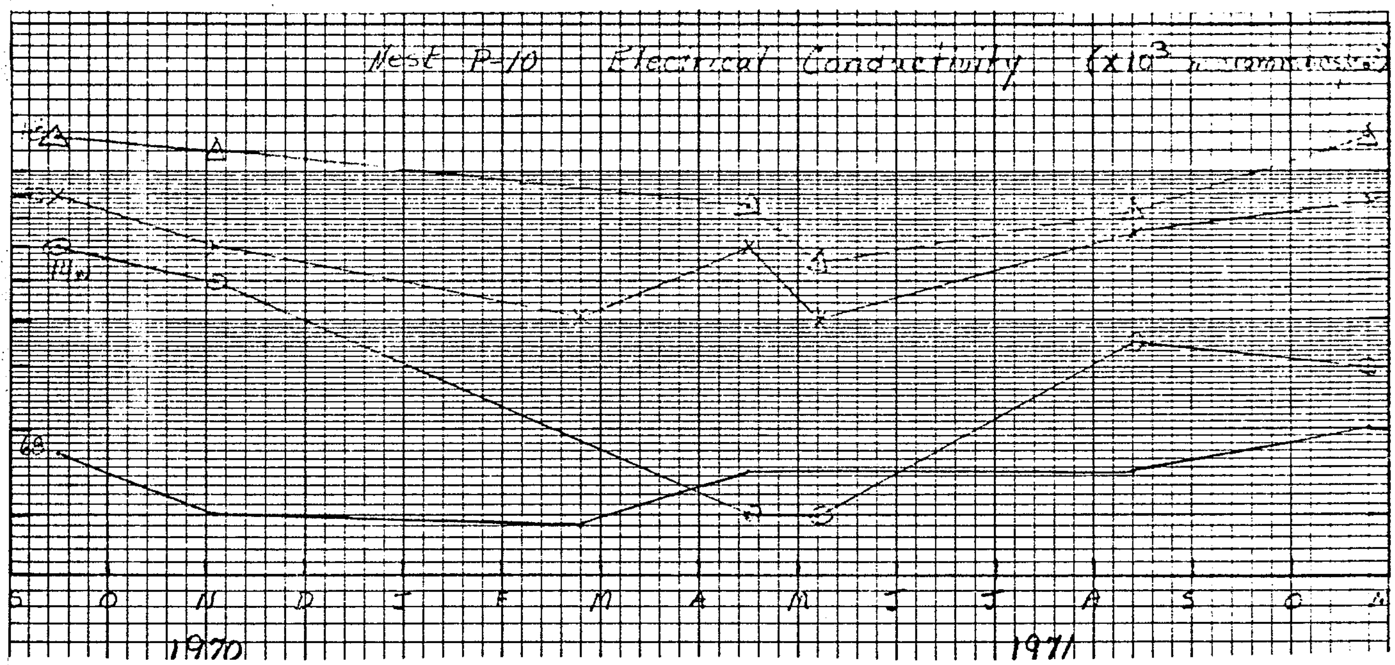

Nest P-3 Electrical
Destroyed
O
N
D
J
F
M
A
M
J
J
A
S
O
N
1970
1971

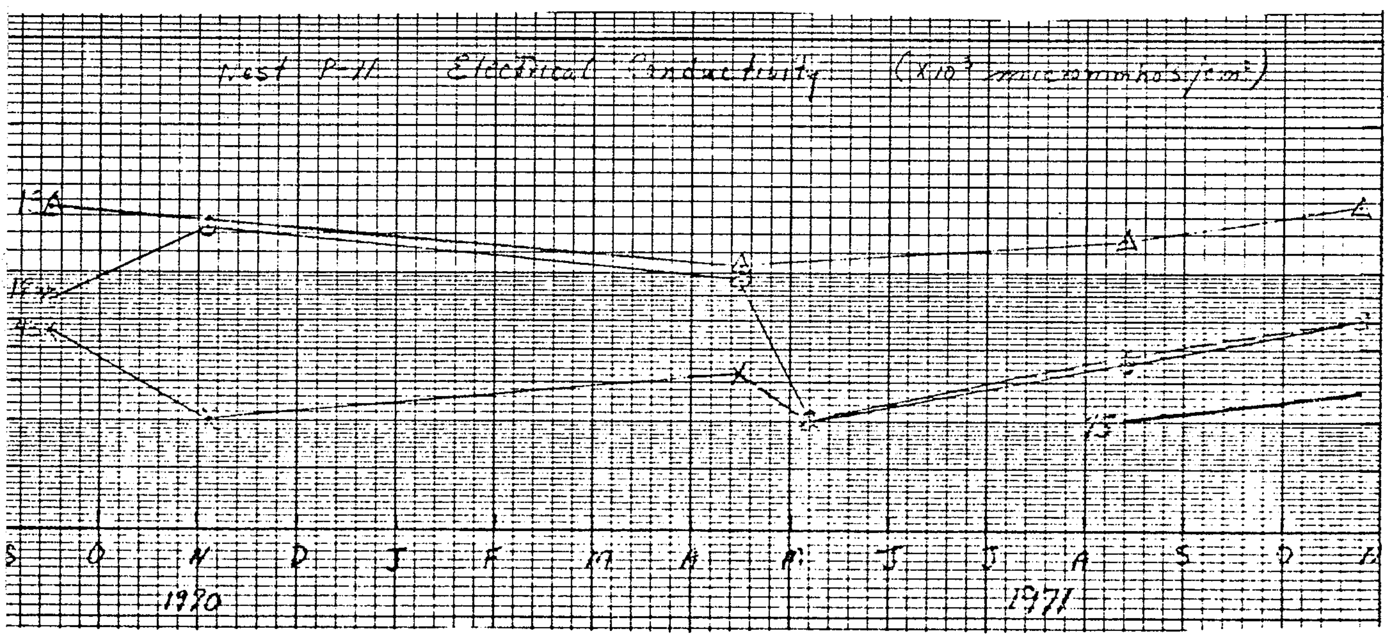

West P-4 Electrical Conductivity
West P-6
S O N D J F M A M J J A S O
1970
1971


Nest P-7 Electrical Conductivity (X 10² micromhos)
EC
1970
1971


Nest P-8 Electrical Conductivity (x10² micromhos/cm²)
1970
1971


Nest P-9 Electrical Conductivity (X10² micromhos/cm²)


Nest P-10 Electrical Conductivity (x10³ micromhos/cm²)
S O N D J F M A M J J A S O N
1970
1971


Nest P-11 Electrical Conductivity (x10³ micromhos/cm²)
S O N D J F M A M J J A S O N
1970
1971

APPENDIX E-1

Groundwater Chemistry at Piezometer Nests 1 to 15, 1971

	PIEZOMETER NUMBER AND DEPTH BELOW GROUND SURFACE											
	P-1-18W		P-1-28		P-1-38		P-1-76					
DATE INSTALLED												
DATE FLUSHED												
DATE SAMPLED	Aug. 10/71		Aug. 10/71		Aug. 10/71		Aug. 10/71					
DATE ANALYZED												
Analyzed By												
pH-Field	7.391		7.161		7.121		8.154					
pH-Lab	7.45		7.25		7.25		7.50					
Cond-Field	725		1175		1350		1450					
Cond-Lab	1310		3010		3870		3300					
°C-Field	°4		°4		°4		°4					
	mg/1	meq/1	mg/1	meq/1	mg/1	meq/1	mg/1	meq/1	mg/1	meq/1	mg/1	meq/1
Na	6.9	0.30	44.85	1.95	209.99	9.13	189.98	8.26				
K												
Ca	142.28	7.10	542.48	27.07	476.95	23.80	465.52	23.23				
Mg	127.19	10.46	183.25	15.07	329.17	27.07	166.96	13.73				
T.CAT.		17.86		44.19		60.00		45.21				
CI	8.16	0.23	24.82	0.70	49.99	1.41	83.33	2.35				
SO_4	441.39	9.19	1703.62	35.47	2374.60	49.44	1752.13	36.48				
HCO_3(titr.)	549.09	9.00	533.84	8.75	625.35	10.25	427.07	7.00				
HCO_3(calc.)												
CO_3												
T.ANS.		18.42		44.92		61.10		45.83				
TDS		36.28		89.11		121.10		91.04				

		PIEZOMETER NUMBER AND DEPTH BELOW GROUND SURFACE											
		P-2-10W		P-2-10		P-2-18		P-2-38		P-2-98W		
DATE	INSTALLED											
	FLUSHED											
	SAMPLED	Aug. 10/71		Aug. 10/71		Aug. 10/71		Aug. 10/71		Aug. 10/71		
	ANALYZED											
Analyzed By												
pH-Field		7.440		7.371		7.495		7.458		7.362		
pH-Lab		7.45		7.45		7.45		7.50		7.35		
Cond-Field		2200		1400		1400		900		900		
Cond-Lab		4100		2700		3060		1620		1600		
°C-Field		°4		°4		°4		°4		°4		
		mg/1	meq/1	mg/1	meq/1	mg/1	meq/1	mg/1	meq/1	mg/1	meq/1	mg/1	meq/1
Na		540.04	23.48	279.45	12.15	374.90	16.30	249.78	10.86	98.90	4.30		
K													
Ca		223.05	11.13	211.62	10.56	250.09	12.48	103.81	5.18	226.84	11.32		
Mg		311.66	25.63	130.72	10.75	94.60	7.78	24.56	2.02	55.94	4.60		
T.CAT.			60.24		33.46		36.56		18.06		20.22		
Cl		33.33	0.94	33.33	0.94	41.49	1.17	49.99	1.41	83.33	2.35		
SO_4		2505.73	52.17	1377.50	28.68	1441.86	30.02	461.09	9.60	487.50	10.15		
HCO_3(titr.)		442.32	7.25	259.29	4.25	305.05	5.00	442.32	7.25	518.59	8.50		
HCO_3(calc.)													
CO_3													
T.ANS.			60.36		33.87		36.19		18.26		21.00		
TDS			120.60		67.33		72.75		36.32		41.22		

	PIEZOMETER NUMBER AND DEPTH BELOW GROUND SURFACE											
	P-3-10W		P-3-6		P-3-10		P-3-18		P-3-38		P-3-78	
DATE INSTALLED												
DATE FLUSHED												
DATE SAMPLED	Aug. 10/71		Aug. 10/71		Aug. 10/71		Aug. 10/71		Aug. 10/71		Aug. 10/71	
DATE ANALYZED												
Analyzed By												
pH-Field	7.665		dry		7.740		7.286		7.434		8.341	
pH-Lab	7.65				7.60		7.35		7.50		8.10	
Cond-Field	3000		dry		2800		2800		3500		2200 at 30'	
Cond-Lab	8690				6840		7320		9770		4660	
°C-Field	4°		4°		4°		4°		4°		4°	
	mg/l	meq/l	mg/l	meq/l	mg/l	meq/l	mg/l	meq/l	mg/l	meq/l	mg/l	meq/l
Na	1699.70	73.90			1499.60	65.20	1499.60	65.20	2199.95	95.65	1099.40	47.80
K												
Ca	540.63	15.74			230.86	11.52	396.19	19.77	784.76	19.39	53.90	2.69
Mg	405.05	33.31			233.47	19.20	225.20	18.52	147.00	12.09	13.98	1.15
T.CAT.		122.95				95.92		103.49		127.13		52.54
Cl	74.82	2.11			91.49	2.58	174.82	4.93	408.14	11.51	1341.45	37.83
SO_4	5330.37	110.98			3990.33	83.08	4271.79	88.94	5044.11	105.02	331.89	6.91
HCO_3(titr.)	610.10	10.00			610.10	10.00	549.09	9.00	579.59	9.50	503.33	8.25
HCO_3(calc.)												
CO_3												
T.ANS.		123.09				95.66		102.87		126.03		52.99
TDS		246.04				191.58		206.46		253.16		105.53

	PIEZOMETER NUMBER AND DEPTH BELOW GROUND SURFACE											
	P-4-10W		P-4-15		P-4-28		P-4-47		P-4-93			
DATE INSTALLED												
DATE FLUSHED												
DATE SAMPLED	Aug. 11/71		Aug. 11/71		Aug. 11/71		Aug. 11/71		Aug. 11/71			
DATE ANALYZED												
Analyzed By												
pH-Field	7.530		7.354		7.211		7.580		8.312			
pH-Lab	7.85		7.65		7.50		7.55		7.90			
Cond-Field	925		700		900		1150 at 25'		1500 at 25'			
Cond-Lab	1460		1100		1480		2090		4100			
°C-Field	4°		4°		4°		4°		4°			
	mg/1	meq/1	mg/1	meq/1	mg/1	meq/1	mg/1	meq/1	mg/1	meq/1	mg/1	meq/1
Na	23.0	1.00	12.88	0.56	57.96	2.52	230.0	10.00	839.96	36.52		
K												
Ca	192.38	9.60	142.28	7.10	153.90	7.68	153.90	7.68	30.86	1.54		
Mg	98.00	8.06	73.57	6.05	35.02	2.88	70.04	5.76				
T.CAT.		18.66		13.66		13.08		23.36		38.06		
Cl	41.48	1.17	58.15	1.64	49.99	1.41	83.33	2.35	1074.79	30.31		
SO_4	475.97	9.91	209.89	4.37	262.72	5.47	667.14	13.89	129.20	2.69		
HCO_3(titr.)	411.82	6.75	396.56	6.50	381.31	6.25	442.32	7.25	411.82	6.75		
HCO_3(calc.)												
CO_3												
T.ANS.		17.83		12.51		13.13		23.49		39.75		
TDS		36.49		26.17		26.21		46.85		77.81		

	PIEZOMETER NUMBER AND DEPTH BELOW GROUND SURFACE											
	P-5-13W		P-5-15		P-5-28		P-5-48		P-5-93			
DATE INSTALLED												
DATE FLUSHED												
DATE SAMPLED	Aug. 11/71		Aug. 11/71		Aug. 11/71		Aug. 11/71		Aug. 11/71			
DATE ANALYZED												
Analyzed By												
pH-Field	7.530		7.328		7.610		7.474		8.312			
pH-Lab	7.90		7.70		7.95		7.80		8.20			
Cond-Field	410		520		490		1100		1550			
Cond-Lab	660		780		860		2010		2810			
°C-Field	4°		4°		4°		4°		4°			
	mg/l	meq/l	mg/l	meq/l	mg/l	meq/l	mg/l	meq/l	mg/l	meq/l	mg/l	meq/l
Na	5.06	0.22	17.02	0.74	64.86	2.82	259.90	11.30	849.85	36.95		
K												
Ca	73.15	3.65	84.57	4.22	96.19	4.80	69.34	3.46	34.67	1.73		
Mg	37.33	3.07	68.09	5.60	44.38	3.65	26.87	2.21	16.29	1.34		
T.CAT.		7.92		10.56		11.27		16.97		40.02		
Cl	16.66	0.47	49.99	1.41	33.33	0.94	58.51	1.65	349.99	9.87		
SO_4	127.76	2.66	171.95	3.58	217.57	4.53	501.43	10.44	721.41	15.02		
HCO_3(titr.)	305.05	5.00	396.56	6.50	396.56	6.50	305.05	5.00	945.65	15.50		
HCO_3(calc.)												
CO_3												
T.ANS.		8.13		11.49		11.97		17.09		40.39		
TDS		16.05		22.05		23.24		34.06		80.41		

	PIEZOMETER NUMBER AND DEPTH BELOW GROUND SURFACE											
	P-6-10W		P-6-15		P-6-23		P-6-38		P-6-57			
DATE INSTALLED												
DATE FLUSHED												
DATE SAMPLED	Aug. 11/71		Aug. 11/71		Aug. 11/71		Aug. 11/71		Aug. 11/71			
DATE ANALYZED												
Analyzed By												
pH-Field	8.006		7.388		7.161		7.235		7.935			
pH-Lab	7.95		7.85		7.65		7.80		8.10			
Cond-Field	7000		6000		500		4000 at 30'		2900 at 30'			
Cond-Lab	15,780		13,860		9770		8550		586			
°C-Field	4°		4°		4°		4°		4°			
	mg/l	meq/l	mg/l	meq/l	mg/l	meq/l	mg/l	meq/l	mg/l	meq/l	mg/l	meq/l
Na	2199.95	95.65	2449.50	106.50	1899.80	82.60	1749.15	76.05	1499.60	65.20		
K												
Ca	411.62	20.54	411.62	20.54	380.76	19.00	342.48	17.09	69.34	3.46		
Mg	2331.19	191.71	1523.40	125.28	510.11	41.95	197.24	16.22	15.20	1.25		
T.CAT.		307.90		252.32		143.55		109.36		69.91		
Cl	233.33	6.58	624.81	17.62	708.14	19.97	924.79	26.08	1383.29	39.01		
SO_4	14146.27	294.53	10674.19	222.24	5412.98	112.70	3439.43	71.61	1064.83	22.17		
HCO_3(titr.)	457.57	7.50	732.12	12.00	671.11	11.00	671.11	11.00	518.58	8.50		
HCO_3(calc.)												
CO_3												
T.ANS.		308.61		251.86		143.67		108.69		69.68		
TDS		616.51		504.18		287.22		218.05		139.59		

		PIEZOMETER NUMBER AND DEPTH BELOW GROUND SURFACE										
	P-7-8		P-7-10W		P-7-13		P-7-18		P-7-28			
DATE INSTALLED												
DATE FLUSHED												
DATE SAMPLED	Aug. 12/71		Aug. 12/71		Aug. 12/71		Aug. 12/71		Aug. 12/71			
DATE ANALYZED												
Analyzed By												
pH-Field	7.505		7.434		7.382		7.731		8.293			
pH-Lab	7.50		7.50		7.85		8.00		8.35			
Cond-Field	800		750		480		600		700 at 24'			
Cond-Lab	1220		1090		680		820		1220			
°C-Field	4°		4°		4°		4°		4°			
	mg/1	meq/1	mg/1	meq/1	mg/1	meq/1	mg/1	meq/1	mg/1	meq/1	mg/1	meq/1
Na	88.09	3.83	104.65	4.55	144.90	6.30	159.85	6.95	279.45	12.15		
K												
Ca	107.82	5.38	92.38	4.61	23.05	1.15	7.62	0.38				
Mg	48.27	3.97	57.15	4.70	22.13	1.82	11.67	0.96	15.32	1.26		
T.CAT.		13.18		13.86		9.27		8.29		13.41		
Cl	16.66	0.47	16.66	0.47	24.82	0.70	16.66	0.47	99.99	2.82		
SO_4	302.11	6.29	153.69	3.20	16.33	0.34	36.98	0.77	89.33	1.86		
HCO_3(titr.)	396.56	6.50	671.11	11.00	549.09	9.00	427.07	7.00	549.09	9.00		
HCO_3(calc.)												
CO_3												
T.ANS.		13.26		14.67		9.81		8.24		13.68		
TDS		26.44		28.53		19.08		16.53		27.09		

	PIEZOMETER NUMBER AND DEPTH BELOW GROUND SURFACE											
	P-8-10W		P-8-10		P-8-18		P-8-28		P-8-48			
DATE INSTALLED												
DATE FLUSHED												
DATE SAMPLED	Aug. 12/71		Aug. 12/71		Aug. 12/71		Aug. 12/71		Aug. 12/71			
DATE ANALYZED												
Analyzed By												
pH-Field	7.672		7.398		7.067		7.499		7.790			
pH-Lab	7.60		7.45		7.10		7.50		7.80			
Cond-Field	5000		4300		3400		3300		4200 at 25'			
Cond-Lab	14,650		10,680		10,260		7600		8920			
°C-Field	4°		4°		4°		4°		4°			
	mg/1	meq/1	mg/1	meq/1	mg/1	meq/1	mg/1	meq/1	mg/1	meq/1	mg/1	meq/1
Na	2849.70	123.90	1849.20	80.40	1999.85	86.95	1799.75	78.25	2249.40	97.80		
K												
Ca	442.48	22.08	411.62	20.54	446.29	22.27	319.23	15.93	53.91	2.69		
Mg	1278.25	105.12	760.00	62.50	498.43	40.99	64.20	5.28	22.13	1.82		
T.CAT.		251.10		163.44		150.21		99.46		102.31		
Cl	2099.94	59.22	1391.45	39.24	1383.29	39.01	1116.64	31.49	3024.73	85.30		
SO_4	8898.99	185.28	5634.39	117.31	4827.49	100.51	2784.77	57.98	465.41	9.69		
HCO_3(titr.)	472.83	7.75	457.57	7.50	655.86	10.75	625.35	10.25	427.07	7.00		
HCO_3(calc.)												
CO_3												
T.ANS.		252.25		164.05		150.27		99.72		101.99		
TDS		503.35		327.49		300.48		199.18		204.30		

	PIEZOMETER NUMBER AND DEPTH BELOW GROUND SURFACE											
	P-9-7		P-9-9W		P-9-15		P-9-18		P-9-28		P-9-59	
DATE INSTALLED												
DATE FLUSHED												
DATE SAMPLED	Aug. 12/71		Aug. 12/71		Aug. 12/71		Aug. 12/71		Aug. 12/71		Aug. 12/71	
DATE ANALYZED												
Analyzed By												
pH-Field	7.778		7.602		7.419		7.378		7.589		8.232	
pH-Lab	7.80		7.70		7.55		7.55		7.60		7.70	
Cond-Field	1300		1150		1700		1750		1500		3500 at 24'	
Cond-Lab	1500		1900		3010		2850		2930		6840	
°C-Field	4°		4°		4°		4°		4°		4°	
	mg/l	meq/l	mg/l	meq/l	mg/l	meq/l	mg/l	meq/l	mg/l	meq/l	mg/l	meq/l
Na	284.97	12.39	314.87	13.69	580.06	25.22	509.91	22.17	559.82	24.34	1474.76	64.12
K												
Ca	11.62	0.58	38.47	1.92	76.95	3.84	96.19	4.80	42.28	2.11	38.47	1.92
Mg	50.22	4.13	78.19	6.43	85.12	7.00	51.32	4.22	35.02	2.88	35.02	2.88
T.CAT.		17.53		21.40		36.06		31.19		29.33		68.92
Cl	25.17	0.71	16.66	0.47	318.78	8.99	291.48	8.22	624.80	17.62	2224.76	62.74
SO_4	558.10	11.62	719.48	14.98	1147.91	23.90	651.28	13.56	57.63	1.20	73.97	1.54
HCO_3(titr.)	152.52	2.50	183.03	3.00	533.84	8.75	564.34	9.25	640.60	10.50	289.79	4.75
HCO_3(calc.)												
CO_3	135.00	4.5	120.00	4.00								
T.ANS.		19.33		22.45		36.64		31.03		29.32		69.04
TDS		36.86		43.85		72.70		62.32		58.65		137.96

	PIEZOMETER NUMBER AND DEPTH BELOW GROUND SURFACE											
	P-10-14W		P-10-18		P-10-43		P-10-68					
DATE INSTALLED												
DATE FLUSHED												
DATE SAMPLED	Aug. 10/71		Aug. 10/71		Aug. 10/71		Aug. 10/71					
DATE ANALYZED												
Analyzed By												
pH-Field	7.590		7.580		7.875		8.510					
pH-Lab	7.65		7.65		8.00		8.00					
Cond-Field	1600		2300		2300		1250					
Cond-Lab	4560		8270		7540		2440					
°C-Field	4°		4°		4°		4°					
	mg/1	meq/1	mg/1	meq/1	mg/1	meq/1	mg/1	meq/1	mg/1	meq/1	mg/1	meq/1
Na	469.89	20.43	1449.46	63.02	1469.70	63.90	579.83	25.21				
K												
Ca	365.52	18.24	323.24	16.13	226.45	11.30	23.05	1.15				
Mg	307.04	25.25	512.42	42.14	127.19	10.46	5.84	0.48				
T.CAT.		63.91		121.29		85.69		26.84				
Cl	49.99	1.41	166.66	4.70	224.82	6.34	99.99	2.82				
SO_4	2774.31	55.68	5302.51	110.40	3495.14	72.77	733.89	15.28				
HCO_3(titr.)	442.32	7.25	411.82	6.75	427.07	7.00	503.33	8.25				
HCO_3(calc.)												
CO_3												
T.ANS.		64.34		121.85		86.11		26.35				
TDS		128.25		243.14		171.80		53.19				

	PIEZOMETER NUMBER AND DEPTH BELOW GROUND SURFACE											
	P-11-12W		P-11-18		P-11-44		P-11-75					
DATE INSTALLED												
DATE FLUSHED												
DATE SAMPLED	Aug. 11/71		Aug. 11/71		Aug. 11/71		Aug. 11/71					
DATE ANALYZED												
Analyzed By												
pH-Field	7.578		7.095		7.151		7.863					
pH-Lab	7.60		7.35		7.35		7.95					
Cond-Field	3000		4000		2800 at 20'		2400 at 30'					
Cond-Lab	6790		11,790		6840		5000					
°C-Field	4°		4°		4°		4°					
	mg/1	meq/1	mg/1	meq/1	mg/1	meq/1	mg/1	meq/1	mg/1	meq/1	mg/1	meq/1
Na	1075.02	46.74	2349.45	102.15	1299.50	56.50	1124.70	48.90				
K												
Ca	338.67	16.90	353.90	17.66	315.43	15.74	11.42	0.57				
Mg	397.99	32.73	826.88	68.00	180.94	14.88	29.18	2.40				
T.CAT.		96.37		187.87		87.12		51.87				
Cl	49.99	1.41	274.82	7.75	374.81	10.57	1149.97	32.43				
SO_4	4352.47	90.62	8018.13	166.94	3379.87	70.37	484.14	10.08				
HCO_3(titr.)	305.05	5.00	838.89	13.75	381.31	6.25	594.85	9.75				
HCO_3(calc.)												
CO_3												
T.ANS.		97.03		188.44		87.18		52.26				
TDS		193.40		376.31		174.30		104.13				

	PIEZOMETER NUMBER AND DEPTH BELOW GROUND SURFACE											
	P-12-16W		P-12-35		P-12-70							
DATE INSTALLED												
DATE FLUSHED												
DATE SAMPLED	Aug. 11/71		Aug. 11/71		Aug. 11/71							
DATE ANALYZED												
Analyzed By												
pH-Field	7.355		10.838		7.981							
pH-Lab	7.55				7.70							
Cond-Field	3800		4000 at 25'		3500 at 40'							
Cond-Lab	12,360				7,890							
°C-Field	4°		4°		4°							
	mg/l	meq/l	mg/l	meq/l	mg/l	meq/l	mg/l	meq/l	mg/l	meq/l	mg/l	meq/l
Na	1449.0	63.00			1549.74	67.38						
K												
Ca	609.82	30.43			26.85	1.34						
Mg	1111.30	91.39			96.92	7.97						
T.CAT.		184.82				76.68						
Cl	3183.24	89.77			2491.42	70.26						
SO_4	4302.05	89.57			119.59	2.49						
HCO_3(titr.)	320.30	5.25			289.79	4.75						
HCO_3(calc.)												
CO_3												
T.ANS.		184.59				77.50						
TDS		369.41				154.18						

	PIEZOMETER NUMBER AND DEPTH BELOW GROUND SURFACE											
	P-13-9W		P-13-20		P-13-40							
DATE INSTALLED												
DATE FLUSHED												
DATE SAMPLED	Aug. 12/71		Aug. 12/71		Aug. 12/71							
DATE ANALYZED												
Analyzed By												
pH-Field	7.650		7.390		7.821							
pH-Lab	8.50		8.55		7.95							
Cond-Field	>8000		5500		3500							
Cond-Lab	34,200		15,080		8550							
°C-Field	4°		4°		4°							
	mg/l	meq/l	mg/l	meq/l	mg/l	meq/l	mg/l	meq/l	mg/l	meq/l	mg/l	meq/l
Na	11598.90	504.30	4649.45	202.15	2174.65	94.55						
K												
Ca	419.43	20.93	357.91	17.86	80.76	4.03						
Mg	2226.13	183.07	311.66	25.63	173.89	14.30						
T.CAT.		708.30		245.64		112.88						
Cl	133.32	3.76	84.04	2.37	299.99	8.46						
SO_4	33322.73	693.79	11222.69	233.66	4449.49	92.64						
HCO_3(titr.)	686.36	11.25	579.59	9.50	640.60	10.50						
HCO_3(calc.)												
CO_3												
T.ANS.		708.80		245.53		111.60						
TDS		1417.10		491.17		224.48						

	PIEZOMETER NUMBER AND DEPTH BELOW GROUND SURFACE											
	P-14-12W		P-14-25A		P-14-25B		P-14-50					
DATE INSTALLED												
DATE FLUSHED												
DATE SAMPLED	Aug. 11/71		Aug. 11/71		Aug. 11/71		Aug. 11/71					
DATE ANALYZED												
Analyzed By												
pH-Field	7.699		7.130		7.370		11.855					
pH-Lab	8.40		8.25		8.45							
Cond-Field	4000		3200		3200		2600 at 32'					
Cond-Lab	17680		9320		8690							
°C-Field	4°		4°		4°		4°					
	mg/l	meq/l	mg/l	meq/l	mg/l	meq/l	mg/l	meq/l	mg/l	meq/l	mg/l	meq/l
Na	3199.30	139.10	1699.70	73.90	1599.65	69.55						
K												
Ca	438.67	21.89	325.05	16.22	309.82	15.46						
Mg	1901.70	156.39	436.54	35.90	346.68	28.51						
T.CAT.		317.37		126.02		113.52						
Cl	2683.25	75.67	1299.96	36.66	1033.30	29.14						
SO_4	11139.59	231.93	3900.99	81.22	3780.92	78.72						
HCO_3(titr.)	549.09	9.00	488.08	8.00	396.56	6.50						
HCO_3(calc.)												
CO_3												
T.ANS.		316.60		125.88		114.36						
TDS		633.97		251.90		227.88						

	PIEZOMETER NUMBER AND DEPTH BELOW GROUND SURFACE											
	P-15-12W		P-15-25		P-15-45							
DATE INSTALLED												
FLUSHED												
SAMPLED	Aug. 11/71		Aug. 11/71		Aug. 11/71							
ANALYZED												
Analyzed By												
pH-Field	7.571		7.717		12.935							
pH-Lab	7.45		7.50									
Cond-Field	5500		6000		7000							
Cond-Lab	28,500		33,090									
°C-Field	4°		4°		4°							
	mg/l	meq/l	mg/l	meq/l	mg/l	meq/l	mg/l	meq/l	mg/l	meq/l	mg/l	meq/l
Na	8199.50	356.50	9049.35	393.45								
K												
Ca	373.14	18.62	388.51	19.39								
Mg	2116.19	173.09	2928.86	240.86								
T.CAT.		548.21		653.70								
Cl	383.32	10.81	649.98	18.33								
SO_4	25239.76	525.50	30005.78	624.73								
HCO_3(titr.)	793.13	13.00	701.62	11.50								
HCO_3(calc.)												
CO_3												
T.ANS.		549.31		654.56								
TDS		1097.52		1308.26								

APPENDIX E-2

Groundwater Chemistry at Piezometer Nests 1 to 11, 1970

	PIEZOMETER NUMBER AND DEPTH BELOW GROUND SURFACE											
	P-1-18W		P-1-28		P-1-38		P-1-76					
DATE INSTALLED												
DATE FLUSHED												
DATE SAMPLED	Sept. 16/70		Sept. 16/70		Sept. 16/70		Sept. 16/70					
DATE ANALYZED	Jan. 5/71		Jan. 5/71		Jan. 5/71		Jan. 5/71					
Analyzed By												
pH-Field	7.27			6.86		6.00		6.75				
pH-Lab												
Cond-Field												
Cond-Lab	1.64			3.25		3.77		3.45				
°C-Field	4°			4°		4°		4°				
	mg/1	meq/1	mg/1	meq/1	mg/1	meq/1	mg/1	meq/1	mg/1	meq/1	mg/1	meq/1
Na	14.9	0.65	55.2	2.4	136	5.9	149	6.5				
K	5.86	0.15	21.1	0.54	29.0	0.74	34.0	.87				
Ca			241	12.03	404	20.68	28.2	14.10				
Mg	140.0	11.47	329.0	26.89	305	25.00	248	20.90				
T.CAT.		12.27		41.86		52.32		41.77				
Cl	22.0	0.62	59.7	1.68	80.3	2.26	138	3.89				
SO_4	318	6.63	1900	39.66	2210	45.99	1730	36.05				
HCO_3(titr.)	396	6.50	214	3.50	277	4.54	366	6.00				
HCO_3(calc.)												
CO_3												
T.ANS.		13.75		44.84		52.75		45.94				
TDS		26.02		86.70		105.07		87.71				

	PIEZOMETER NUMBER AND DEPTH BELOW GROUND SURFACE											
	P-2-10W		P-2-10		P-2-18		P-2-38		P-2-98			
DATE: INSTALLED												
DATE: FLUSHED												
DATE: SAMPLED	Sept. 16/70		Sept. 16/70		Sept. 16/70		Sept. 16/70		Sept. 16/70			
DATE: ANALYZED	Jan. 5/71		Jan. 5/71		Jan. 5/71		Jan. 5/71		Jan. 5/71			
Analyzed By												
pH-Field		7.23		7.14		7.40		7.25	4	7.17		
pH-Lab												
Cond-Field												
Cond-Lab		3.33		3.01		3.28		1.76		1.79		
°C-Field		4°		4°		4°		4°		4°		
	mg/1	meq/1	mg/1	meq/1	mg/1	meq/1	mg/1	meq/1	mg/1	meq/1	mg/1	meq/1
Na	332	14.4	332	14.4	370	16.1	230	10.0	108	4.7		
K	26.6	0.68	23.0	0.59	26.2	0.67	18.0	0.46	14.9	0.38		
Ca	150	7.52	97.8	4.89	146.6	7.33			135.4	6.77		
Mg	206	16.92	179	14.66	175	14.29	52.7	4.32	71.3	5.83		
T.CAT.		39.52		34.54		38.39		14.78		17.68		
Cl	47.6	1.34	59.7	1.68	61.5	1.73	73.2	2.06	106	2.98		
SO_4	1650	34.26	1320	27.44	1700	35.43	350	7.29	494	10.29		
HCO_3(titr.)	366	6.00	305	5.00	274	4.56	305	5.00	274	4.50		
HCO_3(calc.)												
CO_3												
T.ANS.		41.60		34.12		41.66		14.35		17.77		
TDS		81.12		68.66		80.05		29.13		35.45		

	PIEZOMETER NUMBER AND DEPTH BELOW GROUND SURFACE											
	P-3-6		P-3-10W		P-3-10		P-3-18		P-3-38		P-3-78	
DATE INSTALLED												
DATE FLUSHED												
DATE SAMPLED	Sept. 16/70		Sept. 16/70		Sept. 16/70		Sept. 16/70		Sept. 16/70		Sept. 16/70	
DATE ANALYZED	Jan. 5/71		Jan. 5/71		Jan. 5/71		Jan. 5/71		Jan. 5/71		Jan. 5/71	
Analyzed By												
pH-Field		dry		7.58		7.41		7.33		7.40		7.36
pH-Lab												
Cond-Field												
Cond-Lab		dry		8.70		7.86		8.19		10.68		5.17
°C-Field		4°		4°		4°		4°		4°		4°
	mg/l	meq/l	mg/l	meq/l	mg/l	meq/l	mg/l	meq/l	mg/l	meq/l	mg/l	meq/l
Na			1490	65.2	1420	61.9	1470	65.9	2200	95.45	990	43.00
K			44.2	1.13	36.4	0.93	37.9	0.97	57.5	1.47	21.1	0.54
Ca			244	12.22	195.0	9.78	244	12.22	218	10.91	22.6	1.13
Mg			394	32.34	294	24.06	268	22.00	210	17.17	13.8	1.13
T.CAT.				110.89		46.67		99.09		129.64		45.80
Cl			111	3.12	165	2.95	109	3.07	428	12.07	1320	37.15
SO_4			5110	106.45	4310	89.96	4520	94.36	5680	118.16	401	8.37
HCO_3(titr.)			366	6.00	572	9.38	244	4.00	450	7.38	442	7.25
HCO_3(calc.)												
CO_3												
T.ANS.				115.57		102.29		101.43		137.61		52.77
TDS				226.46		198.96		200.42		267.25		98.57

		PIEZOMETER NUMBER AND DEPTH BELOW GROUND SURFACE										
		P-4-10W		P-4-15		P-4-28		P-4-47		P-4-93		
DATE	INSTALLED											
	FLUSHED											
	SAMPLED	Sept. 15/70		Sept. 15/70		Sept. 15/70		Sept. 15/70		Sept. 15/70		
	ANALYZED	Jan. 5/71		Jan. 5/71		Jan. 5/71		Jan. 5/71		Jan. 5/71		
Analyzed By												
pH-Field			6.75		7.08		6.35		7.09		8.27		
pH-Lab												
Cond-Field												
Cond-Lab			2.14		1.31		1.79		2.29		4.47		
°C-Field			4°		4°		4°		4°		4°		
		mg/l	meq/l	mg/l	meq/l	mg/l	meq/l	mg/l	meq/l	mg/l	meq/l	mg/l	meq/l
Na		17.9	0.78	10.1	0.44	41.9	1.82	221	9.6	840	36.5		
K		9.79	0.25	14.1	0.36	20.0	0.51	30.1	6.77	26.6	0.68		
Ca		188	9.40	124	6.20	263	13.16	64	3.20				
Mg		181	14.85	75.5	6.20	77.7	6.39	68.5	5.64	29.4	2.42		
T.CAT.			25.28		13.20		21.88		19.21		39.60		
Cl		78.5	2.21	42.7	1.20	72.8	2.05	85.3	2.40	1070	30.10		
SO_4		1000	20.86	445	9.26	833	17.34	640	13.32	460	9.59		
HCO_3(titr.)		137	2.25	267	4.38	84.2	1.38	198	3.25	640	10.50		
HCO_3(calc.)													
CO_3													
T.ANS.			25.32		14.84		26.77		18.97		50.19		
TDS			50.60		28.04		42.65		38.18		89.79		

	PIEZOMETER NUMBER AND DEPTH BELOW GROUND SURFACE											
	P-5-13W		P-5-15		P-5-28		P-5-48		P-5-93			
DATE INSTALLED												
DATE FLUSHED												
DATE SAMPLED	Sept. 15/70		Sept. 15/70		Sept. 15/70		Sept. 15/70		Sept. 15/70			
DATE ANALYZED	Jan. 5/71		Jan. 5/71		Jan. 5/71		Jan. 5/71		Jan. 5/71			
Analyzed By												
pH-Field		7.14		7.22		7.05		dry		7.99		
pH-Lab												
Cond-Field												
Cond-Lab		1.00		0.85		0.73		dry		3.39		
°C-Field		4°		4°		4°		4°		4°		
	mg/1	meq/1	mg/1	meq/1	mg/1	meq/1	mg/1	meq/1	mg/1	meq/1	mg/1	meq/1
Na	2.99	0.13	14.9	0.65	46.0	2.00			66.8	2.90		
K	12.1	0.31	16.6	0.27	14.9	0.38			21.1	0.54		
Ca			27.6	1.13	26.4	1.32						
Mg	66.3	5.45	52.5	4.32	38.8	3.19			45.7	3.76		
T.CAT.		5.89		6.37		6.89				7.20		
Cl	54.7	1.54	22.0	0.62	47.6	1.34			528	14.88		
SO_4	149	3.10	2.79	5.82	117	2.44			330	6.86		
HCO_3(titr.)	229	3.75	330	5.40	214	3.50			855	14.00		
HCO_3(calc.)												
CO_3												
T.ANS.		8.39		11.84		7.28				35.74		
TDS		14.28		18.21		14.17				42.94		

	PIEZOMETER NUMBER AND DEPTH BELOW GROUND SURFACE											
	P-6-10W		P-6-15		P-6-23		P-6-38		P-6-57			
DATE INSTALLED												
DATE FLUSHED												
DATE SAMPLED	Sept. 15/70		Sept. 15/70		Sept. 15/70		Sept. 15/70		Sept. 15/70			
DATE ANALYZED	Jan. 5/71		Jan. 5/71		Jan. 5/71		Jan. 5/71		Jan. 5/71			
Analyzed By												
pH-Field		7.37		dry		dry		7.33		7.64		
pH-Lab												
Cond-Field												
Cond-Lab		19.27						9.36		7.02		
°C-Field		4°						4°		4°		
	mg/l	meq/l	mg/l	meq/l	mg/l	meq/l	mg/l	meq/l	mg/l	meq/l	mg/l	meq/l
Na	2590	112.25					1560	68.0	1300	56.5		
K	115	2.93					53.2	1.36	30.9	0.79		
Ca	440	22.00					255.6	12.78				
Mg	2720	223.72					293	24.07	22.9	1.88		
T.CAT.		360.90						106.21		59.17		
Cl	417	11.76					920	25.92	1620	45.50		
SO_4	1650	344.60					378	78.68	325	6.77		
HCO_3(titr.)	435	7.13					328	5.38	717	11.75		
HCO_3(calc.)												
CO_3												
T.ANS.		363.49						109.98		64.02		
TDS		724.39						216.19		123.19		

	PIEZOMETER NUMBER AND DEPTH BELOW GROUND SURFACE											
	P-7-8		P-7-10W		P-7-13		P-7-18		P-7-28			
DATE INSTALLED												
DATE FLUSHED												
DATE SAMPLED	Sept. 15/70		Sept. 15/70		Sept. 15/70		Sept. 15/70		Sept. 15/70			
DATE ANALYZED	Jan. 5/71		Jan. 5/71		Jan. 5/71		Jan. 5/71		Jan. 5/71			
Analyzed By												
pH-Field		dry		6.44		7.11		7.41		8.55		
pH-Lab												
Cond-Field												
Cond-Lab				1.06		0.89		1.10		1.84		
°C-Field		4°		4°		4°		4°		4°		
	mg/l	meq/l	mg/l	meq/l	mg/l	meq/l	mg/l	meq/l	mg/l	meq/l	mg/l	meq/l
Na			112	4.88	143	8.4	127	5.52	350	15.2		
K			19.2	0.49	14.5	0.37	14.5	0.37	14.1	0.36		
Ca					22.6	1.13	22.6	1.13	22.6	1.13		
Mg			43.5	3.57	15.9	1.31	18.2	1.50	18.2	1.50		
T.CAT.				8.94		11.21		8.52		18.19		
Cl			29.1	0.82	32.3	0.91	40.8	1.15	90.4	2.54		
SO_4			212	4.42	366	7.62	167	3.48	327	6.82		
HCO_3(titr.)			305	5.00	473	7.75	290	4.75	503	8.25		
HCO_3(calc.)												
CO_3												
T.ANS.				10.24		16.28		9.38		17.61		
TDS				19.18		27.49		17.90		35.80		

	PIEZOMETER NUMBER AND DEPTH BELOW GROUND SURFACE											
	P-8-10W		P-8-10		P-8-18		P-8-28		P-8-48			
DATE INSTALLED												
DATE FLUSHED												
DATE SAMPLED	Sept. 15/70		Sept. 15/70		Sept. 15/70		Sept. 15/70		Sept. 15/70			
DATE ANALYZED	Jan. 5/71		Jan. 5/71		Jan. 5/71		Jan. 5/71		Jan. 5/71			
Analyzed By												
pH-Field		7.40		7.48		6.98		7.45		7.78		
pH-Lab												
Cond-Field												
Cond-Lab		15.36		12.93		10.68		9.36		10.68		
°C-Field		4°		4°		4°		4°		4°		
	mg/l	meq/l	mg/l	meq/l	mg/l	meq/l	mg/l	meq/l	mg/l	meq/l	mg/l	meq/l
Na	2350	102.1	1900	82.9	2230	97.0	1680	73.0	2040	88.8		
K	45.0	1.15	36.0	0.92	39.1	1.00	60.2	1.54	37.9	.97		
Ca	413.6	20.68	413.6	20.68	444	27.22	3.30	16.92				
Mg	1070	88.17	995	81.78	351	28.89	121	9.96	29.7	2.44		
T.CAT.		212.10		186.28		149.11		101.43		92.21		
Cl	1770	49.82	1560	44.02	1390	34.07	1100	31.01	3120	87.74		
SO_4	7930	165.06	6600	137.24	4180	87.02	2990	62.42	4.32	0.09		
HCO_3(titr.)	320	5.25	427	7.00	610	10.00	650	10.63	534	8.75		
HCO_3(calc.)												
CO_3												
T.ANS.		220.13		188.26		136.09		104.06		96.58		
TDS		432.23		374.54		285.20		205.48		188.79		

	PIEZOMETER NUMBER AND DEPTH BELOW GROUND SURFACE											
	P-9-7		P-9-9W		P-9-15		P-9-18		P-9-30		P-9-59	
DATE INSTALLED												
DATE FLUSHED												
DATE SAMPLED	Sept. 15/70		Sept. 15/70		Sept. 15/70		Sept. 15/70		Sept. 15/70		Sept. 15/70	
DATE ANALYZED	Jan. 5/71		Jan. 5/71		Jan. 5/71		Jan. 5/71		Jan. 5/71		Jan. 5/71	
Analyzed By												
pH-Field		7.43		7.31		7.47		7.73		7.55		8.46
pH-Lab												
Cond-Field												
Cond-Lab		2.89		1.89		2.73		2.26		1.49		7.80
°C-Field		4°		4°		4°		4°		4°		4°
	mg/l	meq/l	mg/l	meq/l	mg/l	meq/l	mg/l	meq/l	mg/l	meq/l	mg/l	meq/l
Na	520	22.6	460	20.0	362	15.7	350	15.2	220	9.58	1460	63.5
K	36.0	.92	31.3	.80	26.2	.67	26.2	.67	19.2	.49	33.2	.85
Ca									48.8	2.44	45.2	2.26
Mg	59.5	4.89	75.6	6.22	105	8.65	45.7	3.76	16.1	1.32	11.4	0.94
T.CAT.		28.41		27.02		25.02		19.63		13.83		67.55
Cl	78.5	2.21	47.5	1.34	116	3.26	170	4.80	170	4.80	2440	68.59
SO_4	4.32	0.09	36.0	0.75	306	6.39	635	13.21	309	6.44	11.0	0.23
HCO_3(titr.)	1300	21.25	870	14.25	870	14.25	900	14.75	229	3.75	137	2.25
HCO_3(calc.)												
CO_3												
T.ANS.		28.53		10.34		23.90		22.76		14.99		71.07
TDS		56.94		43.36		48.92		42.39		28.82		138.62

	PIEZOMETER NUMBER AND DEPTH BELOW GROUND SURFACE											
	P-10-14W		P-10-18		P-10-43		P-10-68					
DATE INSTALLED												
DATE FLUSHED												
DATE SAMPLED	Sept. 16/70		Sept. 16/70		Sept. 16/70		Sept. 16/70					
DATE ANALYZED	Jan. 5/71		Jan. 5/71		Jan. 5/71		Jan. 5/71					
Analyzed By												
pH-Field		7.35		7.31		7.55		7.63				
pH-Lab												
Cond-Field												
Cond-Lab		7.02		11.70		8.94		2.66				
°C-Field												
	mg/1	meq/1	mg/1	meq/1	mg/1	meq/1	mg/1	meq/1	mg/1	meq/1	mg/1	meq/1
Na	910	39.5	1840	20.1	1670	72.8	500	21.7				
K	44.2	1.13	54.0	1.38	66.0	1.69	19.2	0.49				
Ca	308	15.42	358	17.86	211	10.53						
Mg	503	41.17	760	62.23	151	12.41	183	1.50				
T.CAT.		97.20		161.57		47.43		23.69				
Cl	71.7	7.02	401	11.33	249	7.01	102	2.88				
SO_4	4370	90.99	7030	146.07	3960	82.53	545	11.33				
HCO_3(titr.)	153	2.50	550	9.00	549	9.00	557	9.13				
HCO_3(calc.)												
CO_3												
T.ANS.		95.51		166.40		98.54		23.34				
TDS		192.71		327.97		195.97		47.03				

	PIEZOMETER NUMBER AND DEPTH BELOW GROUND SURFACE											
	P-11-12W		P-11-18		P-11-43							
DATE INSTALLED												
DATE FLUSHED												
DATE SAMPLED	Sept. 16/70		Sept. 16/70		Sept. 16/70							
DATE ANALYZED	Jan. 5/71		Jan. 5/71		Jan. 5/71							
Analyzed By												
pH-Field		7.13		7.32		7.34						
pH-Lab												
Cond-Field												
Cond-Lab		8.78		13.47		7.62						
°C-Field		4°		4°		4°						
	mg/l	meq/l	mg/l	meq/l	mg/l	meq/l	mg/l	meq/l	mg/l	meq/l	mg/l	meq/l
Na	1270	55.4	2300	100.0	1320	57.5						
K	66.2	1.69	89.0	2.12	59.5	1.52						
Ca	323	16.17	305	15.23	117	5.83						
Mg	570	45.68	824	67.68	144	11.84						
T.CAT.		118.94		185.03		76.69						
Cl	59.6	1.68	242	6.82	380	10.70						
SO_4	5500	114.30	8560	178.22	3100	64.67						
HCO_3(titr.)	244	4.00	442	7.25	214	3.50						
HCO_3(calc.)												
CO_3												
T.ANS.		119.98		192.29		78.87						
TDS		238.92		377.32		155.56						

APPENDIX E-3

Groundwater Chemistry of Farm Wells (I to XI)

Along the Study Area, 1970

GROUNDWATER CHEMISTRY OF FARM WELLS (I TO XI) ALONG THE STUDY AREA, 1970

Farm Wells	Location	Estimated Depth by Farmer	pH	Conductivity (mmhos/cm)	Meq./1.							
					Ca^{++}	Mg^{++}	Na^{+}	Total Cations	$SO_4^{=}$	Cl^{-}	HCO_3^{-}	Total Anions
I	SE 4-2-23W	27'	7.25	2.78	26.15	16.10	.91	43.16	30.75	2.25	9.50	42.50
II	SE 17-2-23W	18'	7.35	2.69	12.30	11.15	13.91	37.36	25.00	0.65	11.00	36.65
III	NC 36-2-24W	185'	7.90	7.02	2.45	4.20	76.08	82.73	0.20	69.90	13.75	83.85
IV	SC 7-3-23W		7.80	8.19	2.80	6.7	86.95	96.45	1.50	83.80	11.00	96.30
V	C 13-3-24W		8.70	2.93	0.50	1.80	27.39	29.69	0.50	19.90	11.25	31.65
VI	NC 14-3-24W	120'	7.85	7.74	3.0	2.45	81.52	86.97	1.50	75.15	11.25	87.90
VII	WC 25-3-24W	90'	7.90	8.06	2.15	2.05	80.43	84.63	0.90	74.40	10.25	85.55
VIII	SC 35-3-24W	140'	7.80	7.45	3.20	2.05	76.08	81.33	16.50	49.25	14.25	80.00
IX	NE 34-3-24W	120'	7.70	8.86	3.95	3.50	90.22	97.67	0	86.35	12.25	98.60
X	SC 10-4-24W	60'	7.15	2.88	7.40	10.45	16.96	34.81	20.18	2.60	8.25	31.03
XI	SW 15-4-24W	97'	8.55	1.38	0	.70	13.91	14.61	5.15	.50	8.25	13.90

APPENDIX F-1

Soluble Salts of Soil Samples Taken at One Foot Intervals to

Ranging to 10 Feet

Various Depths Below Ground Level at Eight Locations in the Study Area

Site No. / Location	Depth of Sample (feet)	Electrical Conductivity mmhos/cm	Meq./l.							
			Ca^{++}	Mg^{++}	Na^{+}	Total Cations	$SO_4^{=}$	Cl^{-}	HCO_3^{-}	Total Anions
B1 SW 4-2-23W	0- 1	0.10	0.94	0.75	0.43	2.12	0.19	0.00	0.50	0.69
	1- 2	0.21	1.88	0.30	0.30	2.48	0.52	0.00	1.50	2.02
	2- 3	0.12	0.38	0.00	0.17	0.55	0.28	0.00	0.25	0.53
	3- 4	0.17	0.94	0.91	0.22	2.07	0.75	0.00	1.25	2.00
	4- 5	0.16	0.94	1.69	0.22	2.85	0.80	0.09	2.00	2.89
Y SW 9-2-23W	0- 1	0.32	0.56	2.63	1.22	4.41	1.46	0.05	2.50	4.01
	1- 2	0.34	0.56	1.62	2.09	4.27	1.55	0.00	3.00	4.55
	2- 3	0.63	2.44	1.62	3.78	7.84	5.26	0.09	1.50	6.85
	3- 4	3.33	28.20	24.25	6.35	58.80	56.49	0.38	1.25	58.12
	4- 5	4.27	25.38	40.04	9.78	75.20	73.98	0.53	1.00	75.51
	5- 6	4.57	26.13	45.49	10.52	82.14	81.03	0.53	1.25	82.81
	6- 7	4.91	28.20	53.39	12.83	94.42	92.97	0.09	1.75	94.81
	7- 8	5.58	27.82	65.05	19.13	112.00	109.23	0.67	1.50	111.40
	8- 9	5.95	28.38	68.62	19.56	116.56	114.30	0.67	1.00	115.97
	9-10	5.46	26.13	62.42	21.73	110.28	107.87	0.77	1.50	110.14
G1 NC 19-2-23W	0- 1	6.06	19.18	28.20	47.83	95.21	94.94	0.90	2.75	98.59
	1- 2	13.84	25.19	74.64	159.78	259.61	258.96	4.18	3.25	266.39
	2- 3	11.04	21.24	51.70	107.60	180.54	178.16	3.31	1.50	182.97
	3- 4	12.28	22.56	52.08	116.30	190.94	188.87	3.36	1.00	193.23
	4- 5	10.80	22.00	48.50	107.60	178.10	175.54	3.17	1.00	179.71
	5- 6	10.92	21.43	48.13	117.38	186.94	183.01	3.17	0.50	186.68

Site No. / Location	Depth of Sample (feet)	Electrical Conductivity mmhos/cm	Meq./1.							
			Ca++	Mg++	Na+	Total Cations	$SO_4^=$	Cl^-	HCO_3^-	Total Anions
	6- 7	13.10	13.16	62.79	164.13	240.08	235.53	5.42	2.00	242.95
	7- 8	16.94	17.67	94.56	192.38	304.61	294.51	6.72	3.50	304.73
	8- 9	21.84	20.68	143.63	268.48	432.79	418.95	9.50	4.75	433.20
	9-10	20.91	22.56	135.17	248.90	406.63	397.60	7.39	4.50	409.49
J NW 12-3-24W	0- 1	1.27	11.47	7.14	1.04	19.65	16.31	3.17	1.50	20.98
	1- 2	2.06	17.48	15.41	1.35	34.24	29.75	1.97	2.50	34.22
	2- 3	1.61	7.33	15.60	1.39	24.32	22.42	0.72	1.25	24.39
	3- 4	1.32	4.51	14.29	2.09	20.89	18.19	0.91	2.00	21.10
	4- 5	1.19	3.38	11.28	3.83	18.49	15.93	3.12	0.75	19.80
	5- 6	1.11	4.14	7.14	4.82	16.10	13.82	3.07	0.50	17.39
	6- 7	1.19	4.51	8.84	4.43	17.78	15.70	0.67	1.75	18.12
	7- 8	2.84	15.04	26.88	8.57	50.49	47.75	1.92	1.75	51.42
	8- 9	4.36	18.99	44.55	16.95	80.49	77.08	1.73	2.50	81.31
	9-10	3.93	9.02	39.29	19.56	67.87	64.67	2.78	0.75	68.20
K NW 13-3-24W	0- 1	0.40	2.44	1.96	0.48	4.88	0.99	0.48	3.00	4.47
	1- 2	0.40	2.82	1.98	0.87	5.67	1.00	0.38	2.75	4.13
	2- 3	1.85	5.08	15.42	9.30	29.80	27.21	0.86	1.25	29.32
	3- 4	3.17	6.20	28.01	16.08	50.29	46.72	2.02	1.50	50.24
	4- 5	7.28	23.50	87.40	36.52	147.42	140.06	4.42	2.00	146.48
	5- 6	9.36	22.56	123.51	48.69	194.76	184.99	7.39	2.00	194.38
	6- 7	10.03	22.18	140.25	52.60	215.03	202.48	9.89	2.00	214.37
	7- 8	10.03	22.75	137.99	55.21	215.95	198.97	13.34	2.00	214.31
	8- 9	10.92	26.51	123.77	60.86	211.14	191.90	16.70	2.75	211.35
	9-10	9.36	23.12	90.59	44.78	158.49	144.03	13.63	1.75	159.41

Site No. / Location	Depth of Sample (feet)	Electrical Conductivity mmhos/cm	Meq./1. Ca++	Mg++	Na+	Total Cations	$SO_4^{=}$	Cl^{-}	HCO_3^{-}	Total Anions
H NE 3-3-24	0- 1	0.57	3.20	1.85	0.78	5.83	2.50	0.38	2.00	4.88
	1- 2	1.96	3.57	14.29	7.48	25.34	22.32	0.34	2.00	24.66
	2- 3	3.02	4.51	28.95	13.48	46.94	44.95	0.53	1.75	47.23
	3- 4	5.17	20.68	54.40	20.43	95.51	94.13	0.77	1.75	96.65
	4- 5	6.55	23.31	72.99	26.08	122.38	122.41	1.06	0.50	123.97
	5- 6	7.67	23.69	103.64	33.47	160.80	158.57	1.44	2.75	162.76
	6- 7	8.19	22.75	98.97	31.73	153.45	152.91	1.44	1.25	155.60
	7- 8	8.77	21.24	102.08	34.34	157.66	156.35	1.82	0.75	158.92
	8- 9	8.54	21.62	102.90	36.52	161.04	156.95	1.92	1.75	160.62
	9-10	8.19	22.00	88.31	32.60	142.91	140.95	1.92	1.00	143.87
D NW 30-2-23W	0- 1	5.61	33.46	29.52	11.87	74.85	39.99	32.45	1.75	74.91
	1- 2	9.36	14.85	78.27	52.17	145.29	114.13	28.32	2.75	145.20
	2- 3	8.05	8.08	68.48	47.39	123.95	98.17	23.23	2.25	123.65
	3- 4	7.50	7.71	59.35	43.47	110.53	88.88	19.49	2.50	110.87
	4- 5	8.19	8.46	65.07	44.55	118.08	95.75	19.97	2.25	117.97
	5- 6	8.05	5.83	65.48	46.72	118.03	94.13	20.45	2.50	117.08
	6- 7	10.80	23.12	87.58	54.32	165.02	138.77	22.75	3.00	164.52
	7- 8	10.34	23.12	85.56	56.50	165.18	138.37	24.09	2.75	165.21
	8- 9	9.83	23.12	73.78	55.48	152.38	126.65	24.00	2.50	153.15
	9-10	9.83	25.00	75.76	56.50	157.26	130.90	24.29	1.50	156.69
T NE 8-4-24W	0- 1	1.44	6.02	3.48	1.57	11.07	9.91	0.20	1.75	11.86
	1- 2	1.06	6.20	3.81	0.87	10.88	6.91	0.10	2.25	9.26
	2- 3	0.98	5.08	4.43	0.69	10.20	6.36	0.10	2.00	8.46
	3- 4	0.39	0.75	2.44	0.56	3.75	1.06	0.00	2.75	3.81
	4- 5	0.36	0.75	1.31	1.09	3.15	0.91	0.00	2.25	3.16
	5- 6	0.34	0.56	1.31	1.65	3.52	0.86	0.00	2.50	3.36

APPENDIX F-2

Soluble Salts of Soil Samples Taken at Various Depths Below Ground Level During the Drilling Program for the Installation of Piezometers

Piezometer Nest No.	Depth of Sample (feet)	Electrical Conductivity (mmhos/cm)	Meq./l.							
			Ca++	Mg++	Na+	Total Cations	$SO_4^{=}$	Cl^{-}	HCO_3^{-}	Total Anions
P-1	10-18	0.31	1.30	1.25	0.48	3.03	0.55	0.72	1.25	2.52
P-1	20-30	3.38	26.35	20.93	3.13	50.41	48.66	0.55	1.00	50.21
P-3	18	5.6	3.80	15.00	51.30	70.10	64.80	2.64	3.25	70.69
P-4	9-12	1.14	5.45	6.35	0.74	12.54	11.10	1.20	1.25	13.5
P-4	18-20	2.07	16.90	6.60	2.00	25.50	24.00	1.20	1.25	26.45
P-4	40-44	3.34	27.40	13.45	7.13	47.98	46.8	1.43	1.25	49.50
P-5	45-48	3.60	28.00	11.55	9.56	49.11	46.50	0.72	0.50	47.72
P-6	20-23	7.60	23.00	33.75	51.29	108.04	101.10	6.96	1.75	109.81
P-6	35-38	6.41	22.70	12.45	49.56	84.71	74.30	8.40	0.75	83.45
P-7	10	0.52	1.00	1.80	3.30	6.10	2.10	0.72	2.50	5.32
P-8	20	6.00	22.85	13.95	42.60	79.40	69.50	8.88	1.25	79.63
P-8	40	9.00	19.95	6.05	87.82	113.82	99.60	13.44	0.75	113.79
P-9	15-18	2.93	9.95	4.59	19.56	34.10	28.43	2.97	1.50	32.90
P-11	14	7.23	21.70	47.12	49.99	118.81	116.0	2.86	1.00	119.86
P-11	19	6.29	20.20	33.40	41.30	94.90	90.00	4.56	2.25	96.81
P-11	28	3.57	8.80	13.83	22.17	44.80	41.70	3.14	1.00	45.84
P-11	30	3.64	10.60	10.20	24.78	45.58	40.60	3.60	1.25	45.45
P-11	35	3.63	10.20	9.40	24.78	44.38	39.10	4.08	2.00	45.18

Piezometer Nest No.	Depth of Sample (feet)	Electrical Conductivity (mmhos/cm)	Meq./1.							
			Ca++	Mg++	Na+	Total Cations	$SO_4^{=}$	Cl^{-}	HCO_3^{-}	Total Anions
P-11	50	4.10	11.65	9.35	31.74	52.74	46.70	4.56	2.00	53.26
P-11	65	3.48	0.95	0.95	38.03	39.90	30.50	5.04	3.75	39.29
P-11	65-75	8.48	7.20	2.30	97.82	107.32	97.98	8.88	0.25	107.11
P-13	15-35	7.98	6.55	3.95	88.69	99.19	96.60	1.92	1.25	99.77
P-14	25	6.29	21.00	19.75	46.51	87.26	76.20	11.52	1.25	88.97
P-14	35	4.77	12.40	10.45	36.95	59.80	50.95	8.40	1.75	61.10
P-14	50	7.08	15.30	7.25	63.90	86.45	76.85	8.88	0.25	85.98
P-15	5	13.24	19.00	52.02	138.04	209.06	205.57	1.92	2.50	209.99
P-15	10-15	14.66	20.30	62.13	148.91	231.34	225.22	2.88	2.50	230.50
P-15	20	19.36	9.40	94.37	217.39	321.16	315.30	5.76	3.50	324.56
P-15	25	16.29	9.60	82.76	182.60	274.96	263.70	8.88	2.00	274.98
P-15	30	14.66	7.20	64.74	159.77	231.71	218.8	8.40	5.50	232.70
P-15	40	6.62	3.30	4.60	69.55	77.45	71.60	4.56	3.00	79.16
P-15	40-45	5.13	2.30	3.60	52.16	58.06	53.30	3.84	2.25	59.39
P-15	45-49	6.41	4.10	7.55	64.77	76.42	70.10	5.04	1.75	76.89
P-15	50	3.02	0.30	1.08	29.56	30.94	26.40	3.12	2.75	32.27

APPENDIX G

Plates Showing Landscape, Methods of Investigation, and Genetic Soils in the Study Area

Plate 1
Natural groundwater spring at base of Turtle Mountain. Area lies between piezometer Nests 10 and 2.

Plate 2
Piezometer Nest 2. Area of strong groundwater discharge. Note salt crusts on soil surface and generally salt tolerant vegetation.

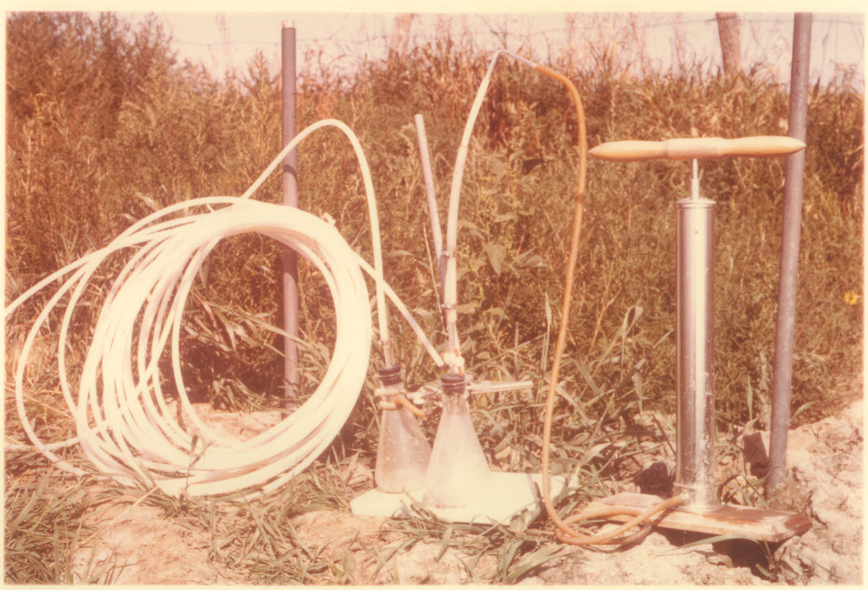


Plate 3
Apparatus used to sample piezometers
-Vacuum pump
-Vacuum bottle
-Ty gon tube

Plate 4
Solid stemmed auger used to install piezometers to depths of 100 feet below ground level. Samples of the different geologic deposits were obtained from the auger.

Plate 5
Giddings Drill used to install water table wells and collect soil samples to depths of 10 feet. Soil samples taken directly from auger at intervals of 1 foot.

Plate 6
Saline Gleyed Carbonated Rego Black soil in stratified lacustrine sediments of Whitewater Basin. Soil is typical of groundwater discharge area.

Plate 7
Orthic Black soil with coarse textured gravelly lense (24"-32"). Note white salt crystals deposited at the bottom of gravel lense (Figure 15, p. 65) in Whitewater Basin sediments. (Discharge Area).

Plate 8
Gleyed Eluviated Black soil in a leached depression in the Leighton Area. Ponded water leaches profile during infiltration. Soil is typical of a fast local recharge flow system.