1992

Hydrogeologic Characterization of a discharge wetland in northeastern Grand Forks County, North Dakota

Dean R. Goebel
University of North Dakota

HYDROGEOLOGIC CHARACTERIZATION OF A DISCHARGE WETLAND IN NORTHEASTERN GRAND FORKS COUNTY, NORTH DAKOTA

by

Dean R. Goebel
Bachelor of Science, University of North Dakota, 1986

A Thesis

Submitted to the Graduate Faculty

of the

University of North Dakota

in partial fulfillment of the requirements

for the degree of

Master of Science

Grand Forks, North Dakota
December
1992

This thesis, submitted by Dean R. Goebel in partial fulfillment of the requirements for the Degree of Master of Science from the University of North Dakota, has been read by the Faculty Advisory Committee under whom the work has been done and is hereby approved.

Philip J. Gerla (Chairperson)

Ronald K. Matheney

John R. Reid

This thesis meets the standards for appearance, conforms to the style and format requirements of the Graduate School of the University of North Dakota, and is hereby approved.

Dean of the Graduate School

PERMISSION

Title Hydrogeologic Characterization of a Discharge Wetland in Northeastern Grand Forks County, North Dakota

Department Geology

Degree Master of Science

In presenting this thesis in partial fulfillment of the requirements for a graduate degree from the University of North Dakota, I agree that the library of this University shall make it freely available for inspection. I further agree that permission for extensive copying for scholarly purposes may be granted by the professor who supervised my thesis work or, in his absence, by the Chairperson of the department or the Dean of the Graduate School. It is understood that any copying or publication or other use of this thesis of part thereof for financial gain shall not be allowed without my written permission. It is also understood that due recognition shall be given to me and to the University of North Dakota in any scholarly use which may be made of any material in my thesis.

Signature____________________________

Date________________________________

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

ACKNOWLEDGMENTS

I would like to express my sincere gratitude towards my committee chairperson Dr. Philip Gerla for his encouragement, mental and physical labor, and constructive criticisms throughout this thesis. In addition, my other committee members, Dr. John Reid and Dr. Ron Matheney are to be commended for their guidance in the preparation of this thesis and enriching my educational experience at UND. This thesis is greatly indebted to the overall expertise and knowledge provided by my committee members.

I would also like to acknowledge the North Dakota Water Resources Research Institute for funding this study. The North Dakota Geological Survey drilled and sampled two borings at the site. Permission to access the Lunby-Stewart wetland area was provided by the U.S. Fish and Wildlife Service. Precipitation data was provided by Mrs. Ken (Betty) Braaten.

Finally, I would like to give special thanks to my family, wife Sue and children Tessa and Jared, for their support and sacrifice throughout this endeavor. Also my parents, Don and Zerline deserve a thank you for their continuing encouragement and direction.

ABSTRACT

Soil salinization associated with saline groundwater discharge results in decreased agricultural production in the central glacial Lake Agassiz plain of North Dakota. Saline discharge occurs in a belt of ephemeral wetlands in the lake plain. The physical and chemical hydrology of the Lunby-Stewart saline discharge wetland were investigated in order to provide information which could facilitate land management strategies applicable to this and other discharge wetlands.

Hydrologic data used to characterize the wetland were obtained from monitoring wells, staff gages, precipitation gages, borings, and earth electrical resistivity soundings. Temporal and spatial variations were observed in the water table, the vertical groundwater gradient, and hydrogeochemistry of this wetland.

The non-integrated wetland hosts two intermittent lakes fringed by saline soils of lacustrine origin. Low permeability sediments underlying the wetland have hydraulic conductivities ranging from 1.0×10^{-7} m/s to 2.8×10^{-9} m/s.

The temporal and spatial variability of the water table, vertical groundwater gradients, and salinity observed during the study period, in conjunction with previous work on North Dakota wetlands, indicate that precipitation (rather than groundwater input or surface runoff) is the primary source of water supplying evapotranspiration losses. The dominance of chloride and presence of boron in ground and surface water at the wetland suggests input from a regional groundwater flow system. Salinity originates from Lower Cretaceous strata underlying the wetland at a depth of 30 to 43 metres.

According to geochemical models, calcite and gypsum are precipitated in the lacustrine glacial sediments as shallow groundwater undergoes evapotranspiratative losses, but dolomite is dissolved. Also, cation exchange of sodium for calcium and magnesium on smectitic clays occurs within the lacustrine sediments and till. Geochemical modeling results were consistent with x-ray diffraction data which indicate the presence of calcite and gypsum in a soil epipedon.

Soil types at the wetland are related to moisture and topography. Soil development and salinity are associated with geomorphic position within the wetland; low-lying soils generally have higher moisture content because of a shallow water table.

INTRODUCTION

Problem Statement

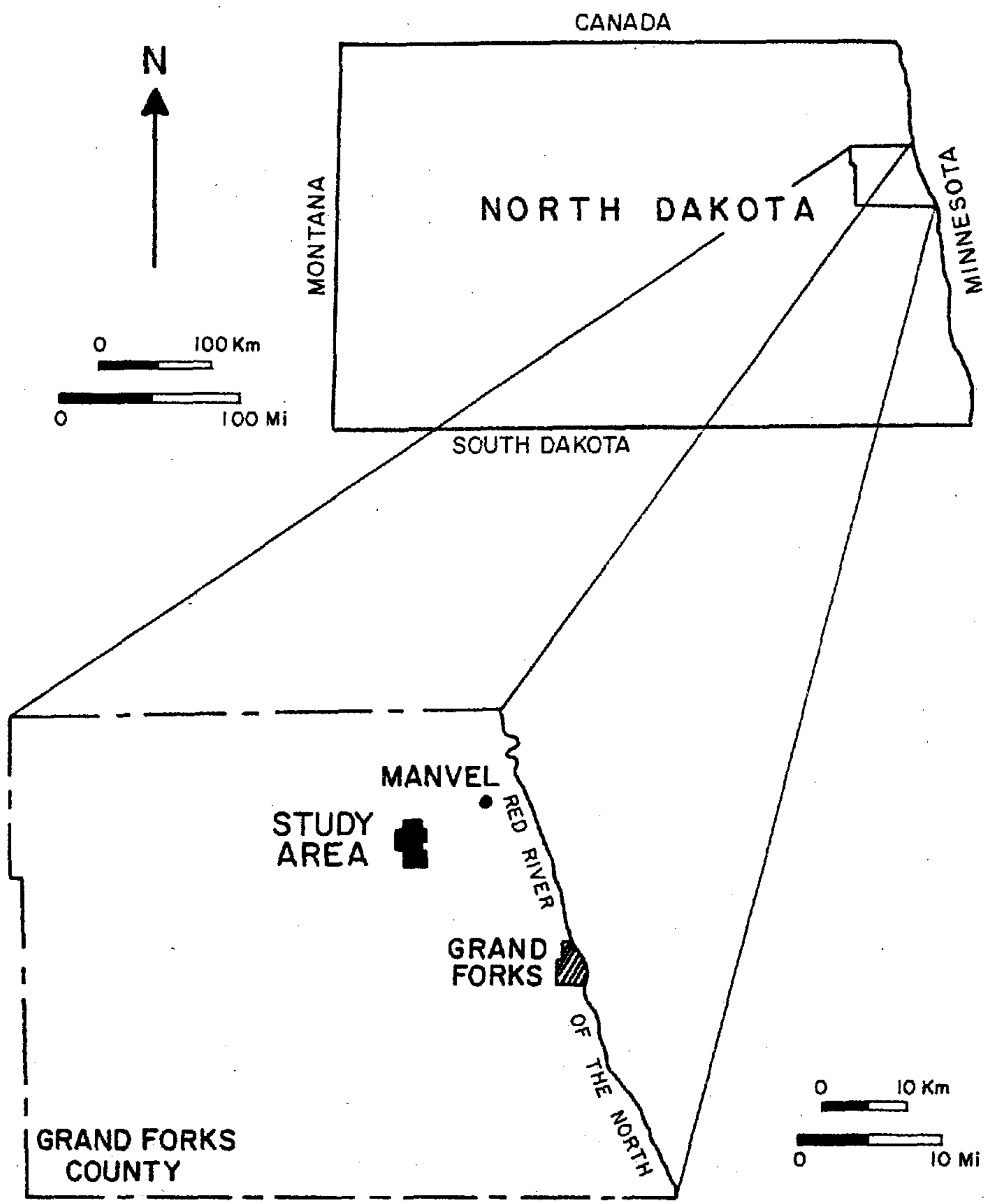
Saline wetlands in the glacial Lake Agassiz plain are important landforms which affect ecological, agricultural, and management concerns. These discharge wetlands play an important role in providing wildlife habitat, flood protection, and base flow to the local river systems. As main tributaries traverse the Lake Agassiz Plain, surface water decreases in quality and contributes to the salinity of the Red River north of Grand Forks (Sandoval et al., 1964; Strobel and Gerla, 1992). Although discharge wetlands function mainly as depression-focused discharge areas during most of the summer and fall, they can also contribute to groundwater replenishment during the spring and early summer (Meyboom, 1966; Lissey, 1971).

Groundwater discharge in the plain has resulted in soil salinization and decreased agricultural production, especially within lands marginal to saline wetlands (Sandoval et al., 1964). Saline artesian waters are assumed to discharge from underlying Cretaceous and Paleozoic strata, providing a salt source for soil salinization (Benz et al., 1961; Sandoval et al., 1964). The size of these saline areas fluctuate seasonally according to the depth of water table. Areas of such soils are increasing, mainly because of farming and other cultural practices (Doering and Sandoval, 1975; Schwartz et al., 1987). Land management strategies are needed to manage these areas properly. Optimal management strategies may be attained through hydrogeological characterization and modeling of these prairie wetland ecosystems.

Objectives

The Lunby-Stewart wetland, located in northeastern Grand Forks County (Figure 1), hosts two temporary lakes fringed by lacustrine-derived saline soils which support salt-tolerant vegetation. The objective of this study was to investigate the physical and chemical hydrogeology of this wetland using field and laboratory studies, involving hydrologic setting, soil types, meteorological parameters, and ground, soil, and surface water interrelationships. This approach was used to test the hypothesis that the wetland is dominantly a discharge zone, where soil and shallow groundwater salinity is mainly a result of geochemical interaction between local and regional flow systems. Wetland geochemistry provides insight regarding

Figure 1. Location of Lunby-Stewart wetland study area.



CANADA
N
MONTANA
NORTH DAKOTA
MINNESOTA
0 100 Km
0 100 Mi
SOUTH DAKOTA
MANVEL
STUDY AREA
RED RIVER
GRAND FORKS
OF THE NORTH
GRAND FORKS COUNTY
0 10 Km
0 10 Mi

wetland position in the groundwater flow system, because distinct geochemical types of water can be associated with local, intermediate, and regional flow systems (Rozkowski, 1967). Regional flow systems typically exhibit higher concentrations of sulfate and chloride compared to shallower groundwater flow systems.

In May of 1990, field work was initiated to characterize the hydrogeological and chemical properties of this wetland. Physical and chemical data were collected over an eighteen-month period.

Functions and Characteristics of Wetlands

General

Wetlands are dynamic ecosystems defined and characterized in terms of hydrology, soils and vegetation. Wetlands serve many purposes which bridge interests in scientific, environmental, and economic considerations.

Cowardin et al. (1979) define wetlands as

> . . . lands transitional between terrestrial and aquatic systems where the water table is usually at or near the surface or the land is covered by shallow water. For purposes of this classification wetlands must have one or more of the following three attributes: (1) at least periodically, the land supports predominantly hydrophytes; (2) the substrate is predominantly undrained hydric soil; and (3) the substrate is nonsoil and is saturated with

water or covered by shallow water at some time during the growing season of each year.

Wetlands provide principal breeding grounds for waterfowl in North America, rich soil resources for agricultural production, and play an important role in the hydrologic cycle (Arndt and Richardson, 1988). Hydrologists have long recognized the role of wetlands in flood control, erosion, water purification, and in groundwater recharge and discharge (Winter, 1989).

Geologic setting and climatic controls are the driving forces in wetland development (Winter, 1989). Water supply and chemical quality of the water is determined mainly by precipitation, surface runoff and its location in the groundwater flow system.

Location in a regional flow system is not the only possible factor responsible for the salinity of wetland waters. Ground and surface water salinity also can reflect lithology of glacial deposits and climate. Climatic trends can constrain the local water budget which, in turn, can affect water inputs and outputs received by a wetland. Salinity of wetland waters can be a function of water balance, and tends to approach that of the dominant water source (Kantrud et al., 1989).

Ion exchange processes also can play a role in water geochemistry. And, surface water chemistry can be modified by the biological activity of aquatic plants (Rozkowski, 1967; Kantrud et al., 1989). Groundwater chemistry also can be altered due to the infiltration of highly mineralized surface water (Rozkowski, 1967).

Wetlands develop in specific geologic, climatic, topographical, groundwater hydrological, and land-use settings (Lissey, 1971; Eisenlohr, 1972; Sloan, 1972; Winter, 1989). These result in the ponding of water and formation of hydric soils. A hydric soil is defined as "a soil that, in its undrained condition, is saturated, flooded, or ponded long enough during the growing season to develop anaerobic conditions that favor the growth and regeneration of hydrophytic vegetation" (Soil Survey Staff, 1985). Hydric soils in the Northern Plains can be recognized on the basis of Lissey's (1971) concept of depression-focused recharge and discharge in terms of their genesis, morphology, and chemistry (Arndt and Richardson, 1988).

Prairie Wetlands

North Dakota contains approximately one million hectares of undrained wetlands, located primarily on the Missouri Coteau and the rolling Drift Prairie (Arndt and Richardson, 1986). Wetlands that occur in the northern prairie region of the United States and Canada are generally depressions of glacial origin, termed prairie potholes or sloughs.

Prairie wetlands tend to be shallow, eutrophic, and saline, depending on their geology, topography, and position in groundwater flow system. These aquatic ecosystems also have the tendency to be non-integrated; water is neither received nor contributed through channelized surface flow. The closed-system dynamics of non-integrated basins have the potential to impound large volumes of water and to produce long-term, rather extreme changes in water depth and biotic conditions in response to climatic trends (Kantrud et al., 1989).

Hydrologic processes are fundamental in determining wetland water chemistry; these processes are the driving force in controlling the movement of chemical constituents to and from wetlands (LaBaugh et al., 1987). The chemical characteristics of these wetlands are quite variable and are governed by depression-focused groundwater recharge, flow-through, and discharge relationships (Rozkowski, 1967, 1969; Rozkowska and Rozkowski, 1969; Stewart and Kantrud, 1971, 1972; Sloan, 1972; Winter and Carr, 1980; LaBaugh et al., 1987).

Recharge wetlands are typically seasonal, fresh water ponds, with associated carbonate-free and non-saline soil pedons located in upland regions. Flow-through wetlands reflect varying degrees of recharge-discharge dominance, resulting in saline and ponding conditions intermediate between recharge and discharge wetlands. Discharge wetlands typically reflect high salinity, pond permanence, and saline soils, with the more saline soils typically containing gypsum (Arndt and Richardson, 1988).

Wetland classification is determined mainly by vegetation/soil, water chemistry, and water regime (duration of ponding or pond permanency). Prairie potholes in the grassland district, such as in North Dakota, are best differentiated on the basis of vegetation (Stewart and Kantrud, 1971; Kantrud et al., 1989). An alternative scheme differentiates inland wetlands from deepwater habitat based on a 2 m low water depth limit (which represents the maximum depth at which emergent plants normally grow).

Many other classification schemes and modifications of the above systems have been used (e.g., Millar, 1976). Wetland classification surveys should be conducted in mid- to late summer in order to accommodate the dynamic nature of vegetation (Kantrud et al., 1989).

PREVIOUS WORK

Regional and Local Description of the Lunby-Stewart Wetland

Physiography

The Lunby-Stewart wetland lies within the Red River Valley, a glacial-lake plain formed by sedimentation within ancient Lake Agassiz. The glacial Lake Agassiz plain occupies a strip of land approximately 64 kilometres wide along the eastern edge of North Dakota and western edge of Minnesota. It has evolved in response to interaction of a variety of conditions and geologic processes, e.g., proximity to and morphology of the Canadian Shield, movement of groundwater in subsurface Cretaceous and Paleozoic strata, differential erosion by running water through time, glacial reshaping, and recent wind, stream and soil-forming events. The final glacial event, late Wisconsinan, was responsible for the formation of glacial Lake Agassiz, which covered a maximum area of 256,000 square kilometres about 12,000 to 9,000 years ago (Bluemle, 1977).

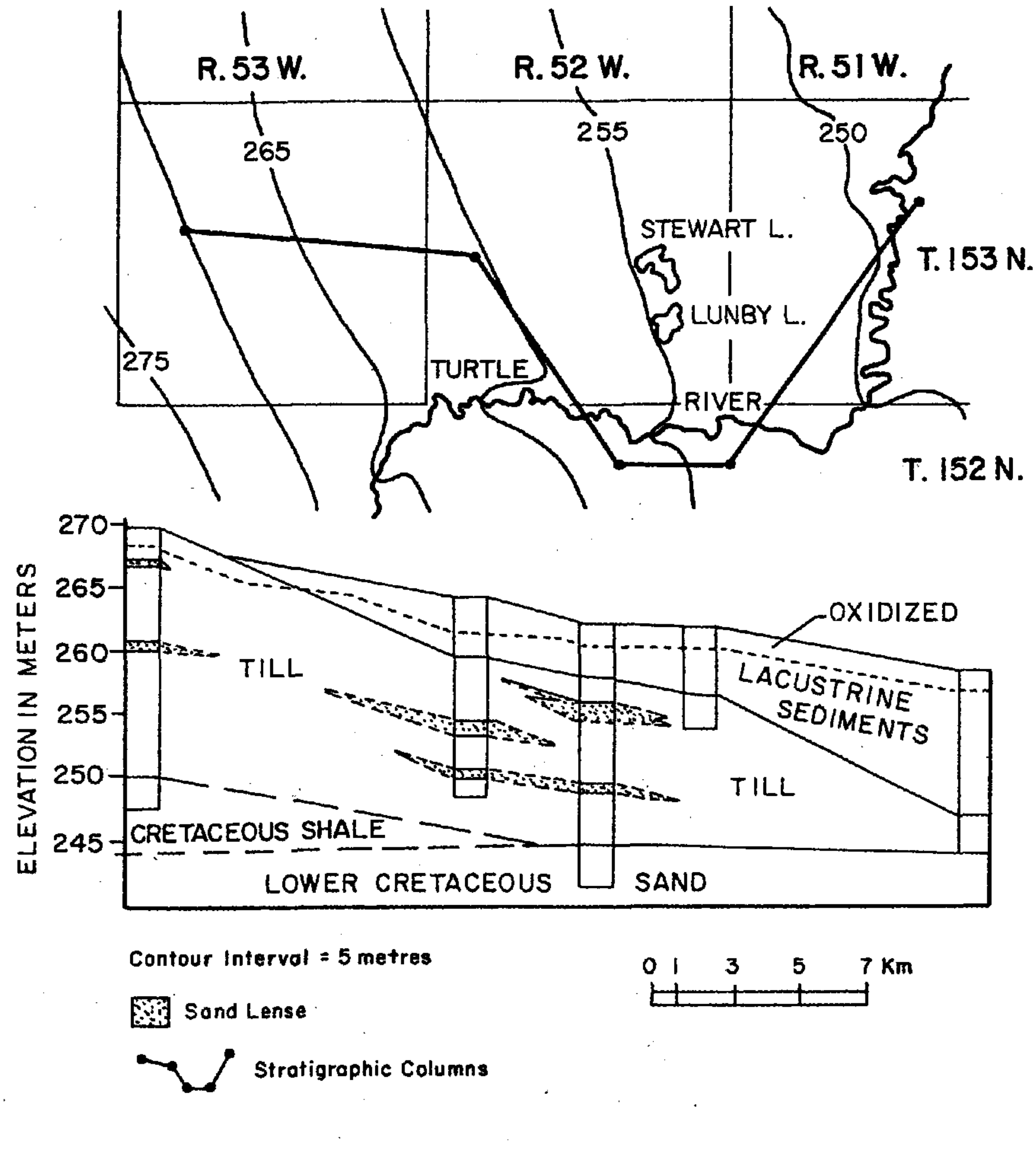
The Lunby-Stewart wetland is located within a federally-managed waterfowl production area (Figure 1). The wetland covers approximately 5.6 square kilometres, with 0.6 square kilometres having intermittent surface water (Lunby and Stewart Lakes) surrounded by emergent and upland vegetation zones. The saline wetland is non-integrated, neither receiving nor contributing to channelized flow; water balance and quality are greatly affected by evapotranspiration, precipitation, and vertical groundwater flow (Goebel and Gerla, 1992). Saline artesian water is believed to be transported upward mainly by advection, concluded using a simple advective model and the comparative salinities of shallow groundwater to that of Lower Cretaceous waters (Goebel and Gerla, 1992).

The wetland exhibits seasonally high water tables. The slope of the water table generally follows the regional topographical gradient which slopes to the northeast (Benz et al., 1961). Elevations range from 253 to 256 metres (Figure 2).

Geology

The Lunby-Stewart wetland lies within lacustrine sediments. Regionally, these sediments thicken to the east (Kelly, 1968). The underlying till units also thin to the

Figure 2. Stratigraphy of the Lunby-Stewart wetland area based on local borehole logs reported by Kelly (1968). Contours depict surface elevation; contour interval is 5 metres.


R. 53 W.
R. 52 W.
R. 51 W.
265
255
250
275
STEWART L.
LUNBY L.
TURTLE
RIVER
T. 153 N.
T. 152 N.
270
265
260
255
250
245
ELEVATION IN METERS
OXIDIZED
TILL
LACUSTRINE SEDIMENTS
TILL
CRETACEOUS SHALE
LOWER CRETACEOUS SAND
Contour Interval = 5 metres
0 1 3 5 7 Km
Sand Lense
Stratigraphic Columns

east; within both the lacustrine and till deposits are small discontinuous sand and gravel lenses up to 3 metres thick (Figure 2).

In the glacial Lake Agassiz plain, glacial sediments overlie Precambrian, Ordovician, Jurassic, and Cretaceous strata (Hanson and Kume, 1970). Near the study area, the Lower Cretaceous strata play an important hydrologic role in the regional groundwater flow regime because they are not overlain by a Cretaceous shale unit which is present beneath most of North Dakota. A water-bearing bedrock unit, the Inyan Kara Formation, subcrops directly below the glacial sediments at a depth of about 30 to 43 metres. The uppermost unit of the Inyan Kara Formation is a fine to coarse-grained quartzose sandstone (Hanson and Kume, 1970), part of the Dakota Group (Bluemle et al., 1986). The sandstone is part of an artesian system which carries saline water under pressure. Upward flow of this artesian water occurs in the central part of the glacial Lake Agassiz plain where the overlying Cretaceous shale is thin or absent.

Soil

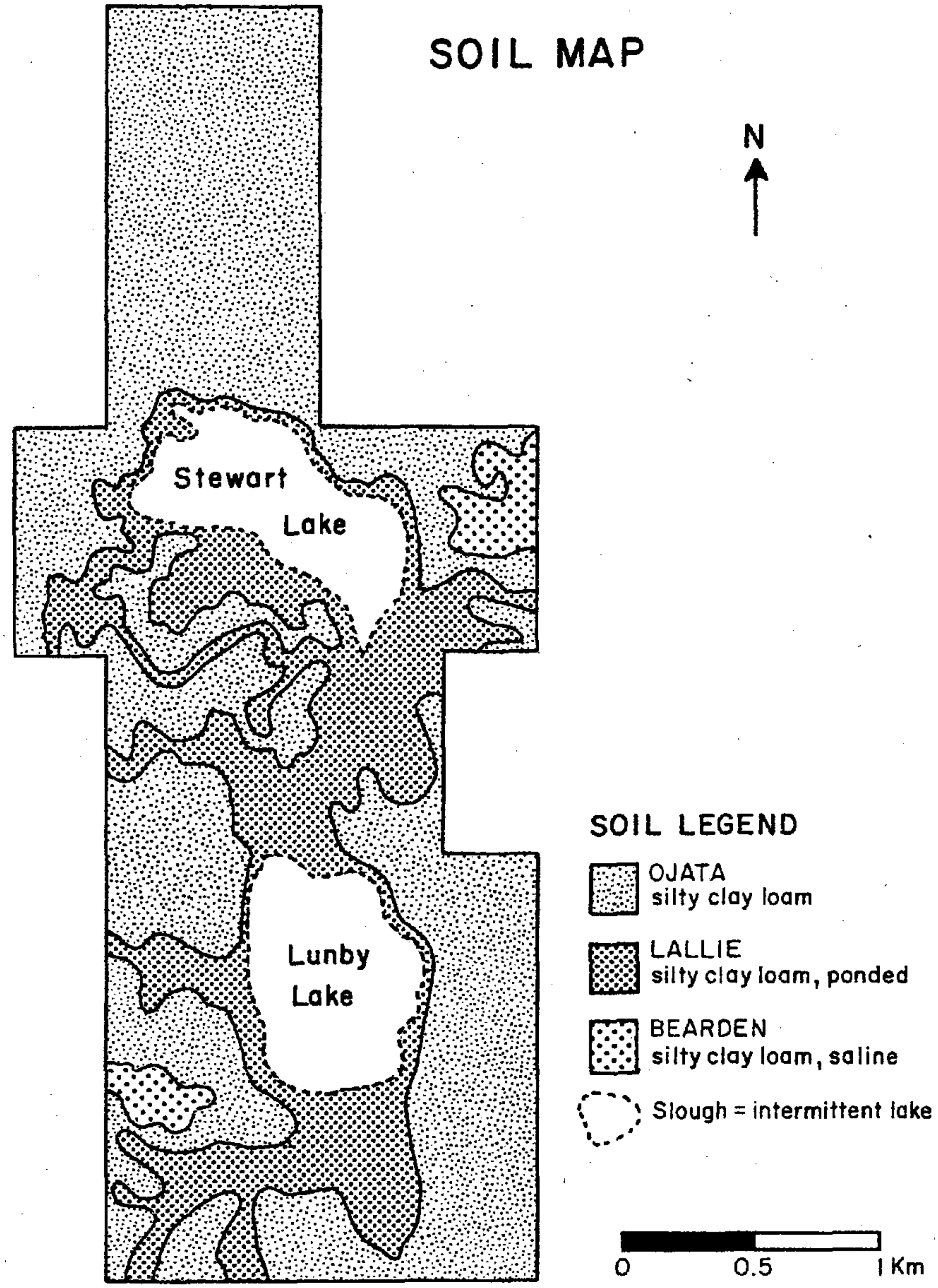
In the glacial Lake Agassiz plain, soil salinity has impacted more than 250000 hectares of agricultural land, half of this being in Grand Forks County (Skarie et al., 1986). Saline soils make up about 23 percent of the total area of Grand Forks County (Doolittle, 1981, p. 60).

Represented soils in the wetlands mainly are the Ojata and Lallie series. A third series, Bearden, is confined to small areas (Figure 3). These soils have been delineated and classified by the Soil Conservation Service (Doolittle et al., 1981). Saline soils in the glacial Lake Agassiz plain of North Dakota generally occur in regions with seasonally high water tables, poor drainage, and hydraulic connection with saline groundwater (Benz et al,. 1961; Sandoval et al., 1964).

The Ojata and Lallie series fall in the aquic moisture regime (Aquoll and Aquent suborders) as a result of the degree and duration of soil saturation (Appendix A). Calciaquoll and Fluvaquent great groups use the prefixes calci and fluv, indicative of calcareous and water-sorted deposits within horizons of the respective Aquoll and Aquent suborders. Typic is a subgroup modifier indicating that these soils are typical of their great groups. Finally, these soils are within the fine, montmorillonitic and fine-silty frigid families of the Lallie and Ojata soil series, respectively.

The Lallie soil is classified as a fine, montmorillonitic (calcareous), frigid Typic Fluvaquent; the Ojata as a fine-silty, frigid Typic Calciaquoll (Doolittle

Figure 3. Soil series represented at the study area (from Doolittle et al., 1982). Refer to Figure 1 for location.


SOIL MAP
N
Stewart
Lake
Lunby
Lake
SOIL LEGEND
OJATA
silty clay loam
LALLIE
silty clay loam, ponded
BEARDEN
silty clay loam, saline
Slough = intermittent lake
0
0.5
1 Km

et al., 1981). The entic modifier (Entisol order) is used for soils that display little or no evidence of developing horizons (Birkeland, 1984, p.47). Such soils may form under low sedimentation and organic matter production, permanently high saline water tables, and perturbation of profile surfaces by wave action (Arndt and Richardson, 1988). Such soils can be found in the wet-meadow and shallow-marsh zones of discharge wetlands. The Ojata soil is in the Mollisol order due to its high percentage of base saturation (high cation exchange capacity) and organic content in the surficial horizons.

Climate

The climate of the area is subhumid continental. Annual precipitation in parts of the glacial Lake Agassiz plain is about 500 mm, with 60% usually falling from early May to the end of August. Average monthly temperatures range from -15 °C in January to 21 °C in July (Jensen, 1972). Snowfall accumulation is normally not heavy; reworking by wind often results in drifting and bare ground. The prevailing wind direction is from the north; highest average windspeed is 21 kilometres per hour, occurring in the spring (Doolittle et al., 1981).

Wetland Geochemistry

Water chemistry in prairie wetlands varies both seasonally and annually. These waters reflect a wide range of chemical constituents within a wide range of salinity, spanning from fresh to extremely saline. Salinity of prairie wetlands can vary with water level, an increase in salinity correlated with a concurrent decrease in water level (LaBaugh et al., 1987).

The major ions found in wetland waters reflect seasonal variations stemming mainly from concentration during freezing, dilution due to snowmelt and runon, concentration by evaporation, dilution from rainfall, and interaction with groundwater (Winter, 1989). Annual variations of major ions are produced mainly by climatic trends and groundwater interactions (Winter, 1989). Prairie lakes in south-central North Dakota also show a wide variation in major-ion concentrations, both seasonally and annually. Based on their dominant-ion constituents, these waters are mainly of the sodium sulfate type (Swanson et al., 1988).

The interaction between groundwater and wetlands can be very complex (Winter, 1983; LaBaugh et al., 1987). Wetland systems can transfer water both to and from the saturated zone, primarily by depression-focused flow (Lissey, 1971). Whether a wetland system is dominated by recharge or discharge depends mainly on the landscape, geology, climate, and location within the groundwater flow system.

In general, discharge occurs where the water table slopes towards the wetland, resulting in a saline, permanent wetland. Groundwater recharge occurs where the water table slopes away from the wetland and the infiltrating surface water is typically fresh and temporary.

Salinity and Wetland Soils

Fine-grained materials such as glaciolacustrine sediments and till host a thick capillary fringe. Under shallow water table conditions, that fringe will increase evapotranspiration. These conditions are conducive to the development of hydric, saline soils associated with shallow groundwater high in total dissolved solids.

Infiltration of water tends to be retarded by clayey and silty soils and by the presence of ground frost at the time surface moisture is the highest (Winter, 1989). Groundwater flow is also extremely slow in these poorly permeable glacial deposits. Because of the low primary permeability, fracture porosity plays an important role in the local flow system (Grisak et al., 1976; Hendry 1982, 1983). This secondary porosity is influenced mainly by weathering at or near the surface, with the most effective local flow systems being established in shallow zones marginal to wetlands (Sloan, 1972). Hydraulic conductivities associated with fractured glacial deposits may be an order of magnitude greater than the unweathered material.

Minor topographic irregularities in northeastern Grand Forks County can influence soil salinity and the growth of vegetation (e.g., trees grow higher in depressions than in adjacent ridges) (Benz et al., 1964). Minor depressions are sites of leaching and recharge to groundwater, while the ridges function as discharge zones with higher salinity. The source of the salt is attributed to the upward leakage of saline water from Lower Cretaceous strata, which subcrop in the area (Benz et al., 1961).

Artificial drainage ditches in the area also can affect salinity and recharge. Skarie et al. (1986) have shown that drainage ditches in the central glacial Lake Agassiz plain can enhance recharge, and also that some of the poorly graded ditches have the potential to cause salinization of soils, especially within pedons approximately 30 metres from ditch margins.

Origin and Transport of the Salinity in the Red River Valley

The salt in the soils in this region originates from the discharge of a regional flow system that extends westward from the area for hundreds of kilometres (Downey, 1986). Downey (1969) suggested that the hydraulic connection between the saline lakes and underlying aquifers in eastern North Dakota resulted after deglaciation. The removal of hydrostatic pressure, induced by deglaciation, could allow water from underlying aquifers to move rapidly upward, eroding the overlying lake sediments and forming depressions, presently occupied by saline soils and lakes. Drill logs indicate the presence of thick deposits of glacial sand and gravel underlying these depressions (Downey, 1973), which are connected hydraulically with the underlying bedrock (Laird, 1944; Benz et al., 1961). Evapotranspiration removes soil water from these discharge areas. Soil salinization results as the salt accumulates. North Dakota wetland salinity depends on the dominant source of water. Saline soils tend to be associated with groundwater as the dominant water input (Fulton et al., 1986).

Concurrent research conducted about 8 kilometres east of the Lunby and Stewart wetland indicates diffusion as the main transport mechanism responsible for soil salinization

(Remenda et al., 1992). Environmental indicators such as isotopes of boron and oxygen have been used in calibrating the diffusive model. The immediate source of the salt there is Lower Cretaceous strata which subcrop approximately 27 metres below ground surface. The thicker sequence of lacustrine sediments at this site (Figure 2) probably accounts for the discrepancy in the results between the two sites. The thicker sequence of till underlying the Lunby-Stewart site probably accounts for the dominant role of advective transport rather than diffusion in developing near-surface soil salinity (Goebel and Gerla, 1992).

Surface salinity at the Lunby-Stewart wetland is assumed to originate from Lower Cretaceous strata, located 30 to 43 metres below ground surface (Figure 2). Saline groundwater from the Lower Cretaceous is transported by advection and diffusion. Upward transport of water high in dissolved minerals has probably been occurring since the drainage of Lake Agassiz, approximately 9,000 years ago (Harris et al., 1974).

FIELD AND LABORATORY METHODS

General

Hydrologic data used to characterize the wetland were obtained from monitoring wells, staff gages, meteorological records, borings, and earth electrical resistivity soundings. Monitoring wells were installed around intermittent Lunby and Stewart Lakes to evaluate water levels and any reversals in vertical flow. Elevations were established for all of the monitoring wells (Appendix B) based on three bench marks chosen in the north, central, and south parts of the wetland. Leveling traverse procedures were used to determine well elevations. Elevations of all wells were determined using a Topcon AT-G1 leveling instrument and stadia rod.

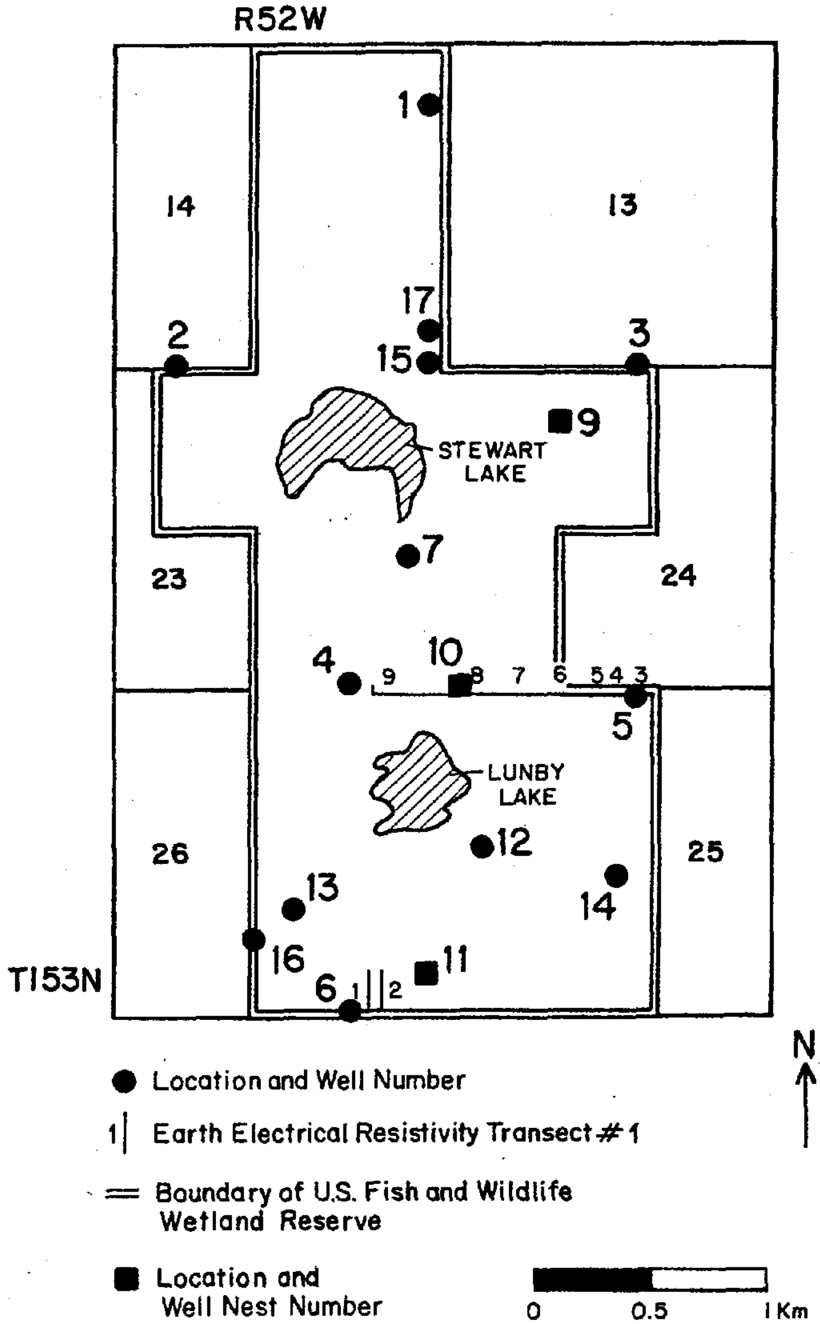
Precipitation

The close proximity of precipitation measurement was important because summer thunderstorms lead to a large spatial variability in precipitation. The data were obtained from Mrs. Ken (Betty) Braaten, approximately 3 kilometres east of the site.

Hydrogeology

Hydrologic data collected at the site were obtained from water table wells and deeper piezometers. Selected monitoring wells were sampled for water analyses on two occasions, once in early August and again near the end of October. The monitoring system included ten single water table wells and five well nests, which ranged from 2 to 12 metres deep (Figure 4). All of the wells, except for the two deepest, were installed using an 8.2 cm diameter hand auger and constructed of 2.54 cm diameter PVC pipe (Appendix A). The two deep wells were installed by the North Dakota Geological Survey using a hollow-stem auger drill rig and constructed of 3.6 cm diameter PVC pipe. Well screens for all of the wells were constructed of hand-slotted PVC either 0.6 or 1.8 metres in length. The screen was packed with washed sand and sealed approximately 0.3 metres above the top with bentonite pellets. The annulus was backfilled to the ground surface with cuttings. Soil descriptions and well construction summaries were

Figure 4. Detailed site map showing well locations and earth electrical resistivity transects within the boundary of U.S. Fish and Wildlife wetland reserve. Refer to Figures 1 and 2 for setting.


R52W
T153N
14
13
23
24
26
25
STEWART LAKE
LUNBY LAKE
N
Location and Well Number
Earth Electrical Resistivity Transect #1
Boundary of U.S. Fish and Wildlife Wetland Reserve
Location and Well Nest Number
0
0.5
1 Km

logged in the field during well installation. An electric probe was used to measure water levels in wells at least once a month and more often during the summer.

Hydraulic Conductivity

Data from slug tests of wells of variable depth were used to estimate hydraulic conductivities representative of the geologic materials. Single-well response data were analyzed using the Bouwer and Rice method (Bouwer, 1989). This method was developed for a rising water level in the well. This was achieved by removing water from the well by either bailing or submersing an iron slug in the well. The iron slug method, unlike bailing, required allowing the water to return to equilibrium and quickly removing the iron slug prior to monitoring well recovery as a function of time.

Groundwater Sampling

Groundwater from selected monitoring wells and the two intermittent lakes were sampled for chemical analyses for calcium, magnesium, sodium, potassium, total alkalinity, boron, sulfate, chloride, pH, temperature, conductance, and

TDS. Initial well development involved purging three or more casing volumes of water using a bailer or peristaltic pump. Because of the slow recovery of the wells, conventional sampling protocol (Lindorff et al., 1987) had to be adjusted. Purging three casing volumes from the wells would leave little or no water to sample; consequently water samples were obtained after allowing sufficient recovery of the well which was previously purged dry. Water samples were filtered (0.45 micron) and collected in polyethylene bottles that were cleaned with detergent and soaked in distilled water. The bottles were placed in a cooler for transportation to the laboratory.

Analytical Techniques

Major ion analyses were performed on ground and surface water samples. Alkalinity, pH, conductance, and temperature were measured in the field using a pH meter and conductivity bridge. Sulfate and boron were determined spectrophotometrically; total alkalinity and chloride were determined by titration using a Hach Kit DR-EL/4 for both techniques (Hach Chemical Co., Loveland, Colorado). Magnesium, calcium, potassium, sodium, specific conductance, and TDS were analyzed by the North Dakota State Health and Consolidated Laboratories. Cation concentrations were obtained using an inductively coupled plasma analyzer, anions by a potentiometric automatic titration method. A complete analysis for water sampled from well 13 was used for quality assurance and control of the parameters obtained from the Hach Kit (Appendix C). At other times during the study, conductance and temperature were measured alone.

Hydrogeochemical Modeling

Geochemistry was modeled using the computer program MINTEQA2 (U.S. EPA, 1989), a chemical speciation model for ground and surface water. This geochemical equilibrium model utilizes input parameters consisting of ground and or surface water chemical analyses and a list of minerals that are to be equilibrated with these waters. An extensive thermodynamic database is invoked in the model specific to common mineral phases and aqueous species. Activity coefficients are calculated theoretically using the extended Debye-Huckel equation. Modeled output consists of a final solution chemistry, complete with speciated solution chemistries and saturation indices of common minerals that may play a role in that solution chemistry.

The computer program BALANCE (Parkhurst et al., 1982) was used to help define and quantify chemical reactions in groundwater as it flows upward from Lower Cretaceous strata to shallow groundwater flow systems. Input data consisted of chemical compositions of two water samples, representative of points along a flow path, and the chemical compositions of a mineral set (phases) selected as the reactants or products in the system. Mass transfer is calculated by the program (amounts of phases entering or leaving the aqueous phase) which accounts for the observed geochemical changes between the two solutions. BALANCE is not constrained by thermodynamic criteria; the appropriate reaction model generated must be consistent with the available data set.

Soil

Stratigraphy of soils and lacustrine sediments were determined on the basis of borehole logging during well installations. Areas of high surface salinity were delineated by visual inspection from color air photographs obtained from the Soil Conservation Service. These salt-encrusted areas develop mainly along the fringe of ponded water, and typically host salt-tolerant vegetation including *Salicornia rubra* and *Hordeum jubatum* (wild barley). The latter was found growing mainly along unmaintained roads which transverse the wetland.

Pits approximately 1 metre deep were dug to examine soil epipedons. Dominant vegetation, relative clay and silt content, color, oxidation structures, fractures, varves, and mineral accumulations were recorded. Munsell color and reaction to dilute hydrochloric acid were also noted. Soil matrix mineralogy was also determined using x-ray diffraction (XRD). The mineral samples were powdered and prepared in the Natural Materials Analytical Laboratory, University of North Dakota. Wet mount slides were analyzed on a Phillips x-ray diffractometer. Major peaks obtained from the output diffractogram were cross-referenced with ASTM standards obtained from JCPDS-International Centre for Diffraction Data (1991), a computer database of mineralogical standards.

Earth Electrical Resistivity

Resistivity soundings can provide useful information on groundwater salinity and hydraulically active zones. Saline water can be discerned from fresh water on the basis of relative differences in resistivity. Subsurface resistivity is also affected by lithological changes, specifically clay content in this case. Resistivity is measured by inducing an electric current into the ground through two current electrodes and measuring the potential difference between potential electrodes (Appendix H). Electrical soundings were generated using the Schlumberger array and interpreted by an iterative method described by Zohdy (1989). The iterative procedure produces a layered model based on field sounding curves. A layered model is obtained by generating a theoretical curve that best fits the observed curve. Calculated resistivity with depth is a function of the distance between the electrodes and the potential difference measured at the potential electrodes. Modeled results of stratigraphy and electrical resistivity could be interpreted to a maximum depth of about 23 metres. Below that depth, the drop between the potential electrodes was less than the resolution of the Soil Test potentiometer.

RESULTS

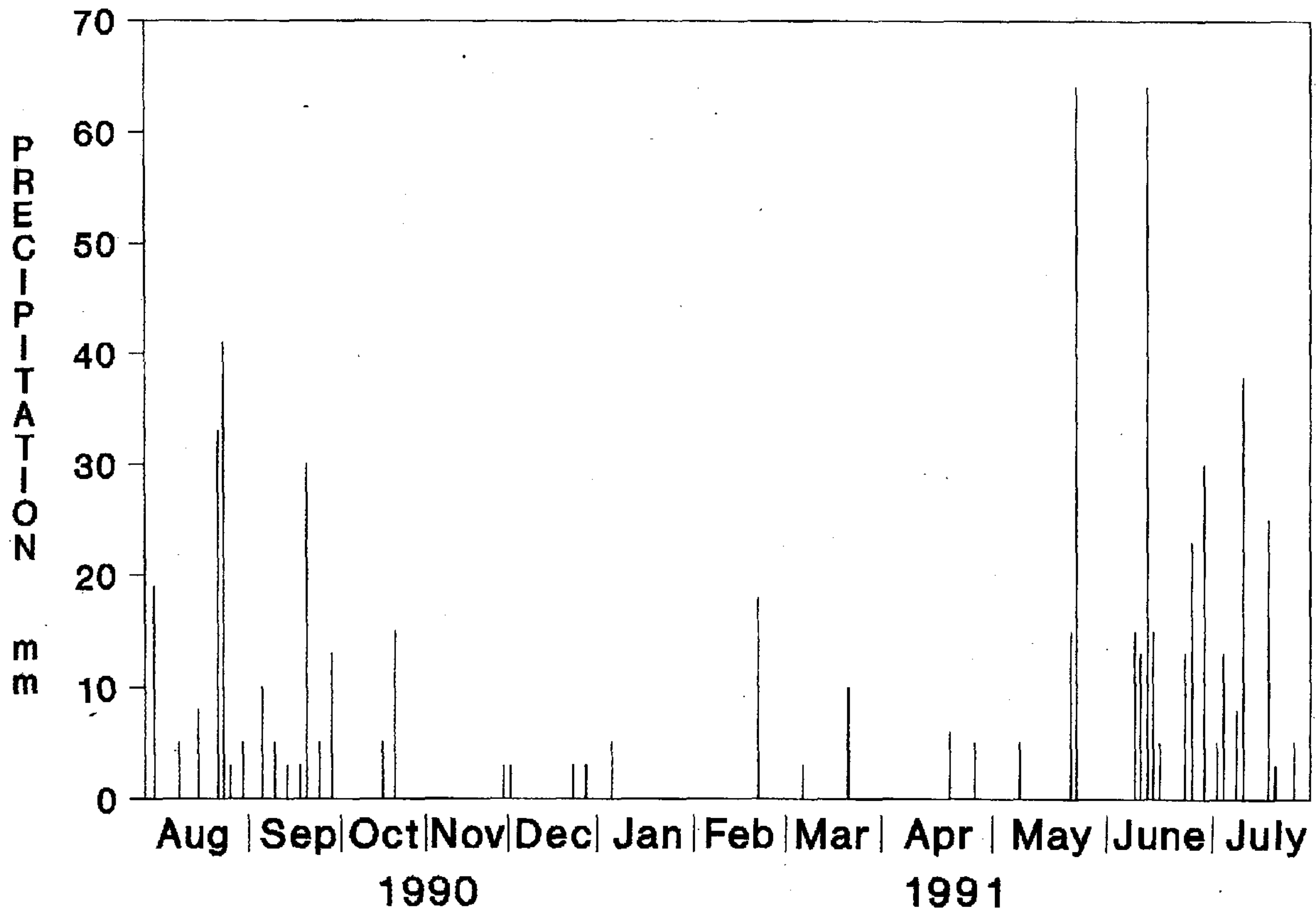
Precipitation

About 600 millimetres of precipitation were recorded from August 1990 to July 1991, approximately 100 millimetres above the mean (Appendix D). Most of this total, 76 percent, occurred as rainfall during the months of August 1990 and May through July 1991 (Figure 5). An estimated 480 millimetres of snow (approximately 48 millimetres water-equivalent) fell during the winter. Wind-blown snow accumulated in the topographic lows, especially in the areas of standing vegetation (e.g., cattails).

Soil

The three soil types classified at the wetland were delineated mainly on their typical moisture content and elevation (Figure 3). The hydric Lallie soil series occupies areas near the slough and intermittent lakes where infiltration is very slow and runoff is ponded. Lallie

Figure 5. Monthly precipitation for the monitoring period (Data obtained from Mrs. Betty Braaten).

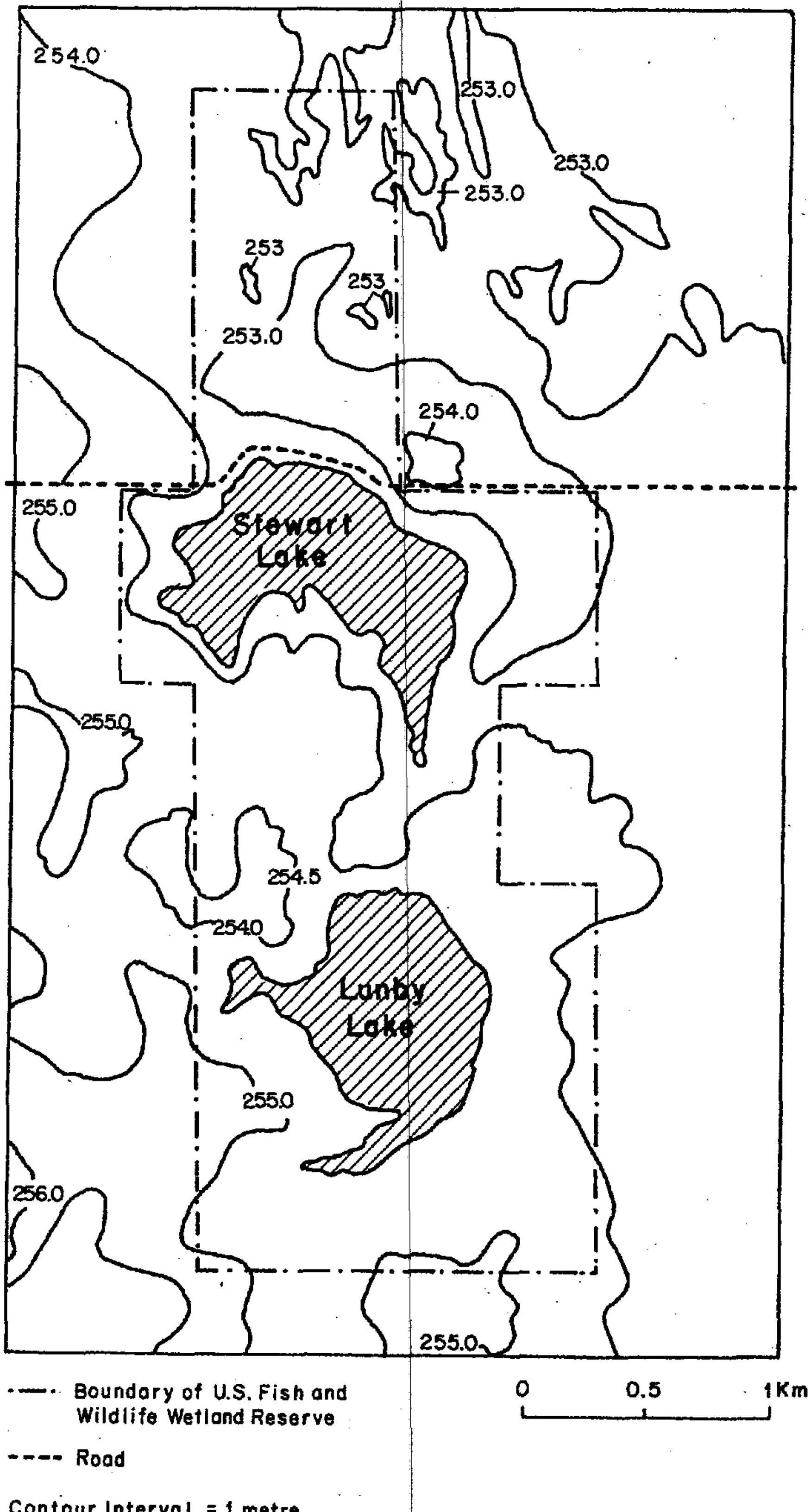

PRECIPITATION mm
70
60
50
40
30
20
10
0
Aug
Sep
Oct
Nov
Dec
Jan
Feb
Mar
Apr
May
June
July
1990
1991

soil typically supports hydrophytes in the peripheral zones around the lakes, with a transition to grass in the slightly higher elevated wet-meadow to low-prairie zones. These vegetation zones typically correspond with wetland topography (Figure 6). Infiltration is slow in adjacent grassland characterized by the Ojata soil series (Doolittle et al., 1981).

In all except two cases, soil horizons were calcareous. The noncalcareous epipedons occurred near well 1 and in a shallow marsh near well 17 (Appendix E). Depth to the water table at well 1 was consistently lower than all other wells during the study period and averaged 2.2 metres below ground surface.

Ojata soil profiles typically contained more macroscopic gypsum and calcite accumulations (e.g., near well 2). Some lower horizons are gypsiferous. Borehole logs at wells 5 and 13 revealed zones of medium to coarse-grained gypsum crystals. The accumulation zones occurred near the lower limit of the permanent water table where color of the clayey silt changes from a brown (10YR 4/3) to a reduced gray (10YR 5/1) hue and oxidation structures were absent.

Figure 6. Topography of the Lunby-Stewart wetland.


N
254.0
253.0
253.0
253.0
253
253
253.0
254.0
255.0
Stewart
Lake
255.0
254.5
254.0
Lunby
Lake
255.0
256.0
255.0
0
0.5
1 Km
Boundary of U.S. Fish and
Wildlife Wetland Reserve
Road
Contour Interval = 1 metre

Mineral accumulations also occurred below the root zone and in fractures. During well installation, mineralization and oxidation selvages were observed along fracture planes. The Ojata series generally contained more fractures than the Lallie series.

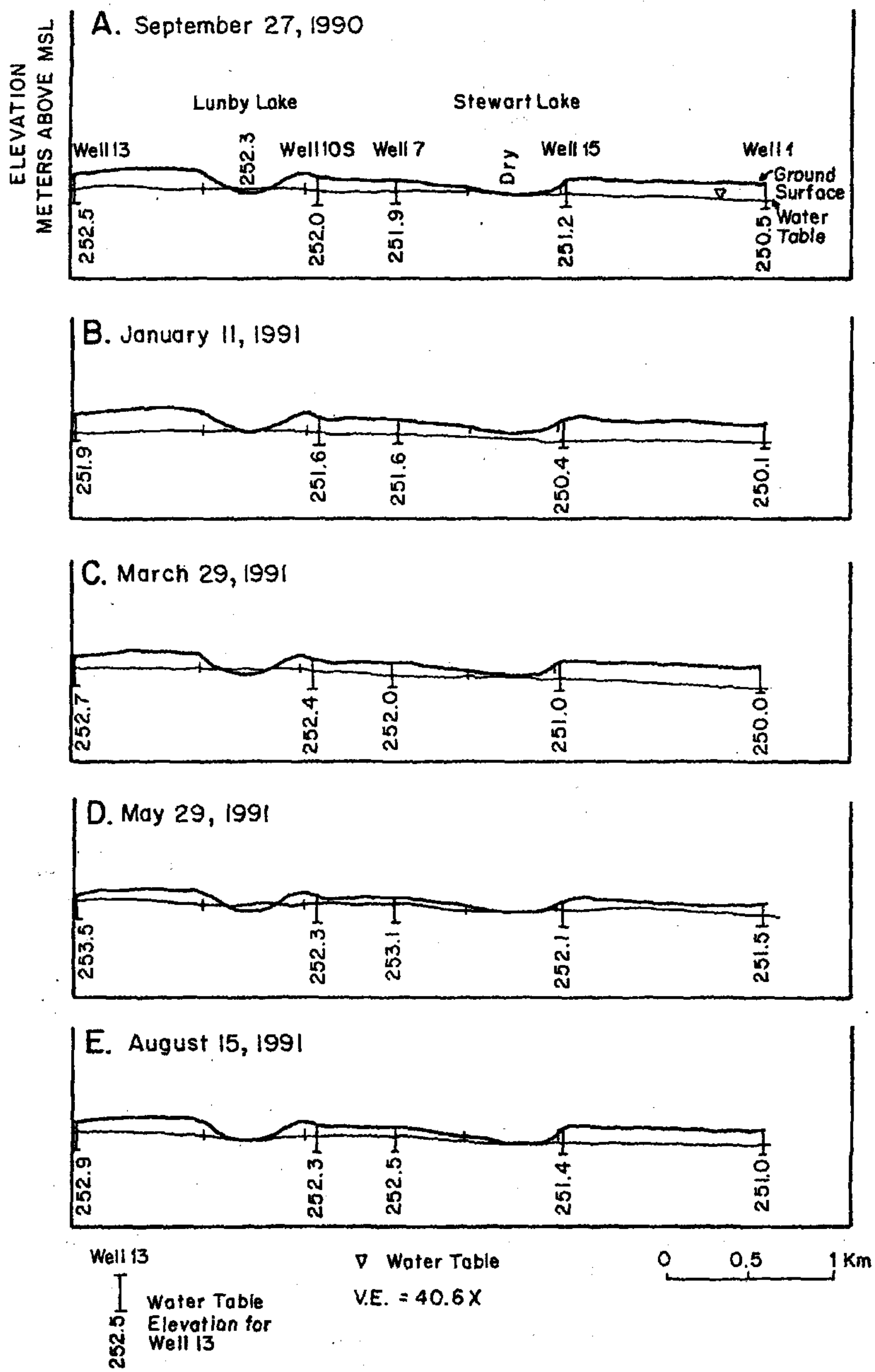
The lacustrine sediments have a high shrink-swell potential (Doolittle et al., 1981) and are subjected to a fluctuating water table, which can result in the origin of desiccation fractures.

Temporal and Spatial Variation of the Water Table

All of the wells completed at the study area are in glaciolacustrine deposits. The upper 4 to 5 metres of the lacustrine clay and silty clay sediments are oxidized and commonly contain fractures (Appendix E).

The slope of the water table is generally to the northeast (Figure 2). Seasonal variations in water levels can cause local changes in the gradient and elevation (Figure 7). These variations can also result in vertical flow reversals, from normally upward to occasionally downward. Typical gradients in all of the nested wells

Figure 7. Relation of wetland water levels to water-table levels for five dates in 1990-91. A, September 27, 1990. B, January 11, 1991. C, March 29, 1991. D, May 29, 1991. E, August 15, 1991.



ELEVATION METERS ABOVE MSL
A. September 27, 1990
Lunby Lake
Stewart Lake
Well 13
252.3
Well 10S
Well 7
Dry
Well 15
Well 4
Ground Surface
Water Table
252.5
252.0
251.9
251.2
250.5
B. January 11, 1991
251.9
251.6
251.6
250.4
250.1
C. March 29, 1991
252.7
252.4
252.0
251.0
250.0
D. May 29, 1991
253.5
252.3
253.1
252.1
251.5
E. August 15, 1991
252.9
252.3
252.5
251.4
251.0
Well 13
252.5
Water Table Elevation for Well 13
∇ Water Table
V.E. = 40.6X
0
0.5
1 Km

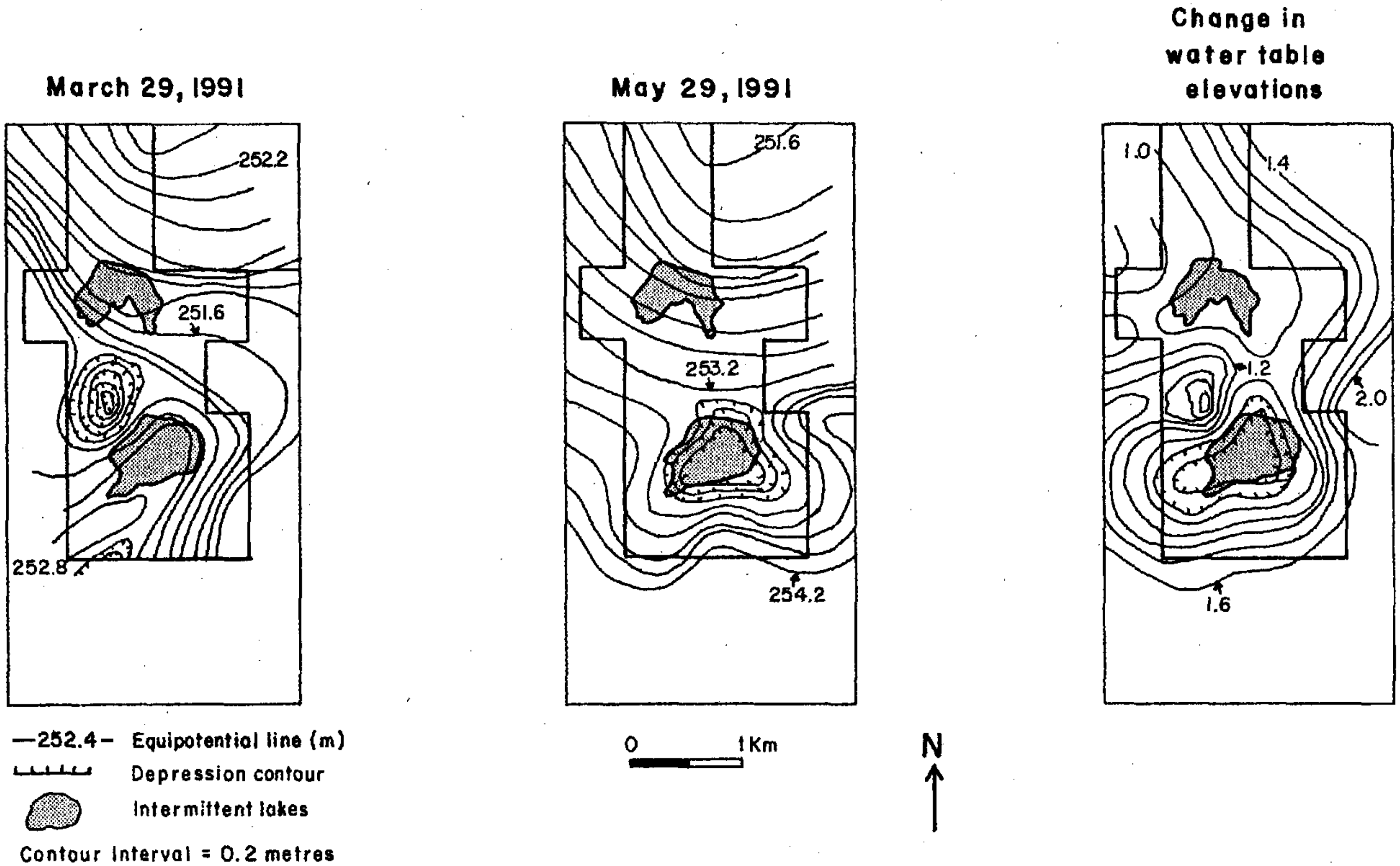
were upward and ranged 0.25 metre per metre. A horizontal gradient of 5.0×10^{-4} was calculated at the wetland, based on water level data from wells 1 and 13.

In summer, 1990, the water table was very low and all surface water was lost from the lake basins. Water table levels continued to drop until approximately the middle of February. All of the monitoring wells indicated a rapid response to spring recharge. Recharge began near the end of February to early March of 1991. Nested wells reflected a flow reversal during this time (Appendix F). Water levels continued to rise until May, which is near the onset of the growing season and time of increased evapotranspiration (Appendix F).

Following the spring melt in March, 1991, a groundwater ridge formed north of Lunby Lake and extended towards Stewart Slough (Figure 8). The ridge corresponded with the distribution of the Lallie soil (Figure 3). By the end of May the groundwater ridge had dissipated (Figure 8). During this same period, approximately 160 millimetres of rain fell, resulting in nearly a 2 metre increase in water levels in the elevated areas.

Similar patterns were also observed during the fall of 1991. Goebel and Gerla (1992) observed a 1.2 metre rise in the water table adjacent to Lunby Lake following a

Figure 8. Water-table contours in spring, 1991, (elevations are in metres). The shaded areas show Stewart Lake (dry) to the north and Lunby Lake to the south.



March 29, 1991
252.2
251.6
252.8
May 29, 1991
251.6
253.2
254.2
Change in water table elevations
1.0
1.4
1.2
2.0
1.6
—252.4— Equipotential line (m)
Depression contour
Intermittent lakes
Contour interval = 0.2 metres
0
1 Km
N

two-month period in which 91 millimetres of rain fell. During the fall, with low evapotranspirative demands, recharge may occur if sufficient precipitation falls.

A spatial variation in water level rise accompanies these infiltration events. Near the lake basins, where the water table is at or near the surface, water levels responded rapidly to infiltration. Yet, the overall rise is greater in the adjacent higher elevations (Figure 8), probably because of water storage in the unsaturated zone.

Hydraulic Conductivity

The hydraulic conductivity of the upper weathered zone (Figure 9) is approximately 1×10^{-7} m/s (about 3 m/yr) (geometric mean). Below about 4.5 metres, hydraulic conductivities are lower by at least one order of magnitude. The deeper zones have fewer fractures than the upper zone (Appendix E). Calculated hydraulic conductivities at depths greater than 10 metres average approximately 3×10^{-9} m/s (about 0.1 m/yr) (Appendix G).

Hydrogeochemistry

Groundwater

Chemical analyses show the groundwater in this area to be of a chloride-type (chloride is the dominant anion), without a dominant cation (Figure 9). Total dissolved solids of the groundwater range from about 10,000 mg/L to greater than 30,000 mg/L (Table 1). Groundwater salinity generally decreases with depth (Table 1), although an exception to this trend occurs within wells on the northern edge of Lunby Lake.

With respect to major ion constituents in groundwater, well 2 is the least concentrated, and well 13 is the most concentrated of all shallow wells sampled. Well 2 is approximately 16 metres from a drainage ditch which supports hydrophytic vegetation, indicative of frequent ponding. Well 16, the deepest well sampled, had low concentrations of major ions relative to the other sampled wells. Well 16 contained the highest concentration of boron at 2.7 mg/L. Boron was detected in only one of the shallow wells. Well 13 was sampled on two separate occasions, and both times groundwater contained detectable concentrations of boron (Appendix C).

Figure 9. Diagram showing weathered and unweathered zones with their measured hydraulic conductivities obtained from slug tests. Also, Stiff diagrams show major ions of all groundwater sampling points. Refer to Figure 4 for well locations.

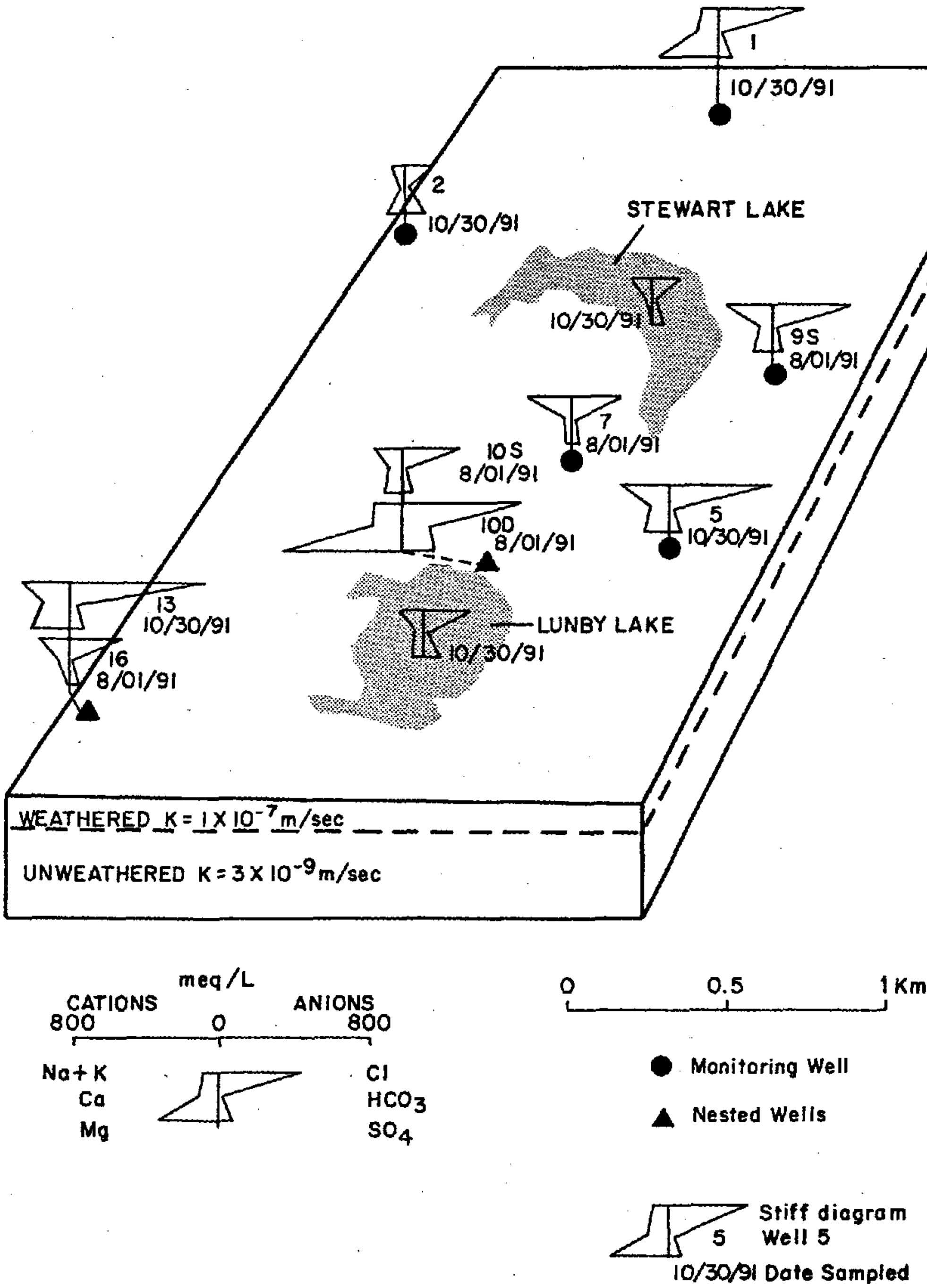

1
10/30/91
2
10/30/91
STEWART LAKE
10/30/91
9S
8/01/91
7
8/01/91
10S
8/01/91
10D
8/01/91
5
10/30/91
13
10/30/91
LUNBY LAKE
10/30/91
16
8/01/91
WEATHERED K = 1 X 10^-7 m/sec
UNWEATHERED K = 3 X 10^-9 m/sec
meq/L
CATIONS
ANIONS
800
0
800
Na+K
Ca
Mg
Cl
HCO3
SO4
0
0.5
1 Km
Monitoring Well
Nested Wells
Stiff diagram
5
Well 5
10/30/91 Date Sampled

TABLE 1
SHALLOW GROUND AND SURFACE WATER ANALYSES

well number	1	2	5
date sampled	30-Oct-91	30-Oct-31	30-Oct-91
depth of screened interval (m)	1.7-3.5	2.0-3.8	2.0-3.8
Ca (mmol/L)	58	20	58
Mg	162	52	73
Na	95	80	281
K	0.4	0.2	0.3
HCO_3	3	5	2
SO_4	26	39	24
Cl	415	133	512
pH	7.4	7.7	7.8
T(·C)	5.8	7.0	7.4
TDS(mg/L)	23700	10300	27500
ionic strength[1](molal)	0.688	0.263	0.662
saturation indices[1]:			
gypsum	0.274	0.289	0.316
calcite	0.504	0.752	0.926
dolomite	1.293	1.772	1.826

well number	7	9S	10S
date sampled	01-Aug-91	01-Aug-31	01-Aug-91
depth of screened interval (m)	1.1-2.6	1.5-3.3	1.4-3.2
Ca (mmol/L)	19	41	43
Mg	16	56	52
Na	240	251	176
K	3.6	0.6	0.4
HCO_3	4	4	6
SO_4	16	16	15
Cl	250	402	287
pH	7.2	7.1	6.7
T(·C)	19.9	19.4	19.4
TDS(mg/L)	16700	22800	19000
ionic strength[1](molal)	0.331	0.523	0.424
saturation indices[1]:			
gypsum	-0.096	0.502	0.060
calcite	0.369	0.501	0.249
dolomite	0.696	1.175	0.618

TABLE 1 (continued)

well number	10D	13	16
date sampled	01-Aug-91	30-Oct-91	01-Aug-91
depth of screened interval (m)	6.6-7.2	2.1-3.9	11.0-11.6
Ca (mmol/L)	65	78	36
Mg	70	109	17
Na	267	294	181
K	0.9	0.4	1.4
HCO_3	4	3	4
SO_4	13	23	12
Cl	499	683	258
pH	7.0	7.6	7.0
T(·C)	19.2	8.1	11.5
TDS(mg/L)	26800	35400	15900
ionic strength[1] (molal)	0.654	0.861	0.333
saturation indices[1]:			
gypsum	0.057	-0.340	0.042
calcite	0.565	0.887	0.283
dolomite	1.215	1.811	0.155

Lakes	Lunby	Stewart
date sampled	30-Oct-91	30-Oct-91
Ca (mmol/L)	29	21
Mg	33	9
Na	146	116
K	2.9	1.4
HCO_3	2	1
SO_4	33	24
Cl	227	143
pH	8.4	8.5
T(·C)	2.9	0.4
TDS(mg/L)	14400	9880
ionic strength[1] (molal)	0.331	0.212
saturation indices[1]:		
gypsum	0.384	0.274
calcite	1.090	0.869
dolomite	1.998	1.095

[1] Ionic strength and saturation indices (SI) were calculated using MINTEQA2 (U.S. EPA, 1989) SI = log (activity product/equilibrium constant).

Shallow wells farthest from the emergent wetland and intermittent lakes generally had higher concentrations of dissolved ions. Wells 13, 5, and 1 showed the highest specific conductance (Table 1). The wells are in Ojata soil which is generally more saline and elevated than the Lallie series (Doolittle et al., 1981).

Shallow wells 7 and 9s, in the Lallie soil within the emergent wetland, had major ion concentrations intermediate between those of elevated wells and the intermittent lakes. The wells are in similar settings within the wetland. Well 7 is next to a shallow marsh zone between Lunby and Stewart Lakes; 9s is within a shallow marsh zone, a low-lying area nearly 1 metre lower in elevation than well 7. The average depth to water table for well 9s was approximately 0.8 metres versus about 1.1 for well 7.

Surface Water

Both of the intermittent lakes had sodium-chloride-type waters (Figure 9), with Lunby Lake having a greater TDS content than Stewart Lake (Table 1). Water was sampled following a brief cold period in which both lakes had ice cover. Autumn rain resulted in the lakes receiving fresh water inputs just prior to freezing. The salinity in Lunby Lake subsequently decreased (prior to freezing), from an electrical conductance of 10,000 microsiemens in the middle of August to 2,300 microsiemens when sampled near the end of October, most likely a result of dilution. During this time the water level rose more than 0.3 metres in well 12 (positioned in the littoral zone of Lunby Lake) (Appendix F).

Lunby Lake showed even greater seasonal variations in salinity and water levels (Figure 7) from late summer to spring. Dissolved solids in the water changed from 19500 mg/L during the end of summer 1991 to 1000 mg/L in March 1992 (Goebel and Gerla, 1992). The water level in well 12 also reflected the rise in Lunby Lake during this period (Appendix B). Boron concentration also varied seasonally in these waters. During the middle of August 1991, boron content was 3.4 mg/L; near the end of October 1991, boron was not detected (Appendix C). Boron variation was probably due to dilution from fall precipitation.

Geochemical Modeling

Results from MINTEQA2 (U.S. EPA, 1989) indicate that the shallow wells are all near or slightly saturated with respect to calcite, gypsum, and dolomite (Table 1). Groundwater samples from the Lower Cretaceous aquifer were nearly or slightly saturated in calcite and dolomite, but gypsum was slightly undersaturated (Table 2). Saturation indices indicate that shallow water is more saturated in calcite, dolomite, and gypsum than Lower Cretaceous water (Figure 10).

Using the computer program BALANCE (Parkhurst et al., 1982), chemical differences between shallow groundwater and Lower Cretaceous waters would require the precipitation of gypsum, calcite, and exchange of sodium for calcium and magnesium on smectite (Table 3). The molalities of major ions in shallow groundwater were adjusted to eliminate the influence of concentration, mainly from evapotranspiration. Chloride concentration averaged an order of magnitude greater in shallow groundwater than the Lower Cretaceous. Based on this observation, the molalities of major ions from shallow groundwater were multiplied by the ratio of the average chloride in the Lower Cretaceous waters to that in the shallow groundwater. Bicarbonate was assumed to be from infiltrated water and was fixed at the average value of shallow groundwater (Table 3).

Soil minerals, obtained from the epipedon near well 2, showed major peaks for gypsum, calcite, and quartz. The presence of gypsum and calcite in this soil epipedon supports the results obtained from BALANCE.

TABLE 2
LOWER CRETACEOUS AQUIFER WATER ANALYSES

well location (township, range, and section)	Lower Cretaceous Aquifer[2] 153-51-10	152-51-4
depth (m)	46.0	42.7(?)
Ca(mmol/L)	7	7
Mg	3	4
Na	51	67
K	0.6	1.0
HCO_3	4	5
SO_4	16	15
Cl	39	56
pH	7.5	7.8
T(·C)	10	10
TDS(mg/L)	4600	5560
ionic strength (molal)	0.087	0.105
saturation indices[1]		
gypsum	-0.146	-0.203
calcite	0.216	0.584
dolomite	0.037	0.846

well location (township, range, and section)	Lower Cretaceous Aquifer[2] 152-26-6	153-52-18
depth (m)	22.9	34.4
Ca(mmol/L)	7	7
Mg	4	4
Na	48	70
K	0.7	1.0
HCO_3	4	5
SO_4	11	12
Cl	45	66
pH	7.7	7.2
T(·C)	10	10
TDS(mg/L)	4260	5690
ionic strength (molal)	0.082	0.094
saturation indices[1]		
gypsum	-0.279	-0.245
calcite	0.519	0.066
dolomite	0.681	-0.225

[1]Saturation indices (SI) were calculated using MINTEQA2 (U.S. EPA, 1989) SI = log (activity product/equilibrium constant). [2]Analyses reported in Kelly (1968)

Figure 10. Saturation indices with respect to calcite, gypsum, and dolomite of shallow groundwater and Lower Cretaceous waters. Saturation indices (SI) were calculated using MINTEQA2 (U.S. EPA, 1989) on water samples from wells 1, 5, 9S, 10S, 10D, and 13; Lower Cretaceous chemical analyses were from Kelly (1968). A, SI for calcite. B, SI for gypsum. C, SI for dolomite. Refer to Tables 1 and 2 for groundwater analyses.

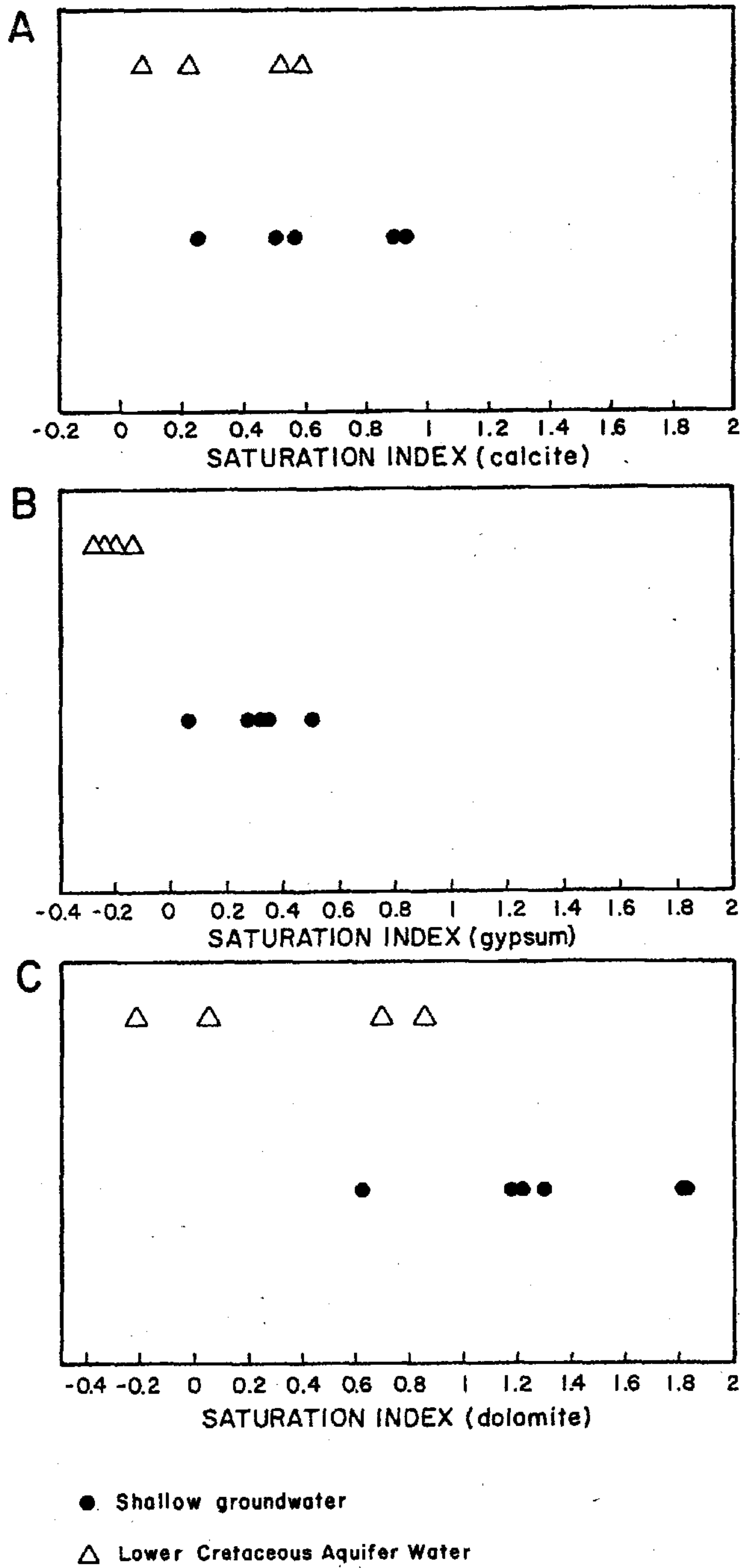

A
-0.2 0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8 2
SATURATION INDEX (calcite)
B
-0.4 -0.2 0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8 2
SATURATION INDEX (gypsum)
C
-0.4 -0.2 0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8 2
SATURATION INDEX (dolomite)
Shallow groundwater
Lower Cretaceous Aquifer Water

Table 3. Calculated mass transfer for mineral-ground water interaction

	Lower Cretaceous aquifer[1] Average	SD[3]	Wetland groundwater[2] Average	SD[3]
Ca(mmol/L)	6.9	0.2	57.2	13.8
Mg	3.9	0.3	87.1	42.1
S	13.4	2.6	19.5	5.5
Na	56.7	8.8	227.4	76.9
Cl	47.9	7.7	466.5	133.3

Difference between the two waters (Cl^- normalized)

Ca(mmol/L)	1.0
Mg	-5.0
S	11.4
Na	33.4
Cl	0.0

Stoichiometric Matrix:

Element	Calcite	Dolomite	CO_2 gas
Ca	1	1	0
Mg	0	1	0
S	0	0	0
C	1	2	1
Na	0	0	0
Cl	0	0	0

Element	Ion Exchange (Ca-Na Smectite)	Gypsum	NaCl
Ca	-1	1	0
Mg	0	0	0
S	0	1	0
C	0	0	0
Na	2	0	1
Cl	0	0	1

Phase mass transfer (mmol/L; negative values indicate dissolution)

Calcite	11.3	Na smectite	16.7
Dolomite	-5.7	Gypsum	11.3
CO_2 gas	-1.1		

[1]Average of analyses in Table 2
[2]Average of analyses in Table 1
[3]One Standard Deviation

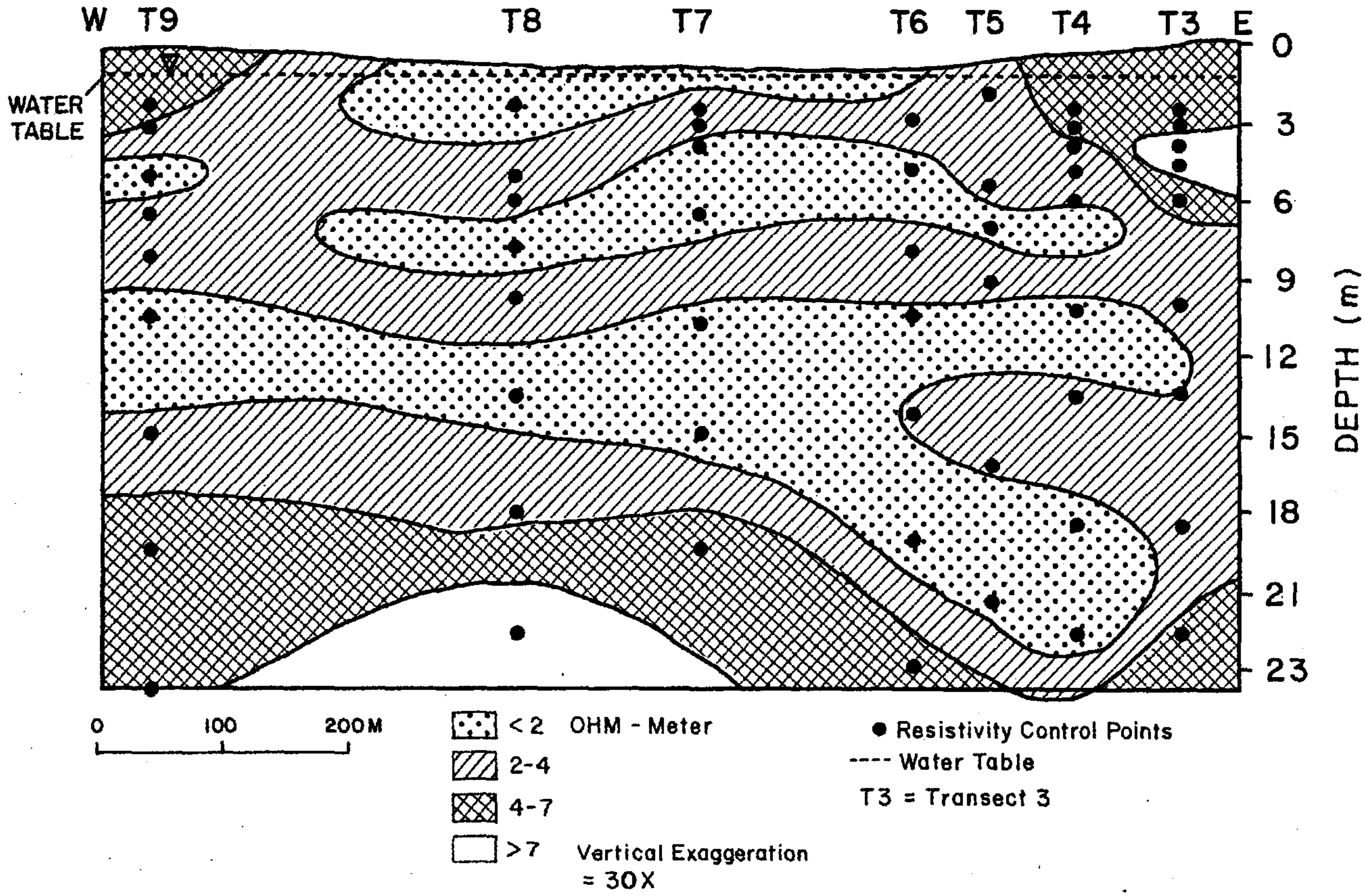
Earth Electrical Resistivity

Subsurface resistivity was measured at the site using electrical soundings at seven locations along an east-west transect (Figure 4). Resistivity sounding data (Appendix H) were also collected at other locations (Figure 4). The easternmost transect was approximately 1 metre higher in elevation than the others along the north-south transect. Sounding data collected along the eastern transect indicated higher resistivity values than those at lower elevation.

Interpreted sounding curves along the east-west transect suggests that groundwater with greater salinity underlies the emergent wetland and Lunby Lake, at the base of the hydraulically active zone (Figure 11). Water analyses from well nest 10 (Table 1) indicate an increase in groundwater salinity with depth.

The variation in resistivity was assumed to be mainly a function of subsurface salinity, although the variability of clay to silt and moisture content in the soils can also have an effect (Fetter, 1988). High clay content results in lower resistivity. Topographic ridges, as determined by logging, tended to have higher contents of silt relative to clay than the adjacent lows (Appendix H).

Figure 11. Profile showing modeled earth resistivity immediately north of Lunby Lake. Resistivity data was collected in summer, 1991. Refer to Figure 4 for location of resistivity transect.



W
T9
T8
T7
T6
T5
T4
T3
E
WATER TABLE
0
3
6
9
12
15
18
21
23
DEPTH (m)
0
100
200M
< 2 OHM - Meter
2-4
4-7
>7
Vertical Exaggeration = 30X
Resistivity Control Points
Water Table
T3 = Transect 3

DISCUSSION

General

The purpose of this study was to characterize the hydrogeology of a discharge wetland and determine if the origin and development of shallow ground and surface water salinity is produced from a regional and local flow system. Groundwater occurrence, physical movement, and geochemistry, in conjunction with soil and meteorological data, were collected to evaluate this wetland.

Configuration of the Water Table

Water table elevations showed a seasonal and spatial variation. Water levels declined during winter but showed a sharp rise in the spring as snow melted and soil thawed. Spring and early summer precipitation contributed to water table rise, with the highest water levels occurring in mid-May. These findings support previously studied water budgets of North Dakota wetlands. Eisenlohr (1972) stated that precipitation, not groundwater nor runoff, is the primary source of water in northern prairie wetlands and that wind is an important climatic factor affecting evapotranspiration. During the summer months, water table fluctuations are gradual at the Lunby-Stewart wetland.

Based on the timing and magnitude of water table and vertical flow fluctuations observed during the study period, snowmelt, along with concurrent spring rains, appears to be the largest contributor to recharge (Appendix F). Frozen sediments at higher elevations can also play a role in recharge; frost can impede infiltration, resulting in runoff into the wetland basins (Lissey, 1971).

Spatial variation in water level rise, observed during spring recharge and major precipitation, probably results from water storage in the unsaturated zone. Well hydrographs (Appendix F) showed the water table dropping throughout the winter. Benz et al. (1968) attributed falling water levels during the winter to water migrating upward from the saturated zone and accumulating at the base of frozen soils. Once thawing begins, water in storage can infiltrate down to the capillary fringe, resulting in the rise of the water table.

The capillary fringe also accounts for variations in water level rise near the wetland basins. Near the lakes, the capillary fringe is truncated because the water table is at or near ground surface. In the higher areas adjacent to the lake basins, the capillary fringe is thicker because of the greater depth to water table. The configuration of the capillary fringe therefore plays a role in how a water table responds to infiltrating water. Water tables can rise at least ten times greater than the equivalent depth of infiltration once percolation intersects the capillary fringe (Gillham, 1984; Gerla, 1992a). This phenomenon occurs mainly because of entrapped air and the fact that the pores in the capillary fringe are tension-saturated. Therefore only a small amount of water is required to overcome air entry pressure (small negative pressure), resulting in pore water pressures greater than or equal to atmospheric pressure.

Water table levels started to decline in mid-May through mid-June; during this period evapotranspiration is the major cause of water loss in northern prairie wetlands (Eisenlohr, 1972; Winter, 1989). June rainfall was the greatest of any month during the study period (Figure 5). Following sufficient rainfall such as this, infiltration can occur during the summer. From mid-June until the end of July, water levels showed a gradual increase (Appendix E).

Soil

All of the soil profiles studied at the wetland are calcareous, except near well 1 and the shallow marsh zones near wells 9 and 17 (Appendix E). Soil epipedons in these three localities are free of calcareous material in approximately the upper 0.5 metre; deeper, the pedons are calcareous. Near well 1, calcareous material might be absent due to the consistently low water table conditions observed throughout the study period. Low water table conditions would inhibit the direct evaporation of groundwater in soil epipedons. This could result in the low concentration of calcareous material; evaporation in upper soil pedons is a function of water table depth and is minimal when depth exceeds 1.5 - 3.0 metres (Schwartz et al., 1987).

Regarding the shallow marsh zone, an influx of fresh water could flush the salts downward thus leaching the upper soil horizon. Arndt and Richardson (1988) observed little to no calcite and gypsum in surface horizons of flow-through wetlands. They attributed this to leaching during spring recharge when snowmelt floods these areas.

Salinity of the wetland soils, as determined by borehole descriptions, air photography, and earth electrical resistivity, varied with location. The Ojata series was generally more mineralized and fractured than the Lallie series soil. Wells 13 and 5 had the highest TDS of all sampled wells; both of these wells are completed in the Ojata series soil. Air photographs indicate salt-encrusted Lallie soil series along the margin of the intermittent lakes. The wetland soils, including salt-encrusted areas, show variable salinities within the unsaturated and saturated zones based on resistivity sounding and geochemistry.

Hydraulic Conductivity

Low hydraulic conductivity of lacustrine sediments at the wetland impedes the movement of groundwater in and out of the wetland. Slug tests of shallow wells in which the screened interval is less than 4.5 metres below the surface reveal higher hydraulic conductivities. These shallow hydraulic conductivities are probably influenced by fractures and possibly by bedding planes (e.g., varves). The low permeability sediments in this zone undergo repetitive wet-dry cycles in response to seasonal water table fluctuations. The high shrink-swell potential of these sediments would promote the formation of desiccation fractures.

Unweathered lacustrine sediments have a smaller hydraulic conductivity. Also, based on borehole logs (Appendix E), some of these shallow sediments on the leeward side (southeast-east) of the intermittent lakes have higher ratios of silt to clay. Bedding planes also may provide for lateral flow within shallow sediments because of less overburden. Grisak et al. (1976) and Hendry (1983), in discussing the role of fracture flow in fine-grained glacial sediments, noted hydraulic conductivity about ten times greater within the shallow hydraulically active zone than the lower till.

Knowledge of the hydraulic conductivity of the underlying lacustrine sediments is important in the determination of groundwater flux. Based on Lissey's (1971) concept of depression-focused flow, discharge does not occur at the same rate over the entire surface of the discharge wetland. Rather, groundwater flow converges toward surface depressions, because total fluid potential is a combination of pressure head and elevation head.

The low permeability of lacustrine sediments results in low rates of upward vertical flux within the wetland. Using Darcy's law and hydraulic conductivity data from slug tests (both weathered and unweathered zones), calculated discharge ranges from 5.0×10^{-8} m^3/s to 1.5×10^{-9} m^3/s. These discharge rates represent the maximum upward vertical groundwater flux that occurs per square metre area of the wetland. Actual flux is less because of recharge and the spatial and temporal variation in discharge rates over the wetland. Vertical hydraulic gradient used in the discharge calculation was 0.5, based on a numerical model calibrated using the spatial distribution of flowing wells that existed during the early development of groundwater in eastern North Dakota (Gerla, 1992b). Strong upward gradients exist over the entire wetland, although the majority of discharge is depression-focused and occurs within the Lallie soil series which occupies the low lying areas of the wetland.

Darcy's law can also be used to estimate lateral flux, or specific discharge, which ranges from about 5×10^{-11} m/s to 1×10^{-12} m/s. As with vertical discharge, rates of lateral flux would vary spatially and temporally within the wetland. The presence of weathering fractures at and near the surface would increase permeability and thus promote lateral flow, especially in the shallow zones marginal to standing water (Sloan, 1972).

Groundwater Chemistry

Variation in major ions in ground and surface water occur within the wetland (Appendix C). Shallow groundwater salinity is assumed to be altered mainly by evapotranspiration, precipitation, and vertical flow. Waters from all of the wells have compositions that reflect interaction between regional and local flow systems (Figure 9). The high concentrations of sodium, chloride, and boron in the ground and surface water indicate discharge from a regional source (Rozkowski, 1967; Benz et al., 1961). Boron concentration between 2.7 and 3.8 ppm, for example, has been used as a natural tracer of deep groundwater from the Dakota artesian system (Sandoval et al., 1964). The chemical compositions of shallow groundwater in lacustrine and especially till sediments are similar to deeper artesian waters, typically high in boron (Benz et al., 1961; Sandoval et al., 1964).

As groundwater discharges upward through lacustrine sediments, boron is probably adsorbed or filtered out (Benz et al., 1961). The 2:1 layer phyllosilicates present (smectite) have the capability to adsorb boron, such that once immobilized, boron becomes incorporated in the tetrahedral layer and leaching can occur only when the lattice structure is destroyed (Uhlman, 1991).

The low concentrations of major ions and TDS in well 2 probably result from the well's proximity to a drainage ditch. Stein and Schwartz (1990) observed ditch-focused recharge caused by artificially routed surface water. The ditches in their study area were aligned N-S and E-W, not according to the local or regional slope of the water table. Because these ditches did not conform to the local and regional slope, longer flow paths could result in increased residence time and thereby increased infiltration.

Soil salinization is also associated with drainage ditches in the glacial Lake Agassiz plain of North Dakota. The most severely impacted saline soils occur around 30 metres from poorly graded ditches (Skarie et al., 1986). Based on water levels, geochemical data, and previous research, some drainage ditches at the wetland have the potential to serve as focal points for recharge. Therefore, the position and screened depth of well 2 would fall in a zone where groundwater is low in salinity; during recharge periods groundwater salinity increases with distance from the ditch.

The intermittent lakes and emergent wetland apparently influence the concentration of dissolved solids in groundwater of nearby wells. This is because snowmelt and spring rainfall are depression-focused and apparently dilute groundwater in the lake basins and emergent wetland more than adjacent grasslands. Wells in the grasslands are completed in soils of the Ojata series, which generally have the highest salinity of the three soil series at the wetland (Richardson and Arndt, 1989).

Salinity generally decreases with depth where shallow groundwater does not interact with evaporated surface water. Well 16 completed at a depth of 11.0 - 11.6 m and located 50 metres from well 13, had significantly fewer dissolved solids (Table 1) than well 13. The lower salinity is probably related to a much greater influence of evaporation on groundwater composition for the shallower well 13.

Well nest 10, on the margin of Lunby Lake, showed a salinity increase with depth (Table 1). This increase was recognized from groundwater chemistry and earth electrical resistivity. Density-driven flow is a probable mechanism for this phenomenon; during the summer Lunby Lake loses water by evapotranspiration, resulting in a water density 2 to 3% greater than fresh water (based on the TDS of water sampled from Lunby Lake and 1000 kg/m^3 as the density of fresh water). Dense water overlying less dense water results in a physically unstable condition which promotes downward flow. Groundwater recharge from evaporated surface water can result in saline water at depth. Descent of groundwater is impeded because of the low permeability and concurrent decrease in hydraulic conductivity with depth of the lacustrine sediments. Stein and Schwartz (1990) concluded that density-driven flow was responsible for the downward movement of saline water through lacustrine sediments in Alberta, Canada, at depths as great as 20 metres.

Shallow groundwater from wells in the emergent wetland have TDS concentrations between those of the other water table wells. The lower concentrations in well 7 relative to 9s, probably result from the greater average depth to water table. Shallow water table conditions near well 9 could result in higher TDS groundwater as a result of evapotranspiration. During the study, well 9s had the smallest average depth to water table of any of the shallow wells; the average was 0.3 m less than that of well 7.

Surface Water Chemistry

The sodium chloride-type water in Lunby and Stewart Lakes (Figure 9) is similar to shallow groundwater composition. The position of the lakes in the groundwater flow system has a major impact on surface water quality. Chloride-type wetlands and lakes in which sodium is the dominant cation are rare in the northern prairies of North America (Swanson et al., 1988).

In addition to the effects of groundwater discharge, surface water chemistry can be altered by fresh water inputs from snowmelt and rainfall or concentrated through evapotranspiration and freezing. Surface water composition, like shallow groundwater, reflects discharge from regional and local flow systems.

Stewart Lake was generally dry during the study period (Figure 7). The only time it contained significant water was early spring and late fall when evapotranspiration was a less important factor in the water budget.

Origin and Development of Ground and Surface Water Salinity

Salinity of ground and surface water at the Lunby-Stewart wetland has probably resulted from the slow upward discharge of deep groundwater from the Lower Cretaceous aquifer (i.e., the regional groundwater flow system). Groundwater chemistry of this water is modified as it interacts with geologic material along a groundwater flow path. In general, ionic composition of groundwater continues to evolve until it reaches equilibrium with respect to the mineralogical composition of geologic material. Once a groundwater system approaches thermodynamic equilibrium, kinetic considerations are not as critical. This allows the use of geochemical models to compute thermodynamic equilibrium relationships between groundwater and certain suites of minerals.

Molar ratios of dissolved constituents vary between the shallow groundwater and waters from the Lower Cretaceous aquifer. Sodium/chloride, sulfate/chloride, and calcium/chloride ratios were lower in the shallow groundwater than in the Lower Cretaceous water. The molar ratio of magnesium to chloride was greater in the shallow groundwater (Table 3). Groundwater saturation indices and ionic strength were determined using MINTEQA2 (U.S. EPA, 1989).

Clay and soil epipedon mineralogy at the wetland are consistent with results obtained from BALANCE. Montmorillonite, a variety of smectite, is the dominant clay mineral within the local lacustrine soils (Sandoval et al., 1964). Elevated magnesium concentration in the shallow waters probably results both from the dissolution of dolomite and the release of magnesium from montmorillonite.

Evapotranspiration concentrates the dissolved solids of soil water in discharge areas, resulting in evaporite precipitation and alteration of soil water chemistry. Arndt and Richardson (1986) applied the Hardie-Eugster model (Hardie and Eugster, 1970) of closed-basin brine evolution (chemical divides), using a solution typical of shallow groundwater found in northern prairie wetlands. The model predicted the early precipitation of calcite followed by gypsum as brine concentrations increased.

Comparison of near-surface concentration of water compared to the Lower Cretaceous artesian system shows a 4 to 17-fold chloride enrichment compared to in situ Lower Cretaceous aquifer waters (Tables 1 and 2). Because chloride is a conservative natural tracer, generally not involved in geochemical reactions, the presence of chloride provides a useful tool in studying groundwater transport in the lacustrine sediments.

These chloride concentrations indicate that advection, rather than diffusion, is the principal transport mechanism. Based solely on a diffusive model (an analytical solution to the diffusion equation) with initial and boundary conditions appropriate to the site, even after 10,000 years, the concentration of chloride would be only 15% of what presently exists in the Lower Cretaceous water (Goebel and Gerla, 1992). However, application of an advective model suggests that the observed salinity could be developed within 10,000 years (Goebel and Gerla, 1992). Vertical hydraulic conductivity calculated from this advective model compares favorably with an estimated hydraulic conductivity of 0.04 m\yr for deep sediments at the site; similarly, an estimated hydraulic conductivity of sediments in the completion interval of well 16 (11.0 - 11.6 m) was 0.06 m/yr.

Earth Electrical Resistivity

Electrical resistivity also was used at the wetland to determine salinity of groundwater. The amount of dissolved solids in groundwater has a negative correlation with resistance; therefore, lower measured resistance should indicate higher groundwater salinity. Geoelectrical sounding data were used to map variations in groundwater salinity. Contoured resistivity sounding data collected along the east-west transect (Figure 4) showed a large zone of low resistivity at depths of 9 to 21 metres (Figure 11). This suggests that saline groundwater accumulates at depth near the base of the hydraulically active zone Beyond this zone, the downward movement of groundwater is probably impeded as evidenced by decreasing hydraulic conductivity. Upward discharge of artesian water from the Lower Cretaceous aquifer could impede downward flow with depth. Hydraulic head data from nested wells at the wetland indicate periods in which pressure head increases with depth (Appendix F). *In situ* hydraulic conductivity tests also indicate a decrease in hydraulic conductivity with depth. Such low permeabilities of the lacustrine sediments can influence the descent of groundwater.

Modeled resistivity along the east-west transect also indicates saline water near the surface (Figure 11). These areas of high surface salinity coincide with salt-encrusted soils devoid of vegetation which are typically marginal to roads that traverse the wetland. Salinization probably occurs as soil water is lost to evapotranspiration, leaving salts behind.

In the southern part of the wetland, resistivity showed a variation because of topographical irregularities (Figures 18 and 19). The slightly higher transect showed higher resistance in the first several metres of depth. Beyond this depth, resistivities were similar and followed the same trend of increasing resistivities downward (Appendix H). The observed higher resistivity at shallower depths at these higher areas is probably a function of soil moisture and texture. Higher amounts of silt are present in the slightly elevated ridges (Appendix E).

SUMMARY AND CONCLUSIONS

The Lunby-Stewart wetland shows variability in water-table levels, vertical gradient, salinity, hydrogeochemistry, and soils. This saline wetland is developed in lacustrine sediments that exhibit seasonally high water tables and hydraulic connection with deeper saline artesian waters.

Following spring recharge in 1991, a shallow groundwater ridge developed beneath Lunby basin. By the end of May, the groundwater ridge dissipated. Also by this time, groundwater that accumulated during the winter within the unsaturated zone in the adjacent highs was released from storage. Infiltrated water resulted in a reversal of the water table gradient. This water released from storage caused the water table to resume its downward slope towards the discharge wetland.

Throughout most of the study period, measurements of nested wells revealed upward flow. Vertical flow was reversed, however, following recharge, especially after significant precipitation during low evapotranspirative demands. Discharge from Lower Cretaceous strata provides a source for wetland salinity, but does not play a significant role in the water budget. Precipitation seems to be the largest contributor, with evapotranspiration leading to the largest loss.

Shallow groundwater, not affected by evapotranspiration of surface water, generally showed a decrease in salinity with depth. Groundwater interaction with dense surface water can result in an increase in salinity with depth until reaching the base of the hydraulically active zone. During the summer, based on the water level and electrical conductivity in Lunby Lake, salinity is controlled mainly by evapotranspiration and dilution. During mid August, Lunby Lake showed the highest recorded electrical conductance and lowest water level.

Concentration by evapotranspiration and freezing can promote the density-driven downward flow of saline water. Results from resistivity and the geochemistry of well nest 10 indicate that salinity can increase with depth as a result of groundwater interaction with more saline water generated by evapotranspiration at the surface. Accumulation of this denser water beneath the slough apparently occurs above the base of the hydraulically active zone, probably from upward flow and decreased permeability at depth.

Water at the wetland shows a time and space variation in major ion constituents. These variations in dissolved species are attributed mainly to interrelationships of evapotranspiration, dilution, and vertical flow. Geochemical modeling and soil mineralogy indicate that dissolution and precipitation of sulfate and carbonate minerals and ion exchange between clay minerals influence wetland hydrogeochemistry. These chemical processes, along with physical processes such as evapotranspiration and freezing, result in a chloride-type shallow groundwater, without a dominant cation. Surface water is of a sodium chloride type. The dominance of chloride and presence of boron reflect groundwater input from the underlying Lower Cretaceous aquifer.

The concentration of chloride is approximately ten times greater for the shallow groundwater than for the Lower Cretaceous aquifer. To develop this salinity, advection must play more of a role in mass transport than diffusion. Application of a simple advective model indicates that such shallow groundwater salinities could develop within 10,000 years. The hydraulic conductivity obtained from this model compares favorably with measured hydraulic conductivities obtained from wells completed in lacustrine sediments at depth of about 12 metres.

Groundwater composition evolves along the upward flow path from the Lower Cretaceous aquifer. Groundwater evolution results in the precipitation of calcite and gypsum and the dissolution of dolomite. Cation exchange of sodium for calcium and magnesium on smectite clays occurs within the till and lacustrine sediments.

Soil type at the wetland is related to the moisture and elevation gradient. Soil development is controlled by high water content because of shallow water table conditions. The two important soil types at the wetland are the Ojata and Lallie soil series. Both of these saline soils can be classified as hydromorphic, where salt accumulation occurs above the capillary fringe. Soil salinity (determined by borings, resistivity, and air photography) can affect groundwater composition. Soil tends to be controlled by its geomorphic position; the low-lying Lallie series is a ponded, hydric soil generally lower in salinity than the Ojata series. The Ojata series develops in the adjacent higher elevated areas, where runoff is slow, and salinity is generally high. Ojata series soils generally exhibited more fractures and mineral accumulation than the Lallie series soils.

Based on data collected during the study period and on previous work, salinization at the Lunby-Stewart wetland can be attributed mainly to its location in a regional and local discharge flow system. Understanding the mechanism and origin of salinization in the glacial Lake Agassiz plain of North Dakota, in relation to physiography, geology, soils, and climate, is a prerequisite for proper management. Characterization of the Lunby-Stewart wetland will provide data useful in determining best management practices for saline wetlands in this region.

APPENDICES

APPENDIX A

Soil Classification

The wetland soils are classified using the terminology and nomenclature of the USDA Soil Conservation Service (Soil Survey Staff, 1975). The hierarchical system places soils into orders (the highest category), suborders, great groups, subgroups, families, and series (the lowest category). Soil classification is based on common soil properties related to how they developed. Orders are differentiated by diagnostic features in the horizons specific to soil-forming processes. Suborders are generally based on moisture regime, soil temperature, and consideration of soil structure and composition. Great groups distinguish soil horizons on the whole and their significant properties. Subgroups are recognized by relating important sets of processes in soil development. Families provide information on similar physical and chemical properties within subgroups. Series are based on soil properties observed in the field used mainly in soil mapping.

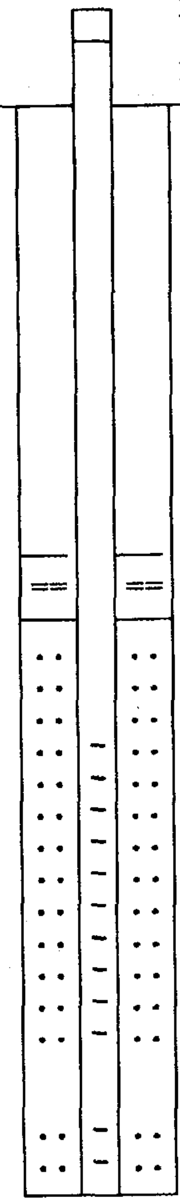
APPENDIX B

Monitoring Well Construction and Elevations

WELL NUMBER: 1
DATE INSTALLED: 6/7/90

DRILLING METHOD: HAND AUGER

ELEV. (MSL) 252.9 — DEPTH FRM SURFACE 0.0 (m)



Riser elev. 253.2 m

Riser height 0.3 m

PIPE:
Diameter 0.025 m
Material PVC
Sch. 20
Length 3.7 m

BACKFILL MATERIAL
Cuttings

251.9 — 1.0 ---

SEAL
Thickness 0.01 m
Type Bentonite
0 pellets

SCREEN:
Diameter 0.025 m
Hand Slotted
Length 1.8 m

FILTER PACK
Type Washed Silica Sand
Length 2.4 m

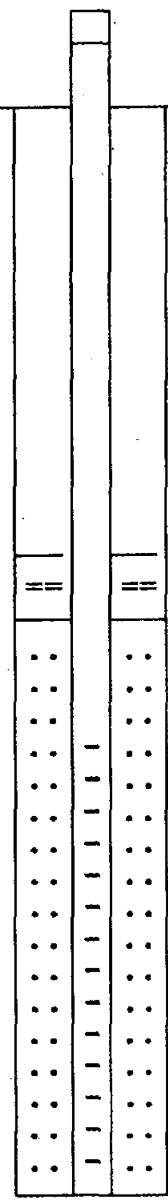
251.1 — 1.8 ---

|<------>|--Diameter of Borehole
0.08m

WELL NUMBER: 2
DATE INSTALLED: 6/7/90

DRILLING METHOD: HAND AUGER

ELEV. (MSL)	DEPTH FRM SURFACE
254.0	0.0 (m)
253.3	0.7 ---
252.1	1.9 ---



Riser elev. 254.3 m

Riser height 0.3 m

PIPE:
Diameter 0.025 m
Material PVC
Sch. 20
Length 3.8 m

BACKFILL MATERIAL
Cuttings

SEAL
Thickness 0.03 m
Type Bentonite pellets

SCREEN:
Diameter 0.025 m
Hand Slotted
Length 1.8 m

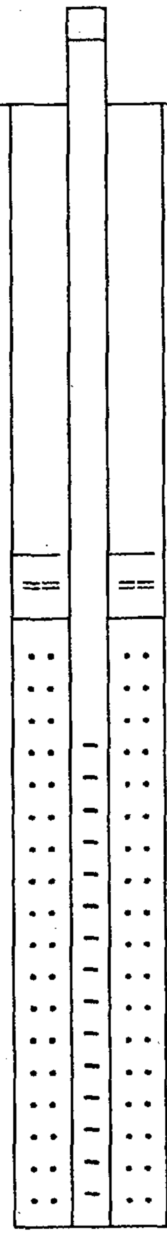
FILTER PACK
Type Washed Silica Sand
Length 3.1 m

|<------>|--Diameter of Borehole 0.08m

WELL NUMBER: 3
DATE INSTALLED: 6/7/90

DRILLING METHOD: HAND AUGER

ELEV. (MSL) | DEPTH FRM SURFACE
253.0 | 0.0 (m)



Riser elev. 253.3 m

Riser height 0.3 m

PIPE:
Diameter 0.025 m
Material PVC
Sch. 20
Length 3.9 m

BACKFILL MATERIAL
Cuttings

251.8 | 1.2 ---

SEAL
Thickness 0.01 m
Type Bentonite pellets

SCREEN:
Diameter 0.025 m
Hand Slotted
Length 1.8 m

FILTER PACK
Type Washed Silica Sand
Length 2.7 m

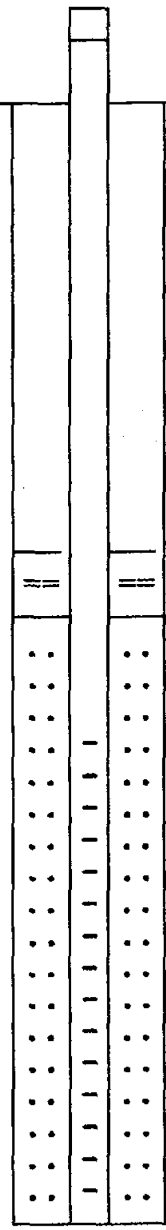
251.0 | 2.0 ---

|<------->|--Diameter of Borehole
0.08m

WELL NUMBER: 4
DATE INSTALLED: 6/4/90

DRILLING METHOD: HAND AUGER

ELEV. (MSL)	DEPTH FRM SURFACE
254.5	0.0 (m)
252.9	1.6 ---
252.5	2.0 ---



|<------->|--Diameter of Borehole
0.08m

Riser elev. 254.8 m

Riser height 0.3 m

PIPE:
Diameter 0.025 m
Material PVC
Sch. 20
Length 3.8 m

BACKFILL MATERIAL
Cuttings

SEAL
Thickness 0.05 m
Type Bentonite pellets

SCREEN:
Diameter 0.025 m
Hand Slotted
Length 1.8 m

FILTER PACK
Type Washed Silica Sand
Length 2.1 m

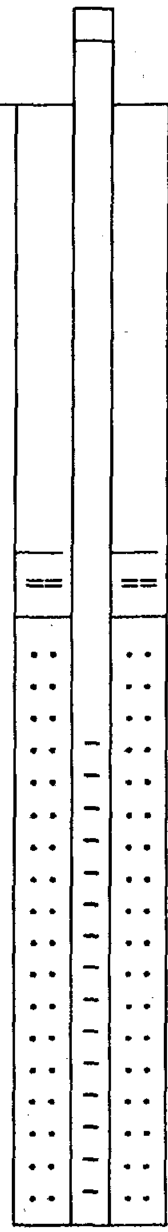
WELL NUMBER: 5 DRILLING METHOD: HAND AUGER
DATE INSTALLED: 6/4/90

ELEV. (MSL) | DEPTH FRM SURFACE

Riser elev. 254.5 m

254.2 0.0 (m)

Riser height 0.3 m



PIPE:
Diameter 0.025 m
Material PVC
Sch. 20
Length 3.8 m

BACKFILL MATERIAL
Cuttings

253.3 0.9 ---

SEAL
Thickness 0.05 m
Type Bentonite pellets

SCREEN:
Diameter 0.025 m
Hand Slotted
Length 1.8 m

FILTER PACK
Type Washed Silica Sand
Length 2.1 m

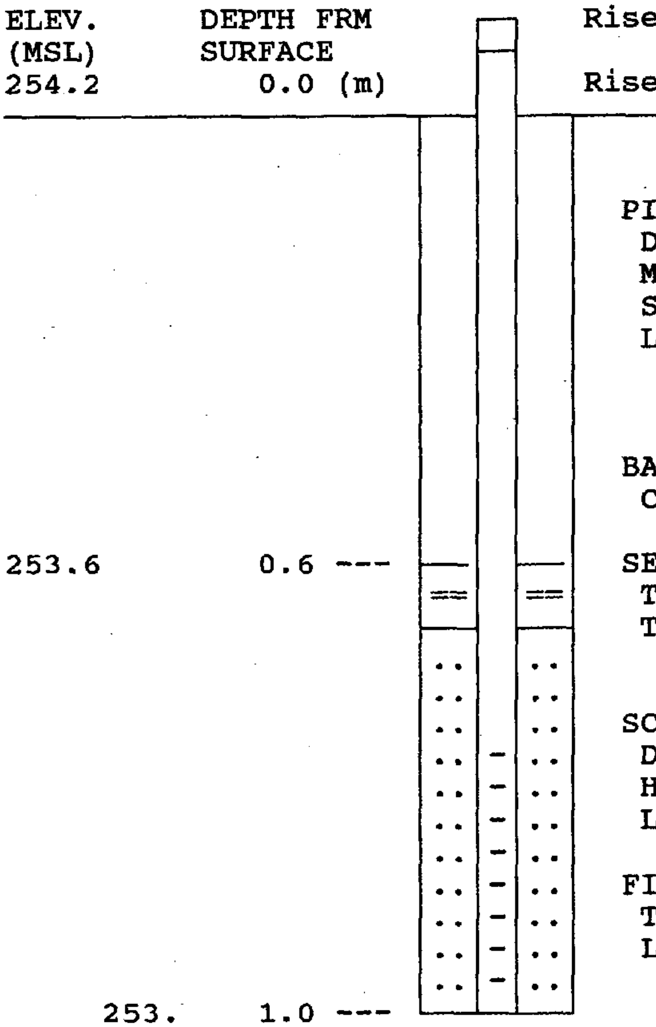
252.2 2.0 ---

|<------>|--Diameter of Borehole
0.08m

WELL NUMBER: 6
DATE INSTALLED: 5/31/90

DRILLING METHOD: HAND AUGER

ELEV. (MSL)	DEPTH FRM SURFACE
254.2	0.0 (m)
253.6	0.6 ---
253.	1.0 ---



Riser elev. 254.5 m

Riser height 0.3 m

PIPE:
Diameter 0.025 m
Material PVC
Sch. 20
Length 2.8 m

BACKFILL MATERIAL
Cuttings

SEAL
Thickness 0.03 m
Type Bentonite pellets

SCREEN:
Diameter 0.025 m
Hand Slotted
Length 1.8 m

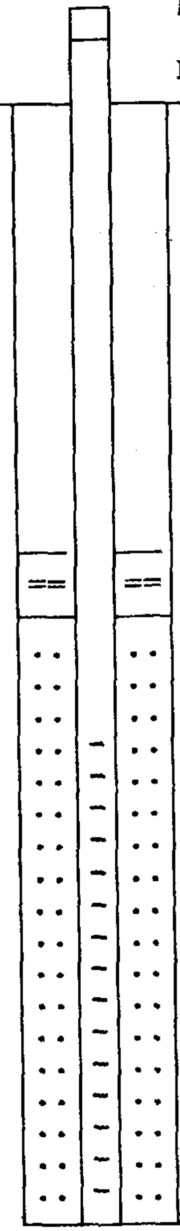
FILTER PACK
Type Washed Silica Sand
Length 2.1 m

|<------->|--Diameter of Borehole
0.08m

WELL NUMBER: 13
DATE INSTALLED: 9/14/90

DRILLING METHOD: HAND AUGER

ELEV. (MSL)	DEPTH FRM SURFACE
254.2	0.0 (m)
253.1	1.1 ---
252.2	2.0 ---



Riser elev. 254.5 m

Riser height 0.3 m

PIPE:
Diameter 0.025 m
Material PVC
Sch. 20
Length 3.9 m

BACKFILL MATERIAL
Cuttings

SEAL
Thickness 0.08 m
Type Bentonite pellets

SCREEN:
Diameter 0.025 m
Hand Slotted
Length 1.8 m

FILTER PACK
Type Washed Silica Sand
Length 2.6 m

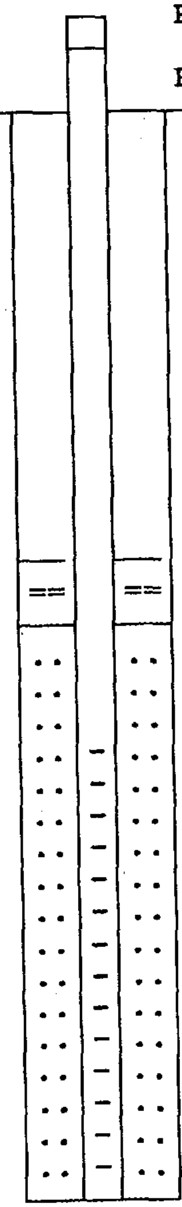
|<------->|--Diameter of Borehole
0.08m

WELL NUMBER: 14

DATE INSTALLED: 9/27/90

DRILLING METHOD: HAND AUGER

ELEV. (MSL)	DEPTH FRM SURFACE
254.4	0.0 (m)
253.4	1.0 ---
252.5	1.9 ---



Riser elev. 254.7 m

Riser height 0.3 m

PIPE:
- Diameter 0.025 m
- Material PVC
- Sch. 20
- Length 3.7 m

BACKFILL MATERIAL
- Cuttings

SEAL
- Thickness 0.23 m
- Type Bentonite powder

SCREEN:
- Diameter 0.025 m
- Hand Slotted
- Length 1.8 m

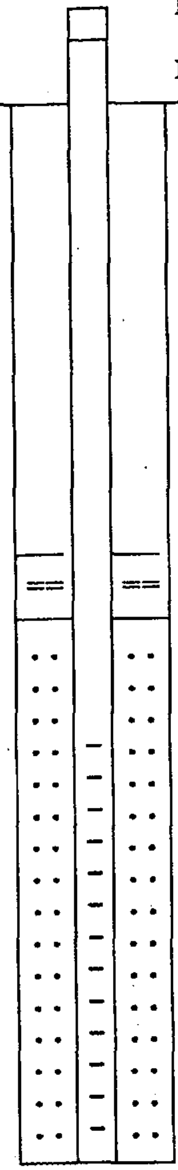
FILTER PACK
- Type Washed Silica Sand
- Length 2.4 m

|<------->|--Diameter of Borehole 0.08m

WELL NUMBER: 15
DATE INSTALLED: 9/27/90

DRILLING METHOD: HAND AUGER

ELEV. (MSL) 253.1 | DEPTH FRM SURFACE 0.0 (m)



Riser elev. 253.4 m

Riser height 0.3 m

PIPE:
Diameter 0.025 m
Material PVC
Sch. 20
Length 3.7 m

BACKFILL MATERIAL
Cuttings

252.3 0.8 ---

SEAL
Thickness 0.23 m
Type Bentonite powder

SCREEN:
Diameter 0.025 m
Hand Slotted
Length 1.8 m

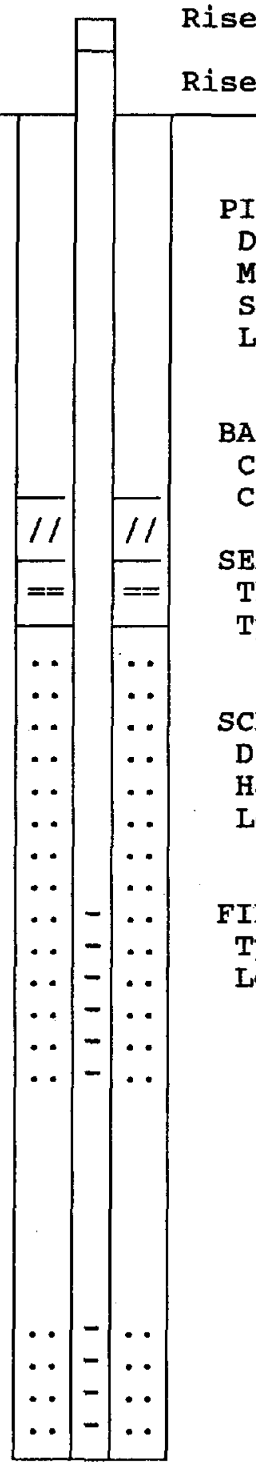
FILTER PACK
Type Washed Silica Sand
Length 2.6 m

251.3 1.8 ---

|<------->|--Diameter of Borehole 0.08m

WELL NUMBER: 16 DRILLING METHOD: HAND AUGER
DATE INSTALLED: 10/19/90

ELEV. (MSL)	DEPTH FRM SURFACE
254.8	0.0 (m)
245.4	9.4
244.9	9.9
243.05	11.8
242.4	12.4



Riser elev. 255.0 .m

Riser height 0.1 m

PIPE:
Diameter 0.05 m
Material PVC
Sch. 40
Length 11.6 m

BACKFILL MATERIAL
Cuttings
Concrete 0.50 m

SEAL
Thickness 1.25 m
Type Bentonite pell. & powder

SCREEN:
Diameter 0.05 m
Hand Slotted
Length 0.6 m

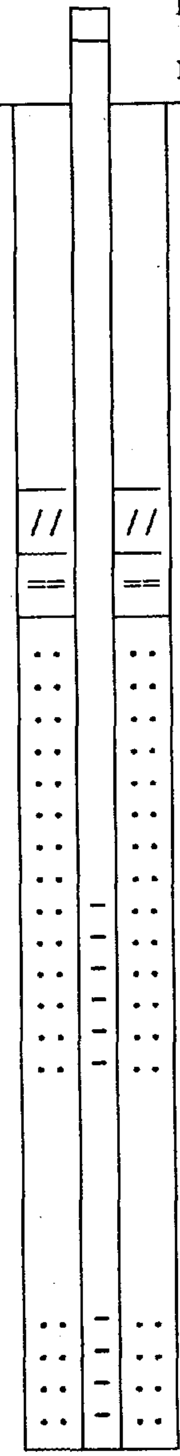
FILTER PACK
Type Washed Silica Sand
Length 1.2 m

|<------>|--Diameter of Borehole 0.20m

WELL NUMBER: 17
DATE INSTALLED: 10/19/90

DRILLING METHOD: HAND AUGER

ELEV. (MSL)	DEPTH FRM SURFACE
253.0	0.0 (m)
243.1	9.9 ---
242.5	10.5 ---
242.0	11.0 ---
241.4	11.6 ---



Riser elev. 253.1 m

Riser height 0.2 m

PIPE:
Diameter 0.05 m
Material PVC
Sch. 40
Length 11.6 m

BACKFILL MATERIAL
Cuttings
Concrete 0.60 m

SEAL
Thickness 0.30 m
Type Bentonite pell. & powder

SCREEN:
Diameter 0.05 m
Hand Slotted
Length 0.6 m

FILTER PACK
Type Washed Silica Sand
Length 0.8 m

|<------>|--Diameter of Borehole 0.20m

APPENDIX C

Geochemical Data

Well No.	Date mo/da/yr	Field Temp. C	Field pH	Field Cond. umhos	Ca mg/L	Na mg/L	K mg/L
1	07/18/91	17.8	6.5	100	NA	NA	NA
1	10/30/91	5.8	7.4	2750	2280	2130	13.8
2	10/30/91	7.0	7.7	880	776	1810	9.72
4	08/22/91	20.2	6.2	4800	NA	NA	NA
5	07/18/91	18.2	6.8	10400	NA	NA	NA
5	10/30/91	7.4	7.8	1930	2240	6260	13.2
7	08/01/91	19.9	7.2	6500	761	5430	140.0
9S	08/01/91	19.4	7.1	6700	1620	5640	24.7
10S	08/01/91	19.4	6.7	7400	1690	3970	17.2
10D	08/01/91	19.2	7.0	12200	2520	5970	35.4
13	08/22/91	19.2	6.5	11800	NA	NA	NA
13	10/30/91	8.1	7.6	4800	3020	6500	13.4
16	08/01/91	11.5	7.0	2150	1430	4090	52.4
Lunby Lake	08/15/91	33.7	8.8	10000	NA	NA	NA
Lunby Lake	10/30/91	2.9	8.4	2300	1160	3300	110.0
Stewart Lake	10/30/91	0.4	8.5	1725	826	2640	53.5

Well No.	Date mo/da/yr	Mg mg/L	Mn mg/L	HCO^3 mg/L	SO^4 Cl mg/L	B mg/L	N mg/L	Total mg/L
1	07/18/91	NA	NA	NA	2425	17000	ND	NA
1	10/30/91	3850	0.06	164	2425	14350	ND	0.30
2	10/30/91	1250	0.01	302	3750	4650	ND	0.05
4	08/22/91	NA	NA	199	3375	11400	ND	NA
5	07/18/91	NA	NA	NA	3250	15900	ND	NA
5	10/30/91	1730	0.04	141	2250	17600	ND	0.27
7	08/01/91	383	1.04	227	1525	8700	ND	0.27
9S	08/01/91	1320	1.23	226	1550	13000	ND	0.65
10S	08/01/91	1240	1.58	288	1375	10000	ND	0.10
13	08/22/91	NA	NA	150	2175	21600	0.3	NA
13	10/30/91	2550	0.15	163	2150	14350	2.0	0.43
16	08/01/91	401	12.7	199	1100	9000	2.7	0.08
Lunby Lake	08/15/91	NA	NA	60	3750	8800	3.4	NA
Lunby Lake	10/30/91	802	0.01	106	3125	7900	ND	ND
Stewart Lake	10/30/91	229	ND	64	2275	5000	ND	ND

Well No.	Date mo/da/yr	Spec. Cond. umhos/cm	TDS mg/L	Total Hrd. $CaCO_3$	Total Hrd. gr/gal	Na %	SAR
1	10/30/91	38200	23700	21500	1260	17.6	6.31
2	10/30/91	16540	10300	7080	414	35.6	9.35
5	10/30/91	44300	27500	12700	743	51.6	24.1
7	08/01/91	16700	27000	3480	203	77.2	40.0
9S	08/01/91	36800	22800	9480	554	56.3	25.2
10S	08/01/91	30600	19000	9330	545	48.0	17.9
10S	08/01/91	43200	26800	13100	767	46.9	22.7
13	10/30/91	54000	35400	18000	1050	43.8	21.0
16	08/01/91	25600	15900	5230	305	62.9	24.6
Lunby Lake	10/30/91	23200	14400	6200	362	53.5	18.2
Stewart Lake	10/30/91	15940	9880	3010	176	65.5	20.9

ND = no detection
NA = not available
SAR = sodium adsorption ratio

TABLE 4
QUALITY ASSURANCE AND CONTROL ON GROUNDWATER PARAMETERS

Shallow groundwater sampled from well 13 (10/30/91)

Results from the Hach Kit		Results from North Dakota State Health and Consolidated Laboratories	
Total Alkalinity	(mg/L)	Total Alkalinity	(mg/L)
	112		163
Sulfate	(mg/L)	Sulfate	(mg/L)
	2150		1600
Chloride	(mg/L)	Chloride	(mg/L)
	23300		21600
Total Hardness	(mg/L)	Total Hardness	(mg/L)
	21200		18000

APPENDIX D

Precipitation Data

DATE mo/da/yr	PRECIPITATION mm	DATE mo/da/yr	PRECIPITATION mm
Data originally reported in tenths of inches by Mrs. Betty Braaten			
08/01/90	19	02/26/91	tr
08/11/90	5	03/01/91	3
08/18/90	8	03/08/91	tr
08/25/90	33	03/13/91	10
08/26/90	41	03/23/91	tr
08/27/90	3	04/14/91	6
08/31/90	5	04/22/91	5
09/05/90	10	04/30/91	tr
09/07/90	5	05/02/91	tr
09/12/90	3	05/05/91	5
09/14/90	3	05/21/91	15
09/18/90	30	05/22/91	64
09/20/90	5	06/09/91	15
09/28/90	13	06/12/91	13
10/13/90	5	06/13/91	64
10/16/90	15	06/14/91	15
10/17/90	tr	06/15/91	5
11/20/90	3	06/25/91	13
12/01/90	3	06/28/91	23
12/13/90	tr	06/30/91	30
12/19/90	tr	07/02/91	5
12/21/90	3	07/05/91	13
12/22/90	3	07/11/91	8
12/24/90	tr	07/12/91	38
12/27/90	tr	07/20/91	25
12/28/90	tr	07/21/91	3
01/01/91	5	07/28/91	5
01/07/91	tr	08/03/91	15
01/13/91	tr	08/05/91	13
01/30/91	tr	08/06/91	13
02/14/91	18		
02/18/91	tr		

APPENDIX E

Borehole and Soil Logs

Soil Borehole Log: Well 1 Logged by: DRG Drilling Method: Hand Auger Sampling Method: Macroscopic Analysis			Surface Elev.: 252.9 m Boring Depth: 3.6 m Start Date: 6/07/90 Completion Date: 6/07/90 Vegetation: grass
MSL elev	Depth fr grd surf	ASTM*	DESCRIPTION OF MATERIAL
252.9	- 0	OL	clay silt loam, 7.5 YR N2/ blk organic, moist, roots, no effer., low plast.
252.3	- 0.6	CL	silty clay, 10 YR 5/1 drk gray to gray, some organics, moist, strong effer., med plast., some med/v. f. gr. gypsum, some oxid. structures along fractures
252.0	- 0.9	CL	silty clay, 10 YR 5/4 olive brwn, inorganic, wet, weak effer., med/high plast., some oxid. structues along fractures
251.4	- 1.5	CH	silty clay, 10 YR 5/3 brwn, inorganic, wet/saturated, weak effer., high plast., blocky oxid. structures, varving
250.8	- 2.1	CH	same as above, saturated
249.3	- 3.6		end of boring

*ASTM = The American Society for Testing and Materials, (1983).

Soil Borehole Log: Well 2 Logged by: DRG Drilling Method: Hand Auger Sampling Method: Macroscopic Analysis			Surface Elev.: 254.0 m Boring Depth: 3.8 m Start Date: 6/07/90 Completion Date: 6/07/90 Vegetation: grass
MSL elev	Depth fr grd surf	AS TM	DESCRIPTION OF MATERIAL
254.0	- 0	OL	clay silt loam, 7.5 YR N2/ blk organic, moist, roots, med effer., low plast.
253.9	- 0.1	OH	silty clay, 7.5 YR N/3 v. drk gray, some organics, moist, strong effer., med plast., v. f. gr. gypsum and calcite below root zone
253.5	- 0.5	CL	silty clay, 2.5 YR 5/4 light olive brwn, inorganic, wet, weak effer., high/med plast., varving, f. gr. euhedral gypsum crystals, some mottling (oxid. structures)
252.3	- 1.7	CH	silty clay, 10 YR 4/3 drk brwn inorganic, saturated, weak effer., high plast., mottling and oxid. along fractures
250.3 250.2	- 3.7 - 3.8	CH	clay/silty clay, 10 YR 5/1 gray, inorganic, saturated, weak effer., high plast. end of boring

Soil Borehole Log: Well 3 Logged by: DRG Drilling Method: Hand Auger Sampling Method: Macroscopic Analysis			Surface Elev.: 253.0 m Boring Depth: 3.9 m Start Date: 6/07/90 Completion Date: 6/07/90 Vegetation: grass
MSL elev	Depth fr grd surf	AS TM	DESCRIPTION OF MATERIAL
253.0	- 0	OL	clay silt loam, 7.5 YR N2/ blk organic, moist, roots, med effer., low plast.
252.8	- 0.2	OH	silty clay, 7.5 YR N/3 v. drk gray, some organics, moist, strong effer., med plast., v. f. gr. gypsum and calcite below root zone
252.5	- 0.5	CL	silty clay, 10 YR 4/3 brwn, inorganic, wet, weak effer., med plast., some v.f. gr. sand @ 0.9 m, mottling and oxid. structures along fractures
251.3	- 1.7	CL	silty clay, 10 YR 4/3 drk brwn, inorganic, saturated, weak effer., med plast., varving, oxid. structures (darker than above)
249.4	- 3.6	CL	silty clay/clayey silt, 10 YR 4/4 drk yellow brwn, inorganic, saturated, weak effer., med/low plast., varving (thicker than above w/ higher silt content)
249.1	- 3.9		end of boring

Soil Borehole Log: Well 4 Logged by: DRG Drilling Method: Hand Auger Sampling Method: Macroscopic Analysis			Surface Elev.: 254.5 m Boring Depth: 3.8 m Start Date: 6/04/90 Completion Date: 6/04/90 Vegetation: grass
MSL elev	Depth fr grd surf	AS TM	DESCRIPTION OF MATERIAL
254.5	- 0	OL	silty clay loam, 7.5 YR N2/ blk organic, moist, roots, high effer., low plast., v. f. gr. gypsum and calcite below root zone
254.3	- 0.2	CL	silty clay, 10 YR 5/2-4/2 grayish brown to dark grayish brwn, inorganic, high effer., med plast., med gr. gypsum and calcite
253.7	- 0.8	CL	silty clay, 10 YR 4/3 Brwn, inorganic, wet, weak effer., med/high plast., mottling oxid. structures
252.8	- 1.7	CH	silty clay, 10 YR 4/3 brwn, inorganic, saturated, weak effer., med/high plast., oxid. structures, thin lenses of med gr. sand
252.7	- 1.8	CH	clay/silty clay 10 YR 5/3 brwn, inorganic, saturated, weak effer., high plast., varving, oxid. structures
251.3 250.7	- 3.2 - 3.8	CH	clay/silty clay 10 YR 5/1 gray, inorganic, saturated, weak effer., high plast.
			end of boring

Soil Borehole Log: Well 5 Logged by: DRG Drilling Method: Hand Auger Sampling Method: Macroscopic Analysis			Surface Elev.: 254.2 m Boring Depth: 3.8 m Start Date: 6/04/90 Completion Date: 6/04/90 Vegetation: grass
MSL elev	Depth fr grd surf	AS TM	DESCRIPTION OF MATERIAL
254.2	- 0	OL	silty clay loam, 7.5 YR N2/ blk organic, moist, roots, high effer., low plast.
253.9	- 0.3	CL	silty clay/clayey silt, 10 YR 3/3 drk brwn, inorganic, moist/wet, high effer., med/low plast., f. to med gr. gypsum and calcite
253.6	- 0.6	CL	silty clay, 10 YR 3/4 drk yellowish brwn, inorganic, wet, weak effer., med plast., med to crs. gr. gypsum along fractures oxid. structures and staining along fractures, some mottling
252.7	- 1.5	CL	silty clay, 10 YR 3/3 drk brwn, inorganic, wet, weak effer., med/high plast., varving
252.4	- 1.8	CH	silty clay/clay with silt, 10 YR 4/2 drk grayish brwn, inorganic, saturated, weak efferv., high plast., varving, med/crs. gr. layer of gypsum, oxid. structures along fractures
251.3 250.4	- 2.9 - 3.8	CH	silty clay, 10 YR 5/1 gray, inorganic, saturated, weak effer., high plast. end of boring

Soil Borehole Log: Well 6 Logged by: DRG Drilling Method: Hand Auger Sampling Method: Macroscopic Analysis			Surface Elev.: 254.2 m Boring Depth: 2.8 m Start Date: 5/31/90 Completion Date: 5/31/90 Vegetation: grass
MSL elev	Depth fr grd surf	AS TM	DESCRIPTION OF MATERIAL
254.2	- 0	OL	clayey silty loam, 7.5 YR N2/ blk, very organic, moist, weak/ high effer., med plast.
253.8	- 0.4	CH	silty clay, 10 YR 5/2 to 4/2 grayish to drk grayish brwn, inorganic, wet/saturated, weak effer., med/high plast., mottling and oxid. structures
252.7	- 1.5	CH	silty clay, 10 YR 5/2 drk grayish brwn, inorganic, saturated, weak efferv., high plast., varving, oxid. strucures along fractures
251.4	- 2.8		
			end of boring

Soil Log: Well 7 Logged by: DRG Drilling Method: Shovel Sampling Method: Macroscopic Analysis			Surface Elev.: 253.6 m Boring Depth: 0.9 m Start Date: 7/31/91 Completion Date: 7/31/91 Vegetation: grass
MSL elev	Depth fr grd surf	AS TM	DESCRIPTION OF MATERIAL
253.6	- 0	OH	clayey silty loam/clayey loam with silt, 10 YR 3/1 v. drk gray, organic, moist, high effer., med plast.
253.3	- 0.3	CH	silty clay, 10 YR 4/2 drk gray brown, inorganic, moist, high effer., high/med plast. oxid. structures
252.7	- 0.9		
			end of log

Soil Log: Well 9 Logged by: DRG Drilling Method: Shovel Sampling Method: Macroscopic Analysis			Surface Elev.: 252.8 m Boring Depth: 0.5 m Start Date: 7/31/91 Completion Date: 7/31/91 Vegetation: cattail
MSL elev	Depth fr grd surf	AS TM	DESCRIPTION OF MATERIAL
252.8	- 0	OH	clayey loam with some silt 2.5 YR N2/ v. drk gray to blk, v. organic, wet, no effer., high plast.
252.6	- 0.2	CH	clay with some silt, 10 YR 3/2 v. drk grayish brwn, some organics, wet, no effer., high plast., some f. gr. sand
252.3	- 0.5		
			end of log

Soil Log: Well 10 Logged by: DRG Drilling Method: Shovel Sampling Method: Macroscopic Analysis			Surface Elev.: 253.8 m Boring Depth: 0.7 m Start Date: 7/31/91 Completion Date: 7/31/91 Vegetation: grass
MSL elev	Depth fr grd surf	AS TM	DESCRIPTION OF MATERIAL
253.8	- 0	OH	clayey silty loam, 7.5 YR N2/ blk, organic, moist, weak effer med plast.
253.4	- 0.4	CL	silty clay 10 YR 5/2 gray brwn, some organics, wet, high effer. med/high plast., some f. gr. sand
253.1	- 0.7		
			end of log

Soil Log: Well 11 Logged by: DRG Drilling Method: Shovel Sampling Method: Macroscopic Analysis			Surface Elev.: 255.0 m Boring Depth: 0.7 m Start Date: 8/22/91 Completion Date: 8/22/91 Vegetation: grass
MSL elev	Depth fr grd surf	AS TM	DESCRIPTION OF MATERIAL
255.0	- 0	OL	silty clayey loam, 10 YR 3/1 v. dark gray, organic, moist, high effer., low plast., v. f. gr. gypsum and calcite below root zone
254.7	- 0.3	CH	clay with silt, 10 YR 5/2 grayish brwn, inorganic, wet, high effer., high plast.
254.0	- 0.7		
			end of log

Soil Borehole Log: Well 13 Logged by: DRG Drilling Method: Hand Auger Sampling Method: Macroscopic Analysis			Surface Elev.: 254.2 m Boring Depth: 3.8 m Start Date: 9/14/90 Completion Date: 9/14/90 Vegetation: grass
MSL elev	Depth fr grd surf	AS TM	DESCRIPTION OF MATERIAL
254.2	- 0	OL	silty clayey loam, 7.5 YR N2/ blk, organic, moist, weak effer low plast., v. f. gr. gypsum and calcite
253.7	- 0.5	CL	silty clay, 10 YR 4/2 drk grayish brwn, inorganic, moist, weak effer., med plas., varving f. gr. gypsum and calcite, mottling
253.3	- 0.9	CL	silty clay, 10 YR 3/2 v. drk grayish brwn, inorganic, moist, weak effer., med plast., some mottling, few pebbles
253.0	- 1.2	CH	silty clay, 10 YR 4/2 drk gray brwn, inorganic, wet, weak effer., high plast., varving, mottling with numerous oxid. structures
252.4	- 1.8	CH	clay with silt, 10 YR 4/3 brwn/ drk brwn, inorganic, saturated, weak effer., high plast., mottling, f. gr. gypsum and calcite, thin lenses of v. f. gr. sand
251.3	- 2.9	CH	clay with some silt, 2.5 YR 3/ v. drk gray, inorganic, saturated, weak effer., high plast., thin layer of silty v. f. gr. sand, layer of med gr. gypsum @ 3.4 m, mottling
250.4	- 3.8		end of boring

Soil Borehole Log: Well 14 Logged by: DRG Drilling Method: Hand Auger Sampling Method: Macroscopic Analysis			Surface Elev.: 254.4 m Boring Depth: 3.7 m Start Date: 9/27/90 Completion Date: 9/27/90 Vegetation: grass
MSL elev	Depth fr grd surf	AS TM	DESCRIPTION OF MATERIAL
254.4	- 0	OL	clayey silty loam, 7.5 YR N2/ blk, organic, moist, high effer low plast.
254.0	- 0.4	CL	silty clay, 10 YR 6/2-5/2 lt brwnish gray to grayish brwn, inorganic, moist/wet, high effer., high plast., f./med gr. gypsum and calcite, thin lenses of f. gr. sand, mottling and oxid. along fractures
252.3	- 2.1	CL	silty clay, 10 YR 4/1 brwn/ gray, inorganic, saturated, weak effer., med plast., some mottling with blocky oxid. structures, thin lenses of f. gr. sand
251.4	- 3.0	CH	silty clay, 10 YR 4/1 brwn/ gray, inorganic, saturated, weak effer., med plast., mottling with blocky oxid. structures, thin lenses of f. gr. sand
251.0	- 3.4	CH	clay with silt, 10 YR 4/1 brwn/ gray, inorganic, saturated, weak effer., high plast., blocky oxid. structures
250.7	- 3.7		end of boring

Soil Borehole Log: Well 15 Logged by: DRG Drilling Method: Hand Auger Sampling Method: Macroscopic Analysis			Surface Elev.: 253.1 m Boring Depth: 3.6 m Start Date: 9/27/90 Completion Date: 9/27/90 Vegetation: grass
MSL elev	Depth fr grd surf	ASTM	DESCRIPTION OF MATERIAL
253.1	- 0	OL	clayey silty loam, 7.5 YR N2/ blk, organic, moist, weak effer low plast., v. f. gr. gypsum and calcite
252.7	- 0.4	CL	silty clay, 10 YR 4/2 drk gray brwn, inorganic, moist, high effer., med plast., abundant med gr. gypsum and calcite, mottling
251.6	- 1.5	CH	silty clay, 10 YR 4/1 brwn/ gray, inorganic, saturated, weak effer., high plast., mottling and oxid. along fractures some f. gr. sand, med gr. gypsum
249.8	- 3.3	CH	clay with silt, 2.5 YR 3/ v. drk gray, inorganic, saturated, weak effer., high plast., some blocky oxid. structures
249.5	- 3.6		
			end of boring

Soil Borehole Log: Well 16 Logged by: Dr. P.J. Gerla Drilling Method: Hollow Stem Auger 0.2 m Sampling Method: Macroscopic Analysis			Surface Elev.: 255.0 m Boring Depth: 11.6 m Start Date:10/19/90 Completion Date:10/19/90 Vegetation: grass
MSL elev	Depth fr grd surf	AS TM	DESCRIPTION OF MATERIAL
253.1	- 0	OL	silty clay top soil, dark grayish brwn, organic rich
252.3	- 0.8	CL	interlayered silty clay and clayey silt, mottled dark brwn and gray, commonly containing fractures coated with Fe oxides med plast., silt-rich layers are dilitant when saturated (lacustrine sediments)
251.6	- 2.7	CH	silty clay, gray, unoxidized occasional small "pockets" of light gray silt to 2.5 cm diameter (lacustrine sediment)
254.6	- 6.7	CH	same as above
241.5	-11.6		end of boring

Soil Borehole Log: Well 17 Logged by: Dr. P.J. Gerla Drilling Method: Hollow Stem Auger 0.2 m Sampling Method: Macroscopic Analysis			Surface Elev.: 253.0 m Boring Depth: 11.6 m Start Date:10/19/90 Completion Date:10/19/90 Vegetation: grass
MSL elev	Depth fr grd surf	AS TM	DESCRIPTION OF MATERIAL
253.1	- 0	OL	silty clay top soil, dark grayish brwn, organic rich
252.3	- 0.8	CL	interlayered silty clay and clayey silt, mottled dark brwn and gray, commonly containing fractures coated with Fe oxides med plast., silt-rich layers are dilitant when saturated (lacustrine sediments)
251.6	- 2.7	CH	silty clay, gray, unoxidized occasional small "pockets" of light gray silt to 8.0 cm diameter (lacustrine sediment)
254.6	- 6.7	CH	silty clay, gray, unoxidized occasional small "pockets" of light gray silt to 2.5 cm diameter (lacustrine sediment)
241.5	-11.6		
			end of boring

Soil Log: Marsh near well 17 Logged by: DRG Drilling Method: Shovel Sampling Method: Macroscopic Analysis			Surface Elev.: ? Boring Depth: 0.5 m Start Date: 7/31/91 Completion Date: 7/31/91 Vegetation: cattails
MSL elev	Depth fr grd surf	AS TM	DESCRIPTION OF MATERIAL
?	- 0	OH	clayey loam, 2.5 YR N2/ blk, v. organic, wet, no effer., high plast., gastropod shell fragments
	- 0.2 - 0.5	CH	clayey loam, 10 YR 3/1 v. dark gray, some organics, wet, no effer., some f. gr. sand
			end of log

APPENDIX F

Water Level Data

WELL ID	WELL 1	WELL 2
MAP COORD.	SE1/4,NE1/4,NE1/4, Sec14,T153N,R52W	NW1/4,NE1/4,NW1/4, Sec23,T153N,R52W
INSTALL. DATE	06/07/90	06/07/90
TOP OF RISER (m-MSL)	253.2	254.3
GROUND SURFACE ELEV. (m-MSL)	252.9	254.0
SCREEN INTERVAL ELEV. (m-MSL)	251.1- 249.3	252.1- 250.2

WELL ID	WELL 3	WELL 4
MAP COORD.	NE1/4,NE1/4,NW1/4, Sec24,T153N,R52W	NE1/4,NW1/4,NE1/4, Sec26,T153N,R52W
INSTALL. DATE	06/07/90	06/04/90
TOP OF RISER (m-MSL)	253.3	254.8
GROUND SURFACE ELEV. (m-MSL)	253.0	254.5
SCREEN INTERVAL ELEV. (m-MSL)	251.0- 249.1	252.5- 250.7

WELL ID	WELL 5	WELL 6
MAP COORD.	NE1/4,NE1/4,NW1/4, Sec25,T153N,R52W	SE1/4,SW1/4,SE1/4, Sec26,T153N,R52W
INSTALL. DATE	06/04/90	05/31/90
TOP OF RISER (m-MSL)	254.5	254.5
GROUND SURFACE ELEV. (m-MSL)	254.3	254.2
SCREEN INTERVAL ELEV. (m-MSL)	252.2- 250.4	253.2- 251.4

WELL ID	WELL 13	WELL 14
MAP COORD.	NW1/4,SW1/4,SE1/4, Sec26,T153N,R52W	SW1/4,NE1/4,SW1/4, Sec25,T153N,R52W
INSTALL. DATE	09/14/90	09/27/90
TOP OF RISER (m-MSL)	254.5	254.7
GROUND SURFACE ELEV. (m-MSL)	254.2	254.4
SCREEN INTERVAL ELEV. (m-MSL)	252.2- 250.4	252.5- 250.7

WELL ID	WELL 15	WELL 16
MAP COORD.	NW1/4,NW1/4,NW1/4, Sec24,T153N,R52W	NW1/4,SW1/4,SE1/4, Sec26,T153N,R52W
INSTALL. DATE	09/27/90	10/19/90
TOP OF RISER (m-MSL)	253.4	255.0
GROUND SURFACE ELEV. (m-MSL)	253.1	254.8
SCREEN INTERVAL ELEV. (m-MSL)	251.3- 249.5	243.8- 243.2

WELL ID	WELL 17
MAP COORD.	SE1/4,SE1/4,SE1/4, Sec14,T153N,R52W
INSTALL. DATE	10/19/90
TOP OF RISER (m-MSL)	253.2
GROUND SURFACE ELEV. (m-MSL)	253.1
SCREEN INTERVAL ELEV. (m-MSL)	242.1- 241.5

	WATER LEVELS					
DATE	WELL 1	WELL 2	WELL 3	WELL 4	WELL 5	WELL 6
08/02/90	250.53	251.55	250.30	252.30	252.39	252.44
08/10/90	250.46	251.44	250.24	252.20	252.31	252.31
09/20/90	250.41	251.28	250.12	251.90	252.12	252.14
09/27/90	250.46	251.29	250.10	251.84	252.12	252.39
10/16/90	250.44	251.23	250.08	251.73	dry	252.33
11/02/90	250.39	251.19	250.07	251.61	251.91	252.32
11/16/90	250.34	251.16	250.05	251.54	251.85	252.30
01/11/91	250.17	251.38	250.28	251.33	251.63	252.05
03/13/91	249.99	251.26	250.42	251.13	251.42	251.79
03/29/91	250.00	252.18	250.85	251.12	251.77	252.12
04/11/91	250.11	252.34	250.77	251.24	252.24	252.40
04/25/91	250.34	252.41	250.81	251.69	252.61	252.92
05/10/91	251.32	253.00	251.56	253.19	253.65	253.70
05/29/91	251.49	252.79	252.02	253.33	253.82	253.76
06/25/91	251.01	252.16	251.23	252.89	252.99	253.23
07/09/91	251.35	252.42	251.54	253.28	253.53	253.71
07/31/91	251.07	252.05	251.16	252.87	252.89	253.19
08/15/91	251.01	251.91	250.95	252.73	252.72	252.94

DATE	WELL 7	WELL 9S	WELL 9D	WELL 10S	WELL 10D	WELL 11S
08/02/90	252.17	251.41	251.52	252.18	252.14	
08/10/90	252.04	251.30	251.59	252.05	252.18	
09/20/90	251.93	251.44	249.36	251.90	252.04	252.81
09/27/90	251.93	251.11	250.06	252.00	252.08	252.79
10/16/90	251.91	251.34	251.09	251.98	252.08	252.68
11/02/90	251.92	251.29	251.45	252.01	252.09	252.61
11/16/90	251.90	251.23	251.58	251.98	252.06	252.56
01/11/91	251.63	250.95	251.28	251.63	251.77	252.39
03/13/91	251.54	250.84	251.46	251.55	251.37	252.33
03/29/91	252.00	251.48	251.51	252.36	252.19	252.63
04/11/91	252.30	251.69	251.65	252.50	252.39	253.07
04/25/91	252.60	251.92	251.81	252.73	252.62	253.28
05/10/91	253.19	252.55	252.06	253.13	252.98	254.03
05/29/91	253.12	252.57	252.43	253.01	252.97	254.18
06/25/91	252.78	252.01	252.39	252.58	252.60	253.61
07/09/91	253.14	252.51	252.42	252.98	252.90	254.05
07/18/91	252.85	252.29	252.00	252.77	252.79	253.78
07/31/91	252.62	251.96	252.19	252.51	252.58	253.55
08/15/91	252.47	251.80	252.24	252.33	252.43	253.41

WATER LEVELS

DATE	WELL 11D	WELL 12	WELL 13	WELL 14	WELL 15	WELL 16
09/20/90	253.01	252.58	252.55			
09/27/90	252.98	252.28	252.52			
10/16/90	252.91	252.11	252.40	251.68	250.57	
11/02/90	252.86	252.07	252.32	251.60	250.52	
11/16/90	252.82	252.05	252.27	251.55	250.48	
01/11/91	252.65	NA	251.94	251.36	250.37	
03/13/91	252.55	NA	251.96	251.20	250.59	252.64
03/29/91	252.66	252.74	252.75	251.28	250.98	252.72
04/11/91	252.91	252.50	252.72	251.33	251.15	252.82
04/25/91	253.19	252.58	252.86	251.68	251.35	252.95
05/10/91	253.75	252.76	253.52	252.80	252.11	253.34
05/29/91	254.12	252.74	253.51	253.00	252.10	253.63
06/25/91	253.73	252.58	253.00	252.69	251.57	253.36
07/09/91	253.99	252.73	253.07	253.12	251.91	253.49
07/18/91	253.91	252.66	253.18	252.94	251.73	253.02
07/31/91	253.73	252.51	253.00	252.95	251.73	253.30
08/15/91	253.60	252.42	252.88	252.66	251.40	252.70
10/30/91		252.76				

DATE	WELL 17
01/11/91	250.37
03/13/91	250.80
03/29/91	250.93
04/11/91	251.12
04/25/91	251.36
05/10/91	252.06
05/29/91	252.23
06/25/91	251.74
07/09/91	251.97
07/18/91	251.73
07/31/91	251.80
08/15/91	251.58

Figure 12. Hydrograph of wells 1, 2, 3, and 15 versus average monthly precipitation. Refer to Figure 4 for well locations.

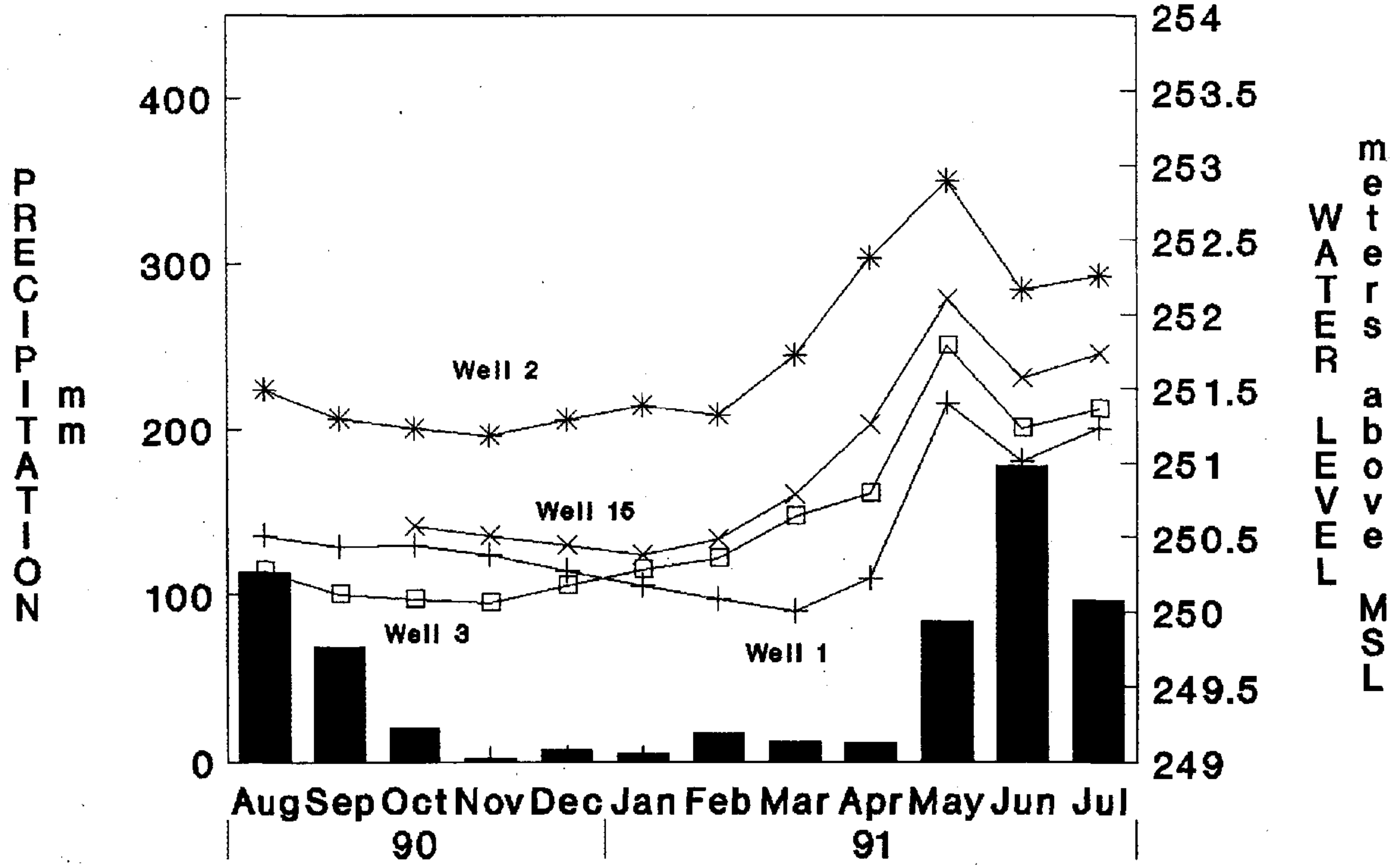
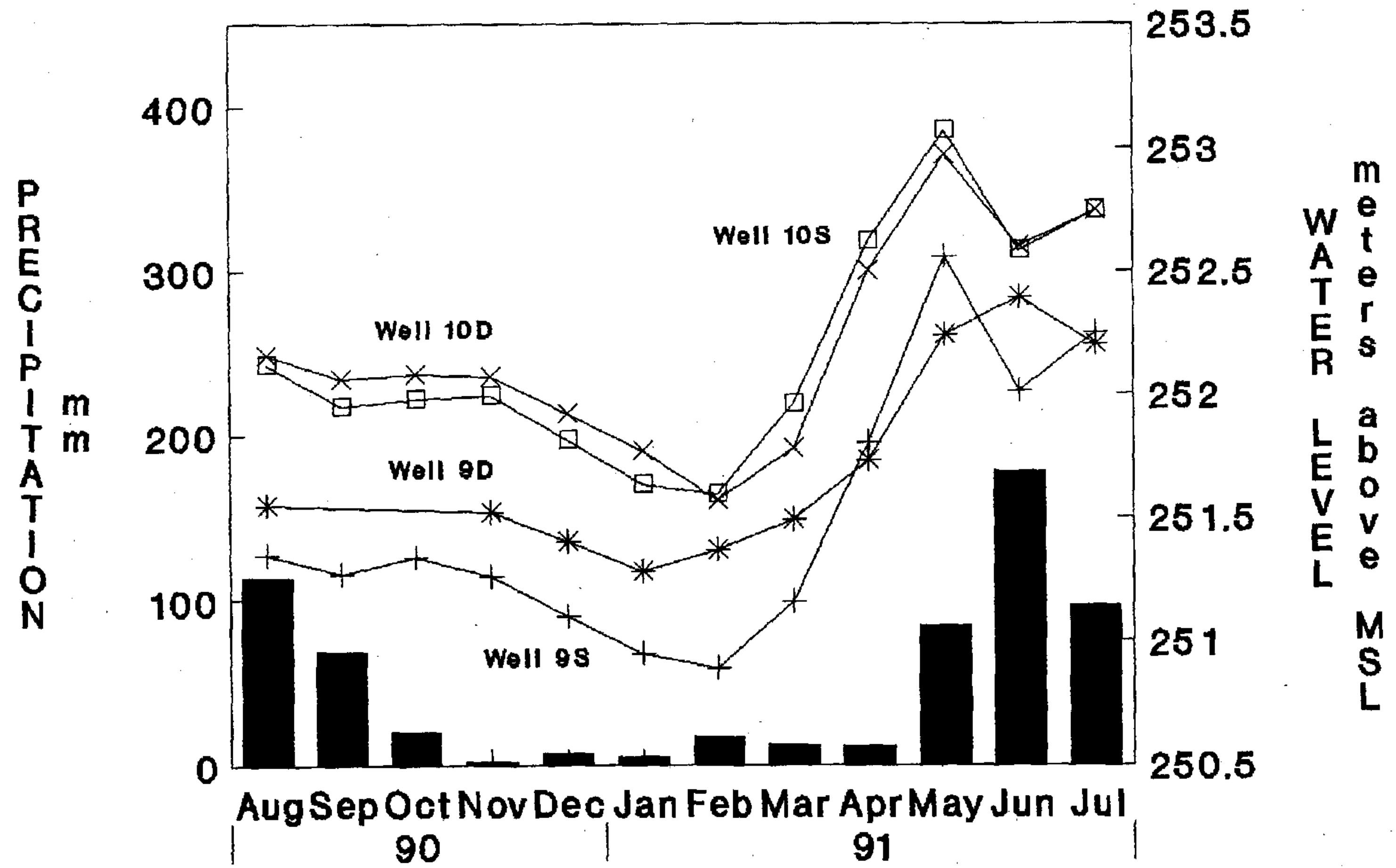
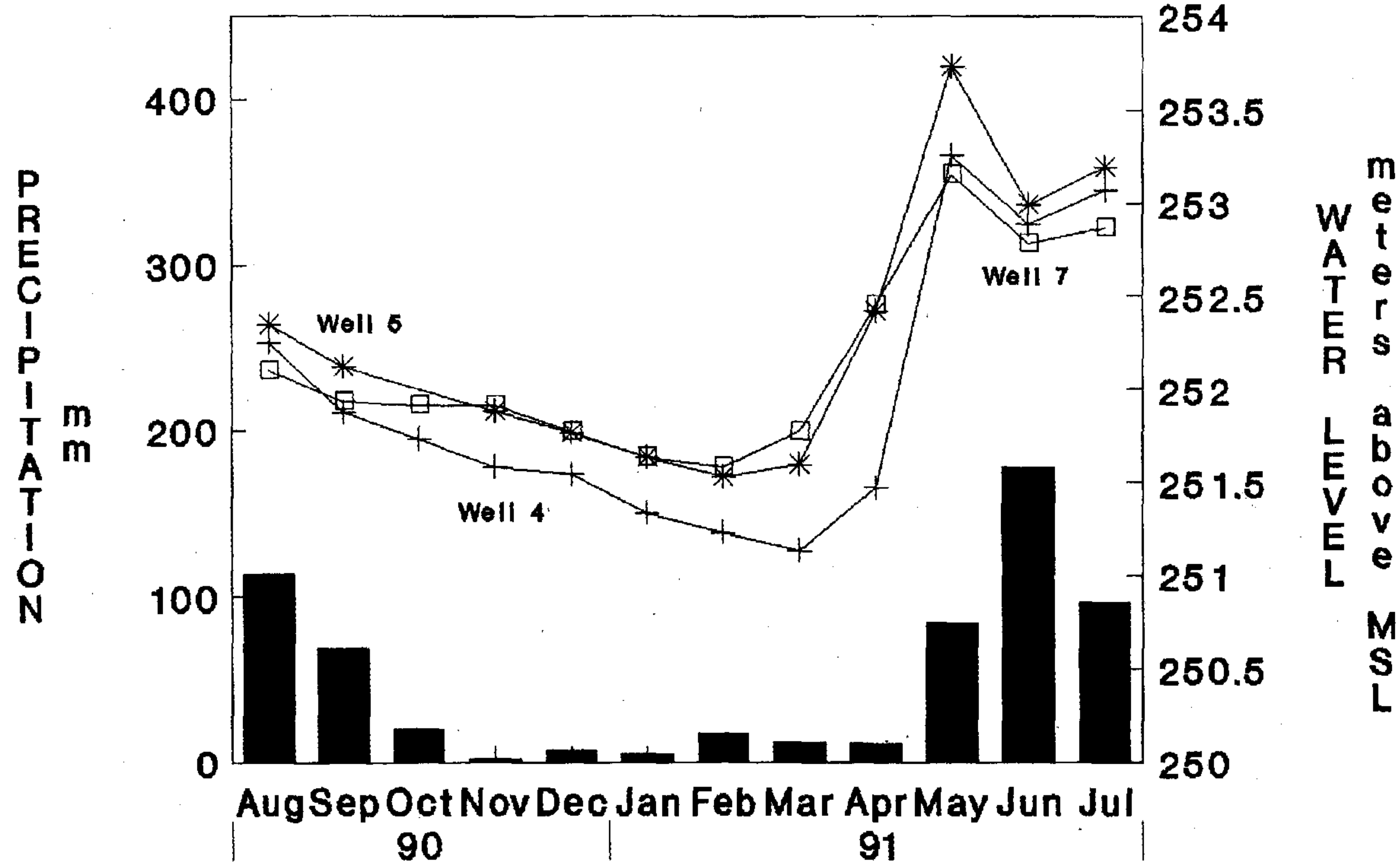

PRECIPITATION mm
400
300
200
100
0
254
253.5
253
252.5
252
251.5
251
250.5
250
249.5
249
WATER LEVEL meters above MSL
Well 2
Well 15
Well 3
Well 1
Aug Sep Oct Nov Dec Jan Feb Mar Apr May Jun Jul
90
91

Figure 13. Hydrograph of wells 9S, 9D, 10S, and 10D versus average monthly precipitation. These nested wells show periods of upward gradient. Refer to Figure 4 for well locations.



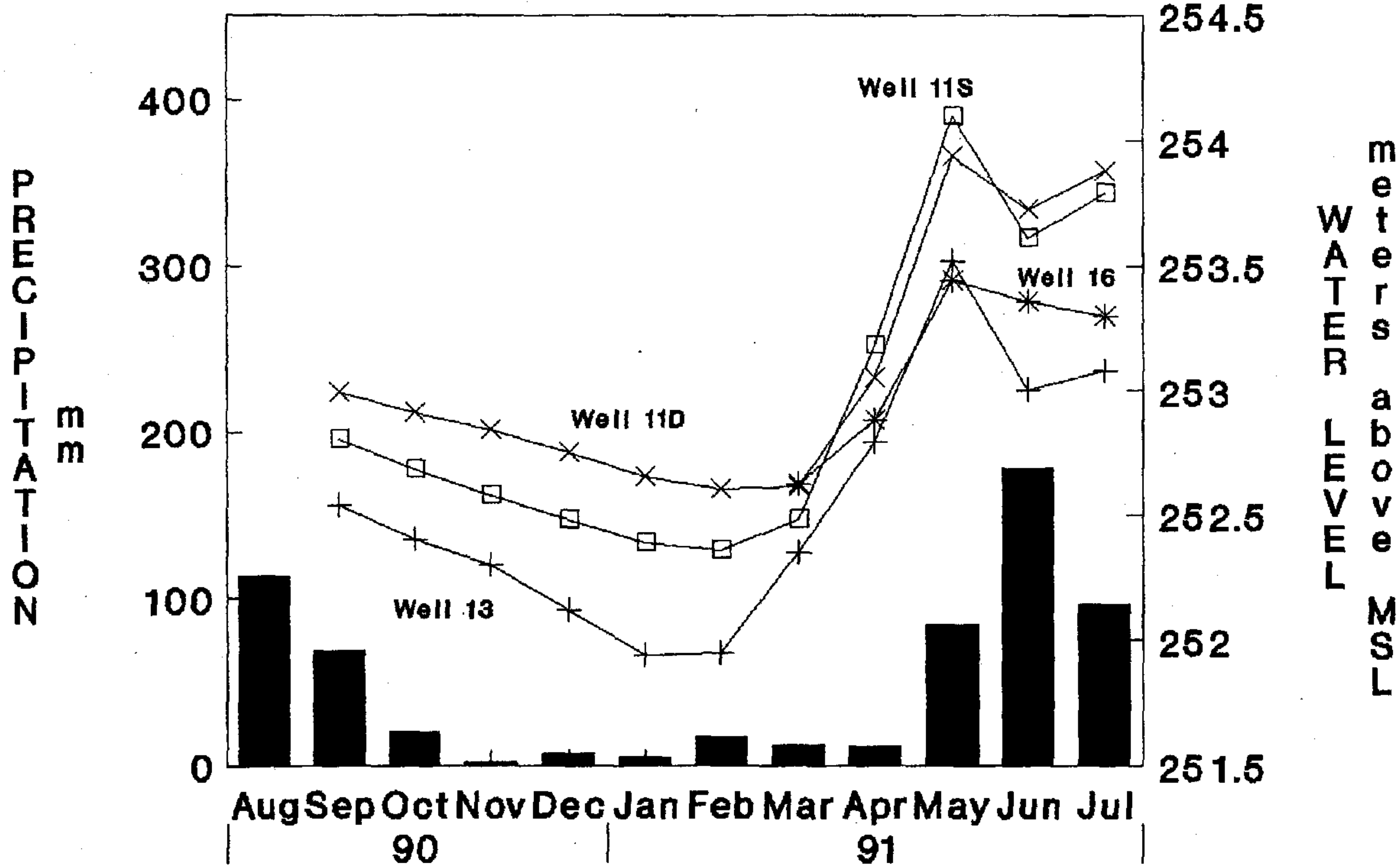
PRECIPITATION mm
400
300
200
100
0
Well 10S
Well 10D
Well 9D
Well 9S
Aug Sep Oct Nov Dec Jan Feb Mar Apr May Jun Jul
90
91
253.5
253
252.5
252
251.5
251
250.5
WATER LEVEL meters above MSL

Figure 14. Hydrograph of wells 4, 5, and 7 versus average monthly precipitation. Refer to Figure 4 for well locations.



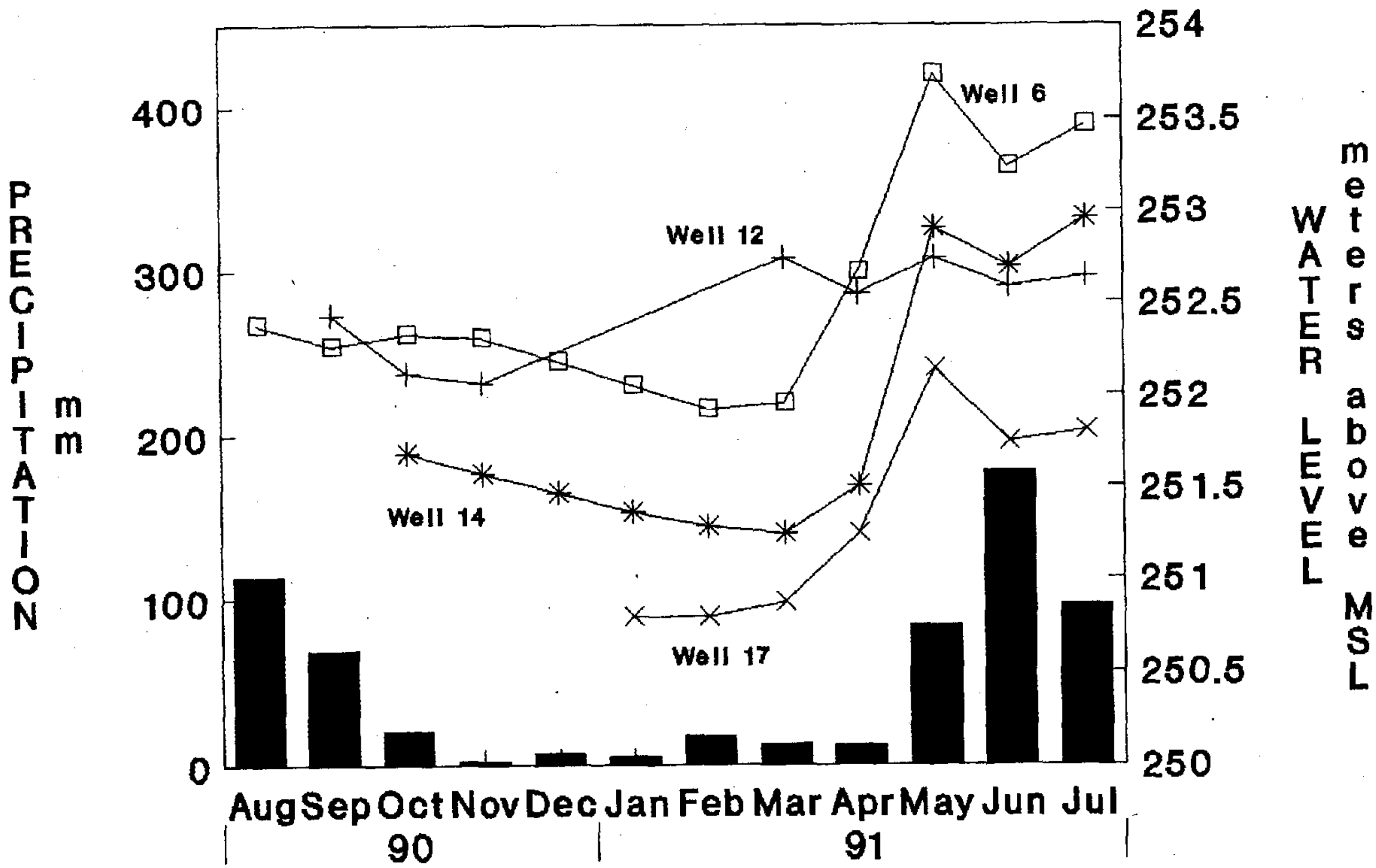
PRECIPITATION mm
WATER LEVEL meters above MSL
400
300
200
100
0
254
253.5
253
252.5
252
251.5
251
250.5
250
Well 5
Well 4
Well 7
Aug Sep Oct Nov Dec Jan Feb Mar Apr May Jun Jul
90
91

Figure 15. Hydrograph of wells 13, 16, 11S, and 11D versus average monthly precipitation. Wells 11S and 11D show periods of upward gradient. Refer to Figure 4 for well locations.



PRECIPITATION mm
WATER LEVEL meters above MSL
400
300
200
100
0
254.5
254
253.5
253
252.5
252
251.5
Well 11S
Well 16
Well 11D
Well 13
Aug Sep Oct Nov Dec Jan Feb Mar Apr May Jun Jul
90
91

Figure 16. Hydrographs of wells 12, 14, 6, and 17 versus average monthly precipitation. Refer to Figure 4 for well locations.



PRECIPITATION mm
400
300
200
100
0
254
253.5
253
252.5
252
251.5
251
250.5
250
WATER LEVEL meters above MSL
Well 6
Well 12
Well 14
Well 17
Aug
Sep
Oct
Nov
Dec
Jan
Feb
Mar
Apr
May
Jun
Jul
90
91

APPENDIX G

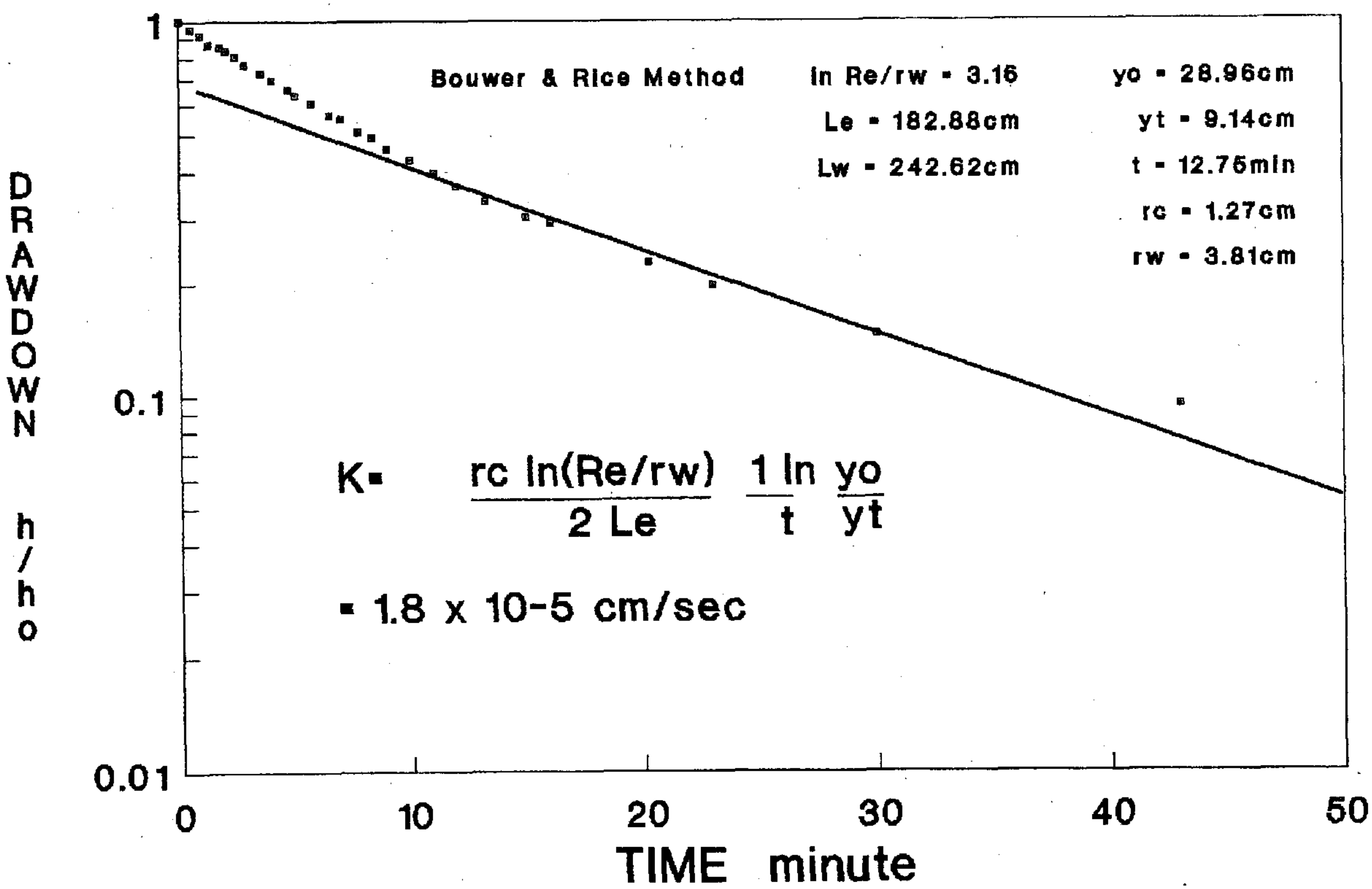
Hydraulic Conductivity Data

Well 1 SLUG TEST ANALYSIS (BOUWER AND RICE)

Ref. Value: 1.688 m
Ho : 0.585 m
To : 00:00:00
(bailed slug water displacement)

TIME	WATER LEVEL (m)	HEAD CHANGE (H)	HEAD RATIO (H/Ho)	ELAP. TIME (min)
static	1.688			
00:00:00	2.274	0.585	1.0	0.0
00:00:30	2.243	0.555	0.948	0.50
00:00:55	2.225	0.536	0.917	0.92
00:01:15	2.194	0.506	0.865	1.25
00:01:45	2.188	0.500	0.854	1.75
00:02:00	2.176	0.487	0.833	2.00
00:02:25	2.158	0.470	0.802	2.42
00:02:50	2.137	0.448	0.766	2.83
00:03:30	2.115	0.427	0.729	3.50
00:04:00	2.097	0.408	0.698	4.00
00:04:40	2.073	0.384	0.656	4.67
00:05:00	2.060	0.372	0.635	5.00
00:05:40	2.042	0.353	0.604	5.67
00:06:30	2.018	0.329	0.563	6.50
00:07:00	2.011	0.323	0.552	7.00
00:07:45	1.987	0.299	0.510	7.75
00:08:20	1.975	0.286	0.490	8.33
00:09:00	1.957	0.268	0.458	9.00
00:10:00	1.938	0.250	0.427	10.00
00:11:00	1.920	0.231	0.396	11.00
00:12:00	1.902	0.213	0.365	12.00
00:13:15	1.884	0.195	0.333	13.25
00:15:00	1.865	0.176	0.302	15.00
00:16:00	1.859	0.171	0.292	16.00
00:20:15	1.823	0.134	0.229	20.25
00:23:00	1.804	0.116	0.198	23.00
00:30:00	1.774	0.085	0.146	30.00
00:43:00	1.743	0.055	0.094	43.00

Figure 17. Plot of slug test data for well 1 using the Bouwer and Rice (1989) method. Refer to Figure 4 for well location.

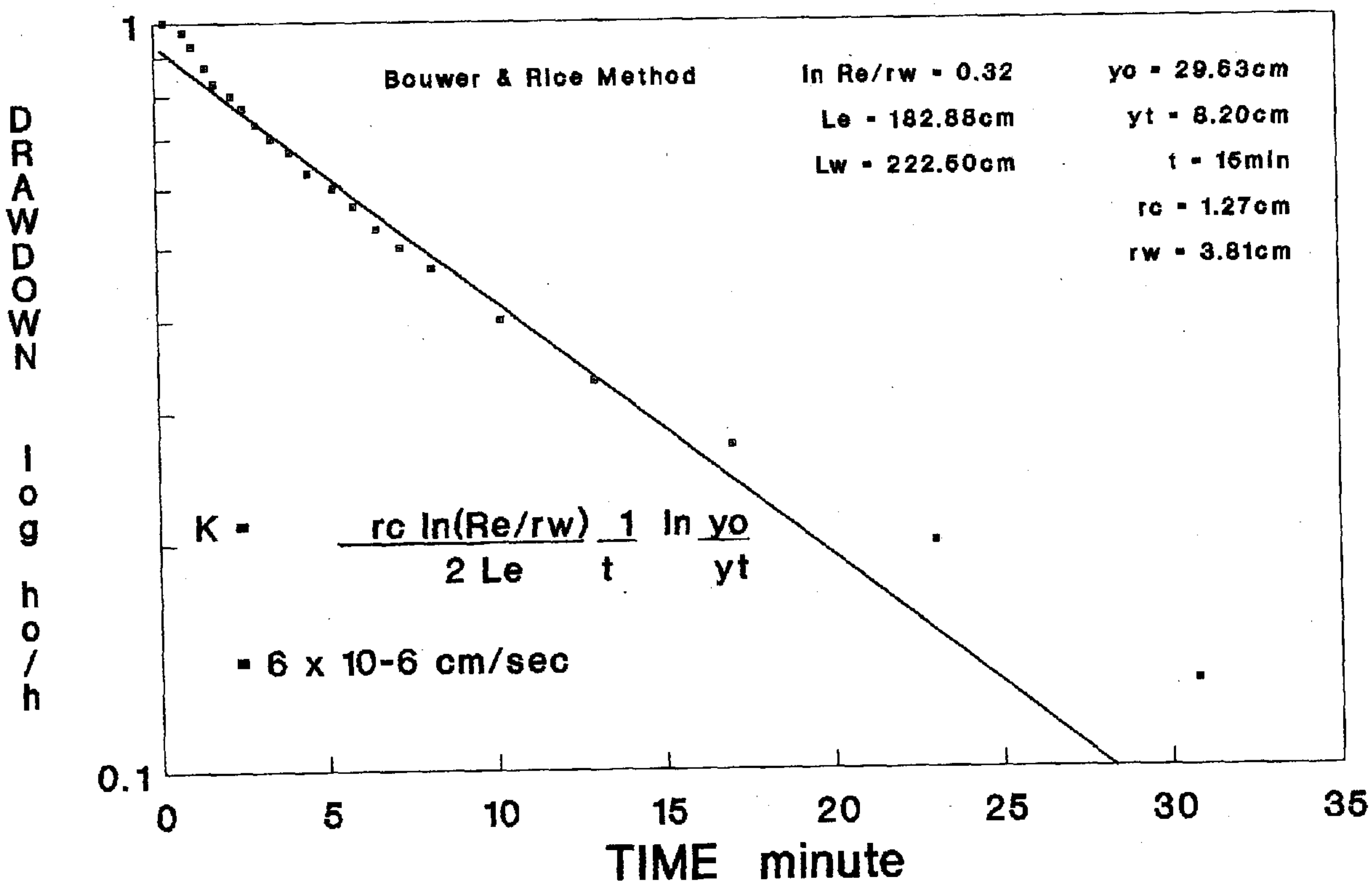

Bouwer & Rice Method
ln Re/rw = 3.16
Le = 182.88cm
Lw = 242.62cm
yo = 28.96cm
yt = 9.14cm
t = 12.75min
rc = 1.27cm
rw = 3.81cm
K= rc ln(Re/rw) / 2 Le · 1/t ln yo/yt
= 1.8 x 10-5 cm/sec
DRAWDOWN h/ho
1
0.1
0.01
0
10
20
30
40
50
TIME minute

Well 5 SLUG TEST ANALYSIS (BOUWER AND RICE)

Ref. Value: 1.890 m
Ho : 0.091 m
To : 00:00:00
(iron slug water displacement)

TIME	WATER LEVEL (m)	HEAD CHANGE (H)	HEAD RATIO (H/Ho)	ELAP. TIME (min)
static	1.890			
00:00:00	1.795	0.094	----	0.0
00:00:17	1.798	0.091	1.0	0.28
00:00:51	1.801	0.088	0.967	0.85
00:01:06	1.804	0.085	0.934	1.10
00:01:30	1.810	0.079	0.868	1.75
00:02:17	1.816	0.073	0.835	2.28
00:02:38	1.820	0.070	0.769	2.63
00:03:00	1.822	0.067	0.736	3.00
00:03:27	1.825	0.064	0.703	3.45
00:04:00	1.829	0.060	0.659	4.00
00:04:30	1.832	0.058	0.637	4.50
00:05:17	1.835	0.055	0.604	5.28
00:05:54	1.838	0.052	0.571	5.90
00:06:33	1.841	0.049	0.538	6.55
00:07:17	1.844	0.046	0.505	7.28
00:08:10	1.847	0.043	0.472	8.17
00:10:10	1.853	0.036	0.396	10.17
00:12:55	1.859	0.030	0.329	12.92
00:17:00	1.865	0.024	0.264	17.00
00:23:00	1.870	0.018	0.198	23.00
00:30:45	1.880	0.012	0.132	30.75
01:15:00	1.883	0.006	0.066	75.00

Figure 18. Plot of slug test data for well 5 using the Bouwer and Rice (1989) method. Refer to Figure 4 for well location.

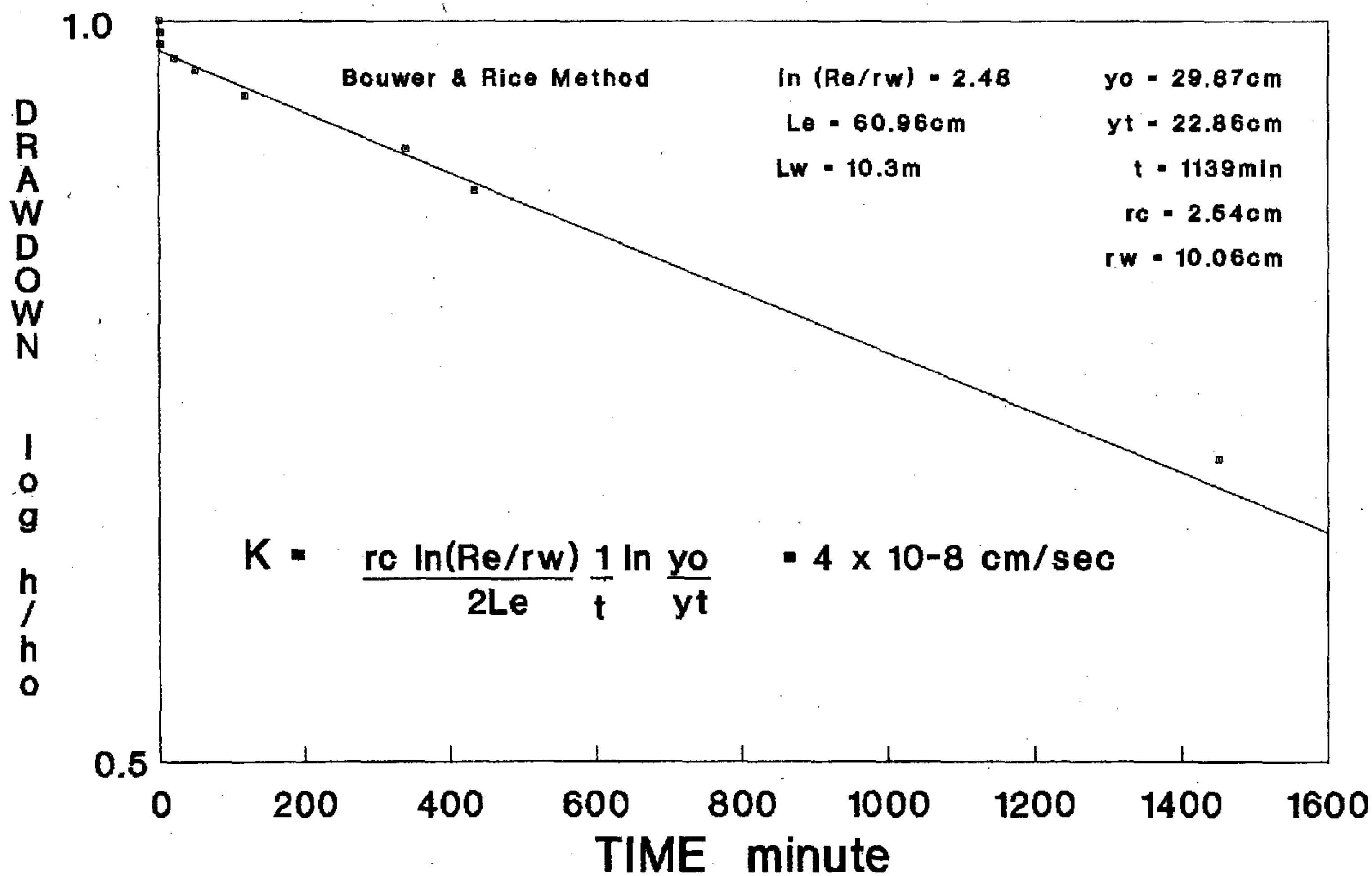

Bouwer & Rice Method
ln Re/rw = 0.32
Le = 182.88cm
Lw = 222.50cm
yo = 29.63cm
yt = 8.20cm
t = 15min
rc = 1.27cm
rw = 3.81cm
K = rc ln(Re/rw) / 2 Le · 1 / t · ln yo / yt
= 6 x 10-6 cm/sec
DRAWDOWN log ho/h
1
0.1
0
5
10
15
20
25
30
35
TIME minute

Well 16 SLUG TEST ANALYSIS (BOUWER AND RICE)

Ref. Value: 1.650 m
Ho : 0.262 m
To : 00:00:00
(iron slug water displacement)

TIME	WATER LEVEL (m)	HEAD CHANGE (H)	HEAD RATIO (H/Ho)	ELAP. TIME (min)
static	1.650			
00:00:00	1.390	0.262	1.00	0.00
00:02:15	1.393	0.260	0.990	2.25
00:13:48	1.396	0.256	0.978	13.80
00:33:28	1.400	0.253	0.965	33.47
01:34:30	1.402	0.250	0.953	94.50
04:31:50	1.405	0.247	0.942	271.83
06:09:08	1.414	0.238	0.907	369.13
24:49:20	1.440	0.210	0.802	1489.33

Figure 19. Plot of slug test data for well 16 using the Bouwer and Rice (1989) method. Refer to Figure 4 for well location.



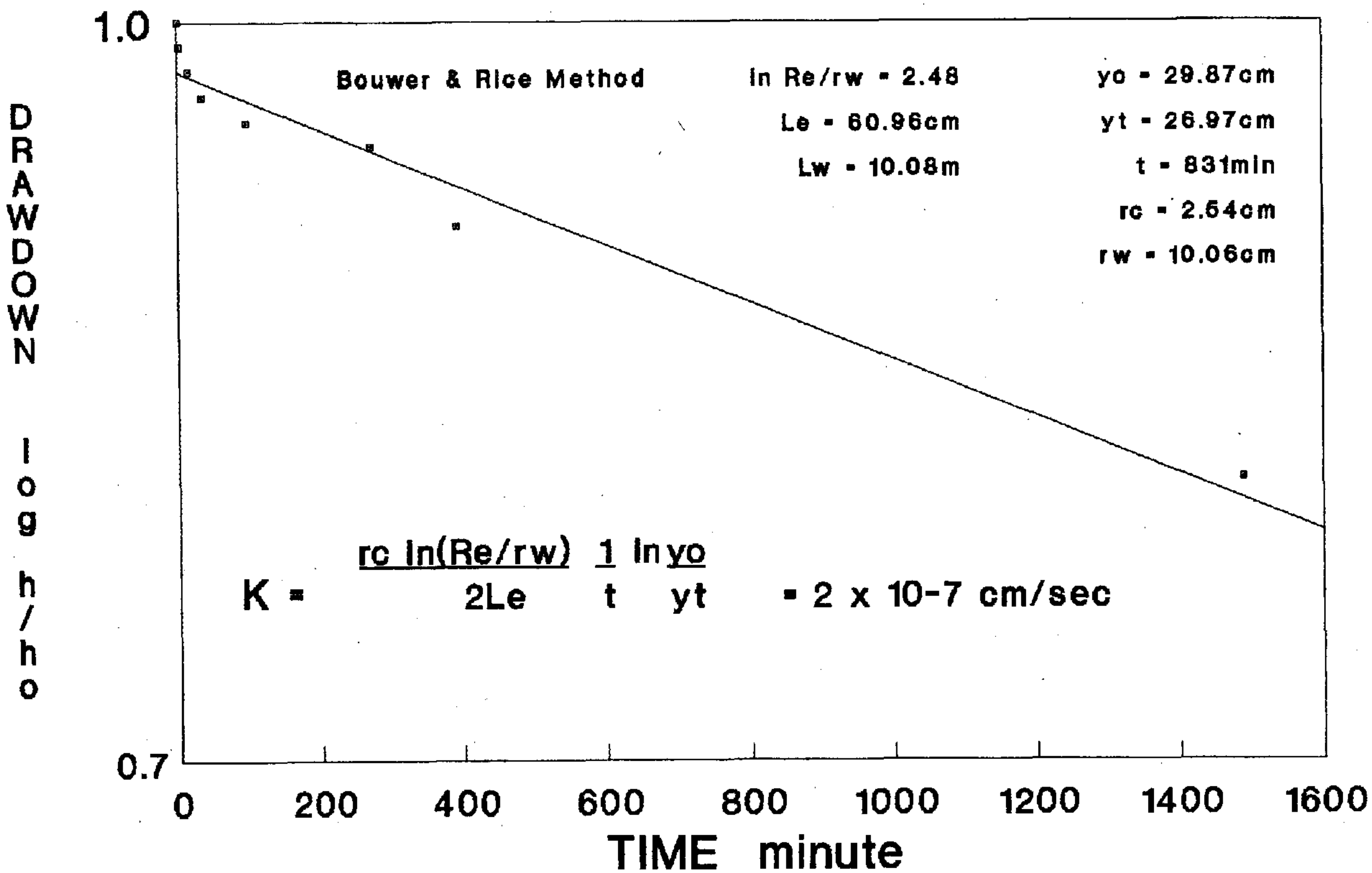
1.0
0.5
DRAWDOWN log h/ho
Bouwer & Rice Method
ln (Re/rw) = 2.48
Le = 60.96cm
Lw = 10.3m
yo = 29.87cm
yt = 22.86cm
t = 1139min
rc = 2.54cm
rw = 10.06cm
K = rc ln(Re/rw) / 2Le · 1/t · ln yo/yt = 4 x 10-8 cm/sec
0
200
400
600
800
1000
1200
1400
1600
TIME minute

Well 17 SLUG TEST ANALYSIS (BOUWER AND RICE)

Ref. Value: 1.435 m
Ho : 0.271 m
To : 00:00:00
(iron slug water displacement)

TIME	WATER LEVEL (m)	HEAD CHANGE (H)	HEAD RATIO (H/Ho)	ELAP. TIME (min)
static	1.435			
00:00:03	1.164	0.271	1.00	0.05
00:00:40	1.167	0.268	0.989	0.67
00:01:30	1.170	0.265	0.978	1.50
00:20:00	1.173	0.262	0.966	20.00
00:50:00	1.183	0.253	0.933	118.50
05:40:00	1.195	0.241	0.888	433.50
24:10:00	1.256	0.180	0.663	1450.00

Figure 20. Plot of slug test data for well 17 using the Bouwer and Rice (1989) method. Refer to Figure 4 for well location.

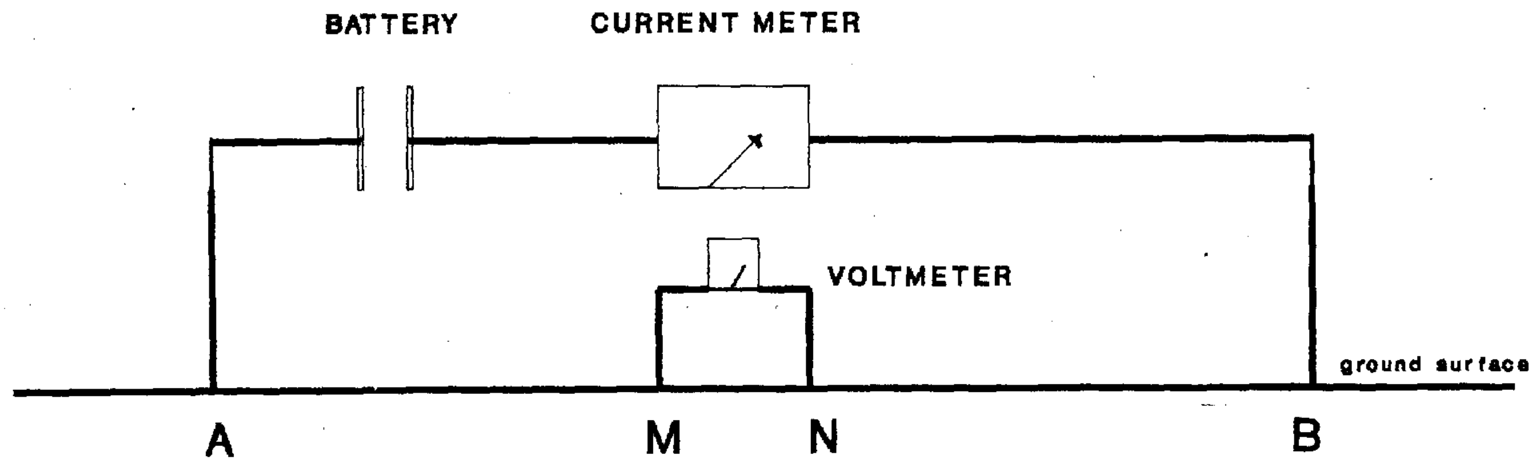


Bouwer & Rice Method
ln Re/rw = 2.48
Le = 60.96cm
Lw = 10.08m
yo = 29.87cm
yt = 26.97cm
t = 831min
rc = 2.54cm
rw = 10.06cm
K = rc ln(Re/rw) / 2Le 1 / t ln yo / yt = 2 x 10-7 cm/sec
1.0
0.7
DRAWDOWN
log h/ho
0
200
400
600
800
1000
1200
1400
1600
TIME minute

APPENDIX H

Resistivity Data

Figure 21. Schlumberger electrode array and equation for apparent resistivity.



$$\text{Apparent Resistivity} = \frac{\pi (AB/2)^2 - (MN/2)^2}{MN} \frac{V}{I}$$

A = Positive Current Electrode

B = Negative Current Electrode

M and N = Potential Electrodes

V = Voltage Drop

I = Electrical Current

A and B = Current Electrodes

M and N = Potential Electrodes

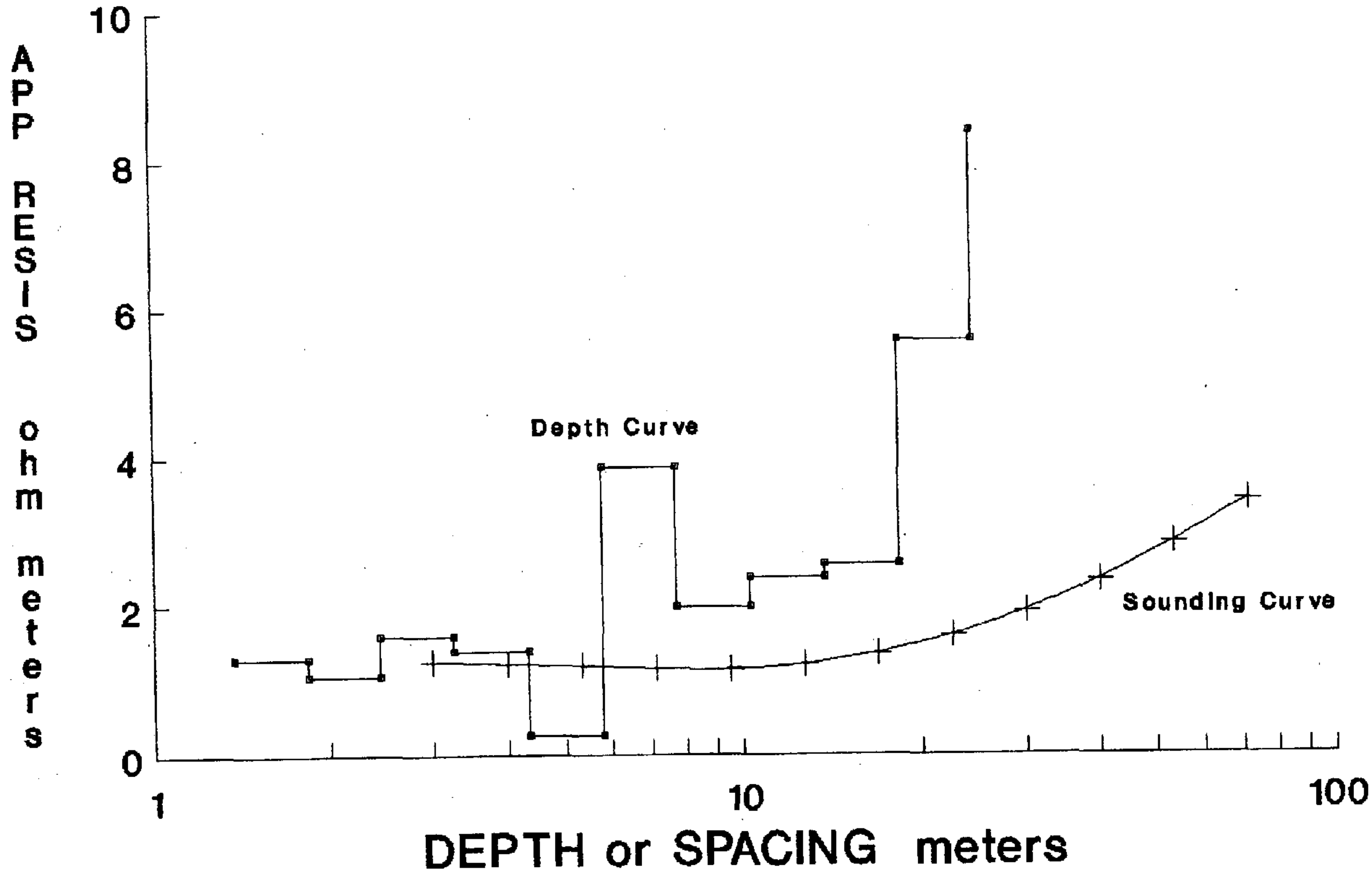
Transect 1

SPACING OF CURRENT ELECTRODES (m)	POTENTIAL DROP(mV) SPACING = 1.0 m	POTENTIAL DROP(mV) SPACING = 10.0 m
3.00	8.79	
4.00	4.89	
5.33	2.61	
7.11	1.60	
9.49	0.89	
12.65	0.38	
16.87	0.40	
22.50	0.22	
30.00	0.13	1.60
40.00		0.94
53.35		0.70
71.14		0.51

Transect 2

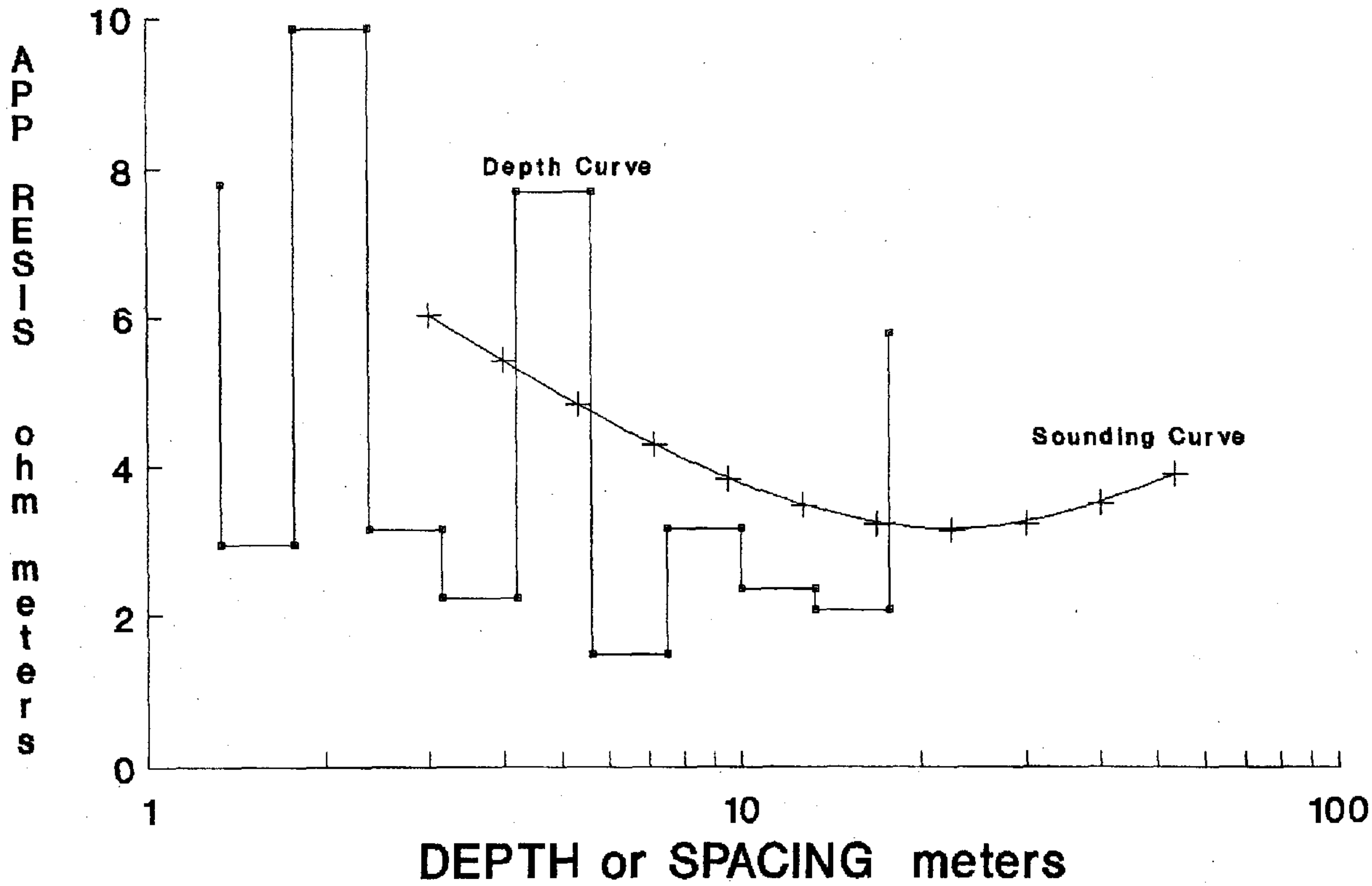
SPACING OF CURRENT ELECTRODES (m)	POTENTIAL DROP (mV) SPACING = 1.0 m	POTENTIAL DROP (mV) SPACING = 10.0 m
3.00	42.85	
4.00	20.80	
5.33	11.23	
7.11	5.28	
9.49	2.61	
12.65	1.43	
16.87	0.69	
22.50	0.40	
30.00	0.34	2.50
40.00		1.37
53.35		0.88
71.14		

Figure 22. Earth resistivity plots measured along transect 1 of apparent resistivity versus depth or spacing. Refer to Figure 4 for location.



APP RESIS ohm meters
10
8
6
4
2
0
Depth Curve
Sounding Curve
1
10
100
DEPTH or SPACING meters

Figure 23. Earth resistivity plots measured along transect 2 of apparent resistivity versus depth or spacing. Refer to Figure 4 for location.


APP RESIS ohm meters
10
8
6
4
2
0
Depth Curve
Sounding Curve
1
10
100
DEPTH or SPACING meters

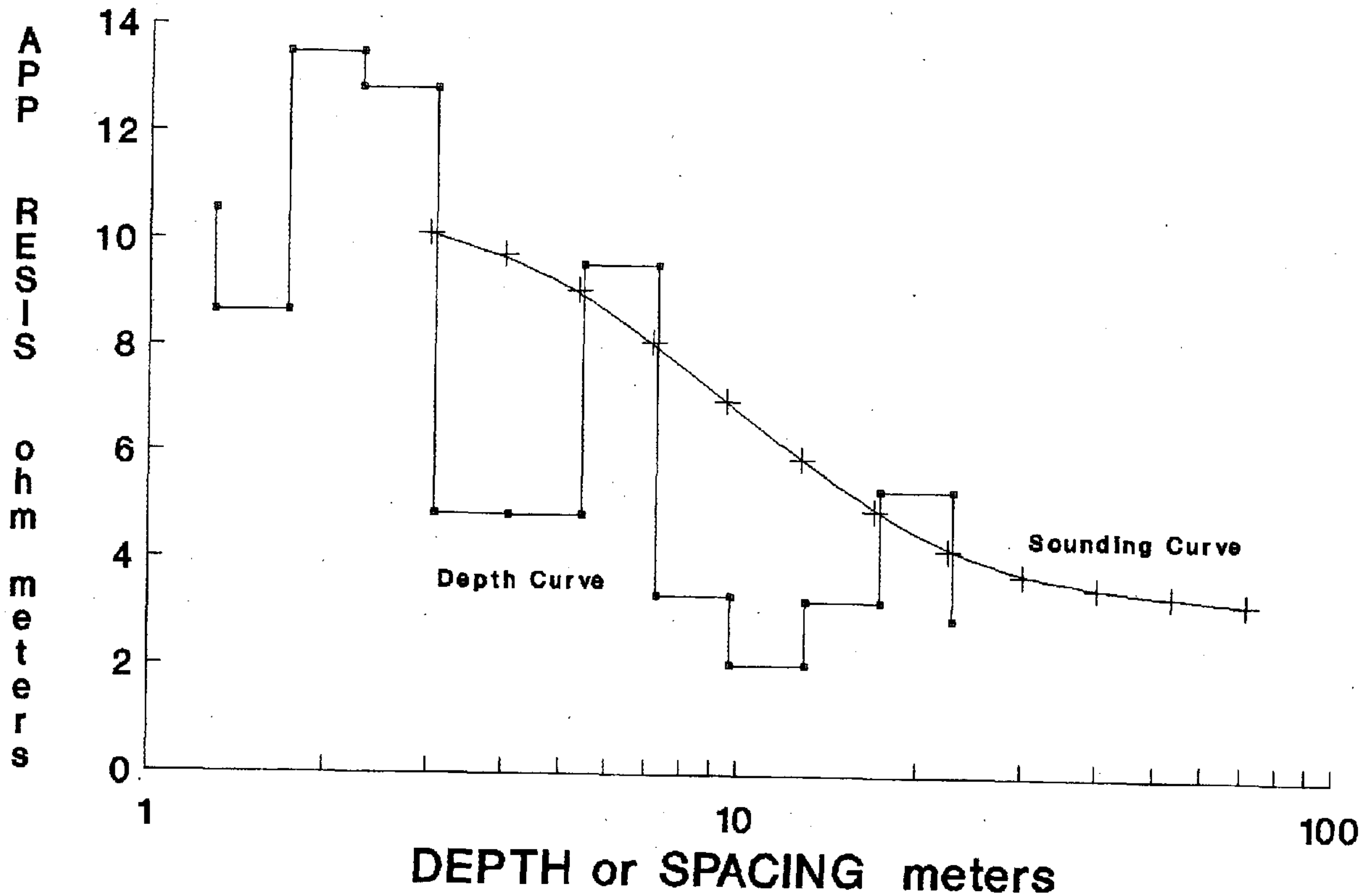
Transect 3

SPACING OF CURRENT ELECTRODES (m)	POTENTIAL DROP (mV) SPACING = 1.0 m	POTENTIAL DROP (mV) SPACING = 10.0 m
3.00	70.50	
4.00	35.90	
5.33	22.20	
7.11	11.40	
9.49	4.24	
12.65	2.14	
16.87	1.36	
22.50	0.49	
30.00	0.22	2.20
40.00		1.38
53.35		0.89
71.14		0.40

Transect 4

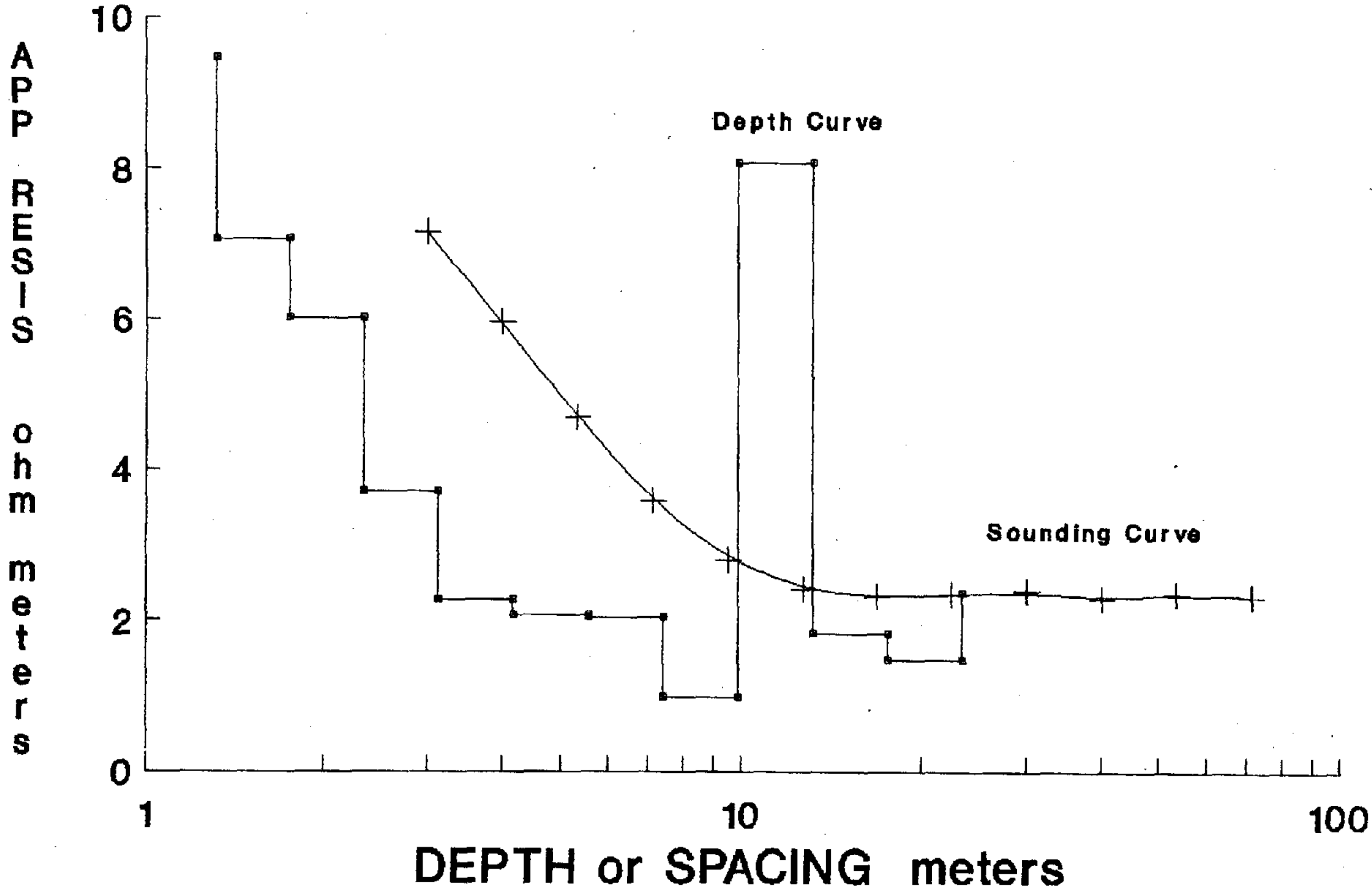
SPACING OF CURRENT ELECTRODES (m)	POTENTIAL DROP (mV) SPACING = 1.0 m	POTENTIAL DROP (mV) SPACING = 10.0 m
3.00	50.70	
4.00	23.50	
5.33	10.86	
7.11	4.56	
9.49	1.95	
12.65	0.97	
16.87	0.52	
22.50	0.24	
30.00	0.26	2.27
40.00		0.87
53.35		0.46
71.14		0.29

Figure 24. Earth resistivity plots measured along transect 3 of apparent resistivity versus depth or spacing. Refer to Figure 4 for location.



APP RESIS ohm meters
14
12
10
8
6
4
2
0
1
10
100
DEPTH or SPACING meters
Depth Curve
Sounding Curve

Figure 25. Earth resistivity plots measured along transect 4 of apparent resistivity versus depth or spacing. Refer to Figure 4 for location.



APP RESIS ohm meters
10
8
6
4
2
0
Depth Curve
Sounding Curve
1
10
100
DEPTH or SPACING meters

Transect 5

SPACING OF CURRENT ELECTRODES (m)	POTENTIAL DROP (mV) SPACING = 1.0 m	POTENTIAL DROP (mV) SPACING = 10.0 m
3.00	15.74	
4.00	9.11	
5.33	5.06	
7.11	2.94	
9.49	1.68	
12.65	0.93	
16.87	0.58	
22.50	0.38	
30.00	0.20	1.85
40.00		0.90
53.35		0.74
71.14		0.46

Transect 6

SPACING OF CURRENT ELECTRODES (m)	POTENTIAL DROP (mV) SPACING = 1.0 m	POTENTIAL DROP (mV) SPACING = 10.0 m
3.00	13.68	
4.00	7.46	
5.33	4.30	
7.11	2.20	
9.49	1.37	
12.65	0.79	
16.87	0.62	
22.50	0.30	
30.00	0.19	1.78
40.00		0.95
53.35		0.67
71.14		0.37

Figure 26. Earth resistivity plots measured along transect 5 of apparent resistivity versus depth or spacing. Refer to Figure 4 for location.

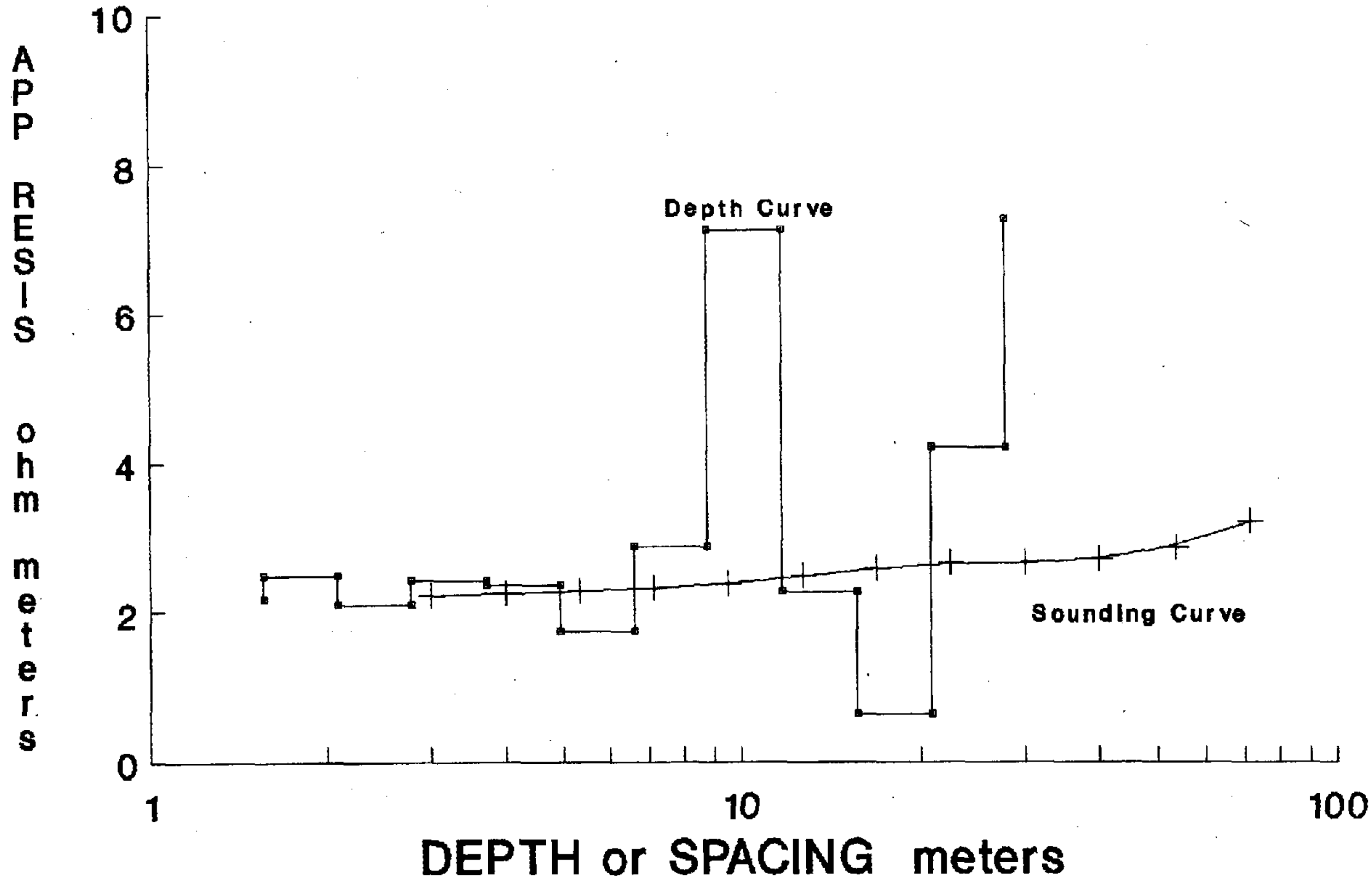
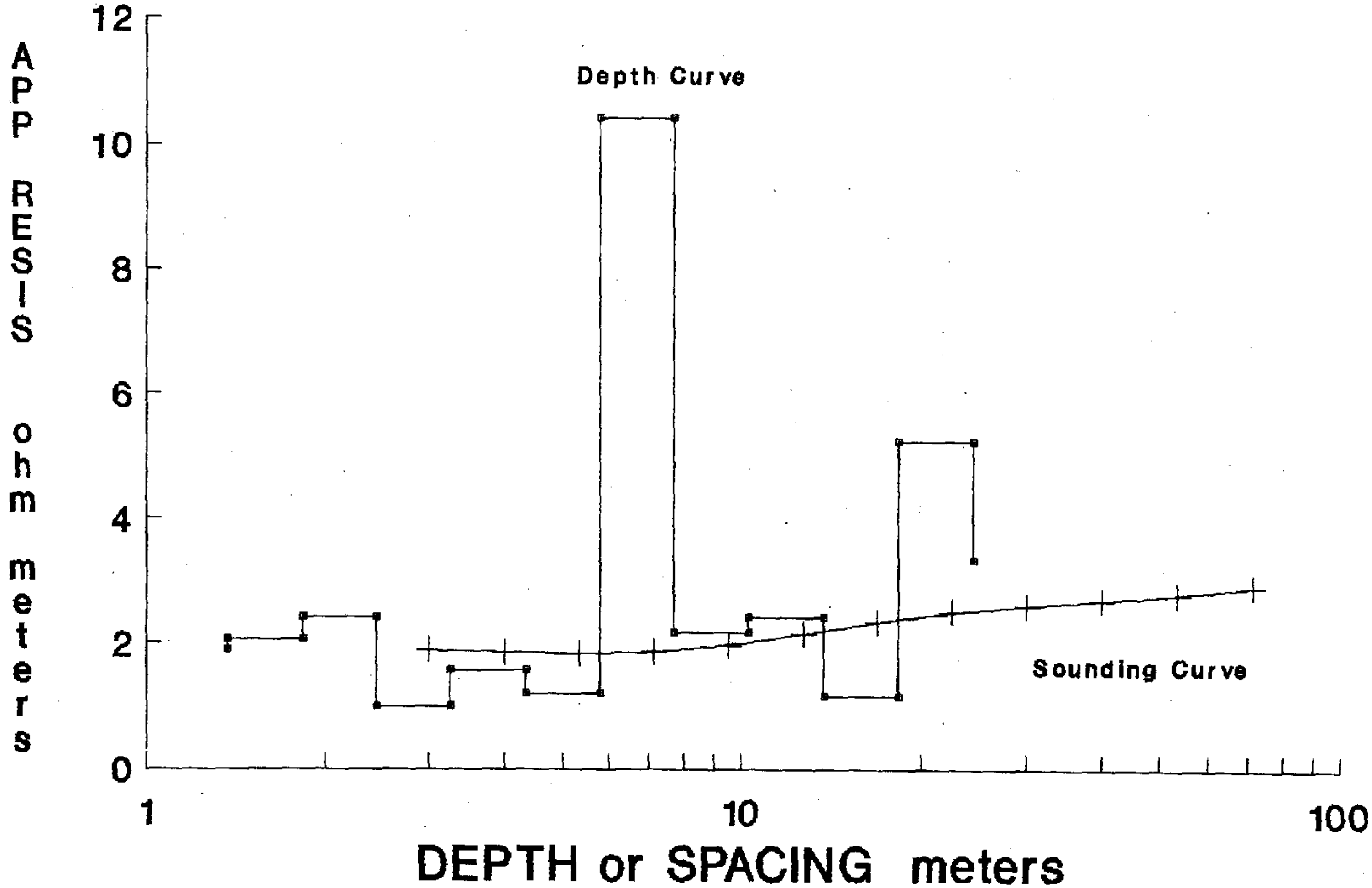

10
8
6
4
2
0
APP RESIS ohm meters
Depth Curve
Sounding Curve
1
10
100
DEPTH or SPACING meters

Figure 27. Earth resistivity plots measured along transect 6 of apparent resistivity versus depth or spacing. Refer to Figure 4 for location.



APP RESIS ohm meters
12
10
8
6
4
2
0
Depth Curve
Sounding Curve
1
10
100
DEPTH or SPACING meters

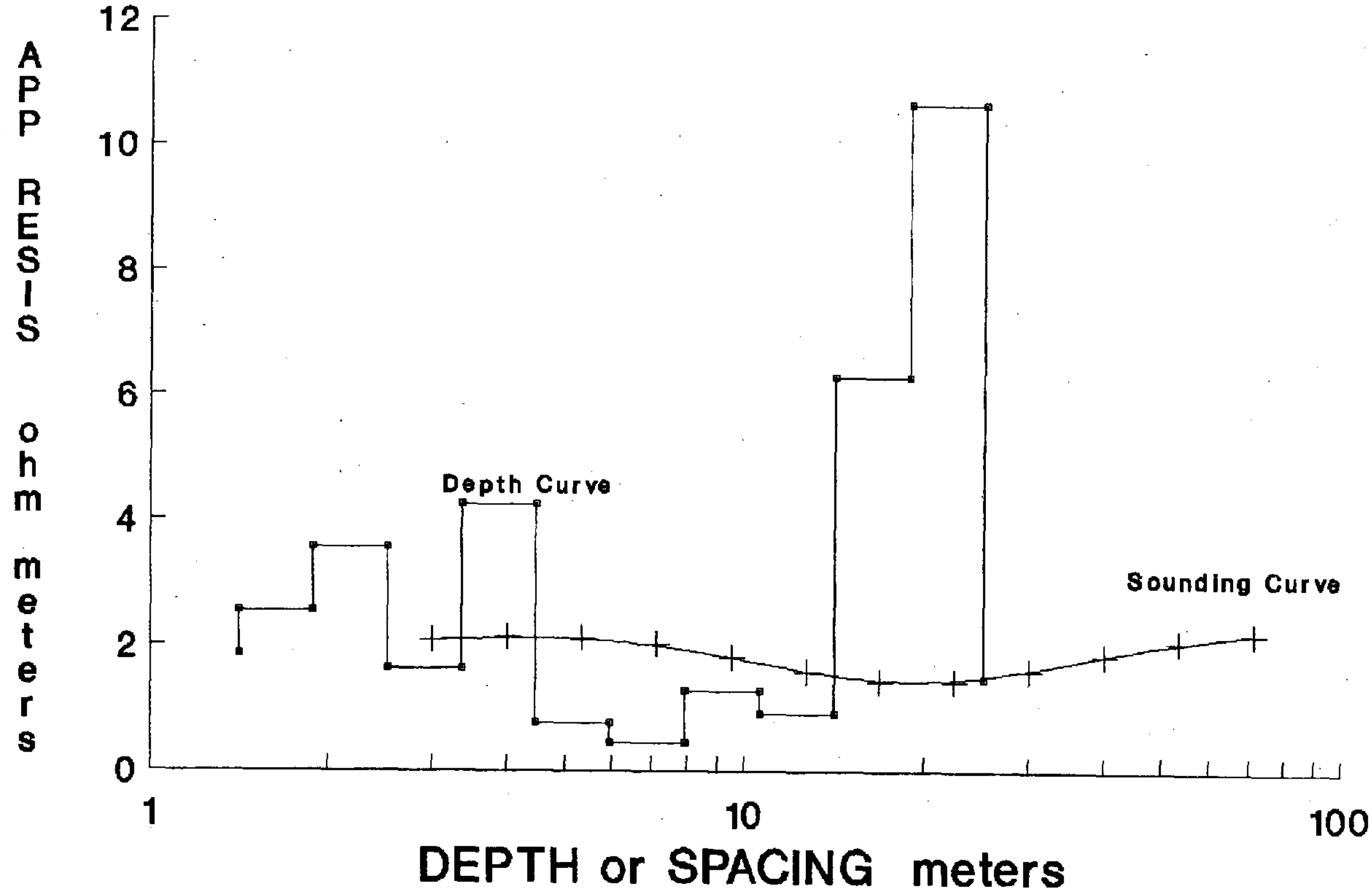
Transect 7

SPACING OF CURRENT ELECTRODES (m)	POTENTIAL DROP (mV) SPACING = 1.0 m	POTENTIAL DROP (mV) SPACING = 10.0 m
3.00	14.50	
4.00	8.50	
5.33	4.90	
7.11	2.38	
9.49	1.39	
12.65	0.58	
16.87	0.29	
22.50	0.19	
30.00	0.11	1.55
40.00		0.86
53.35		0.55
71.14		0.25

Transect 8

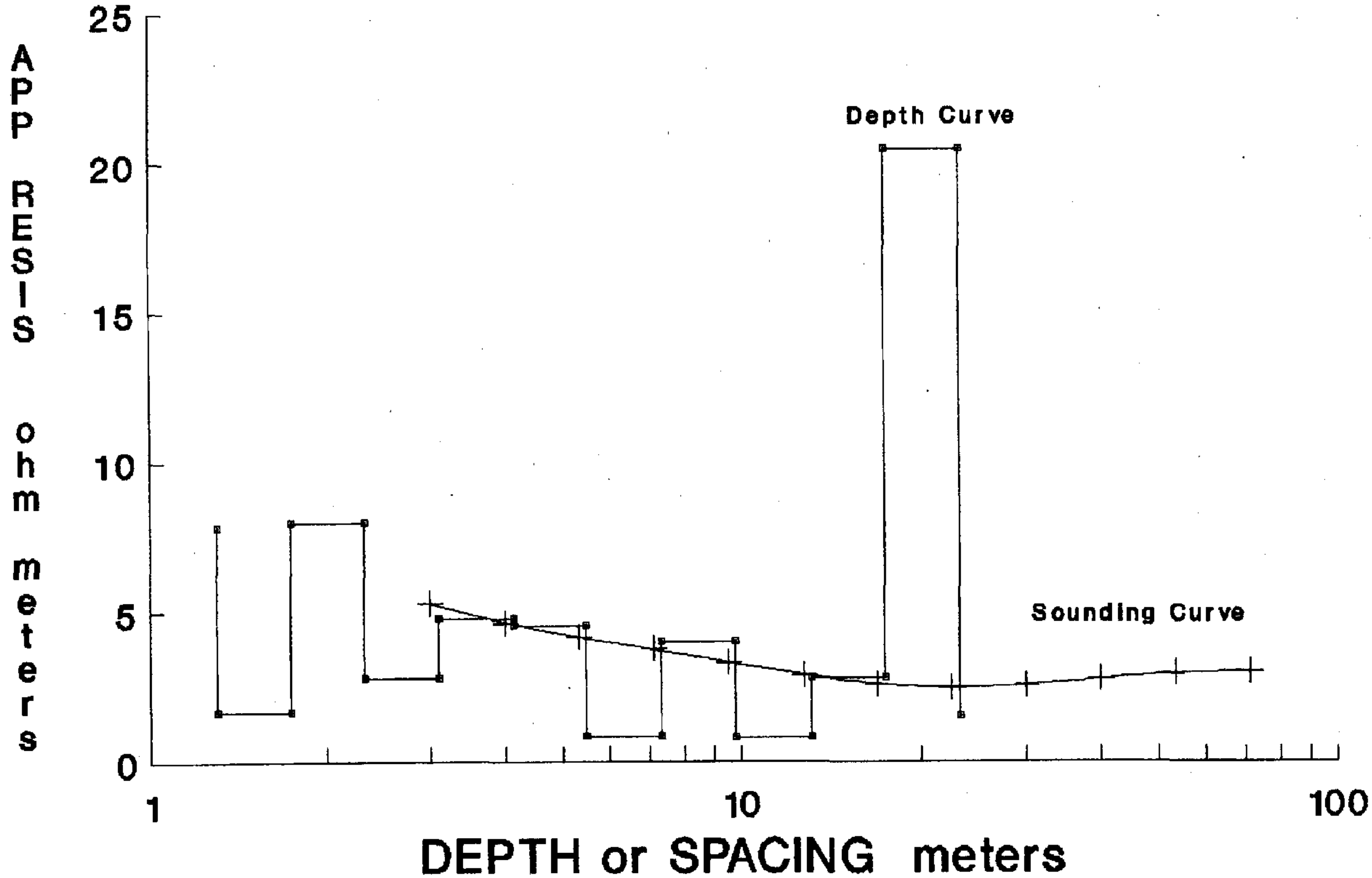
SPACING OF CURRENT ELECTRODES (m)	POTENTIAL DROP (mV) SPACING = 1.0 m	POTENTIAL DROP (mV) SPACING = 10.0 m
3.00	38.4	
4.00	16.50	
5.33	12.60	
7.11	4.50	
9.49	2.41	
12.65	1.20	
16.87	0.52	
22.50	0.37	
30.00	0.25	2.14
40.00		1.10
53.35		0.75
71.14		0.33

Figure 28. Earth resistivity plots measured along transect 7 of apparent resistivity versus depth or spacing. Refer to Figure 4 for location.



12
10
8
6
4
2
0
APP RESIS ohm meters
Depth Curve
Sounding Curve
1
10
100
DEPTH or SPACING meters

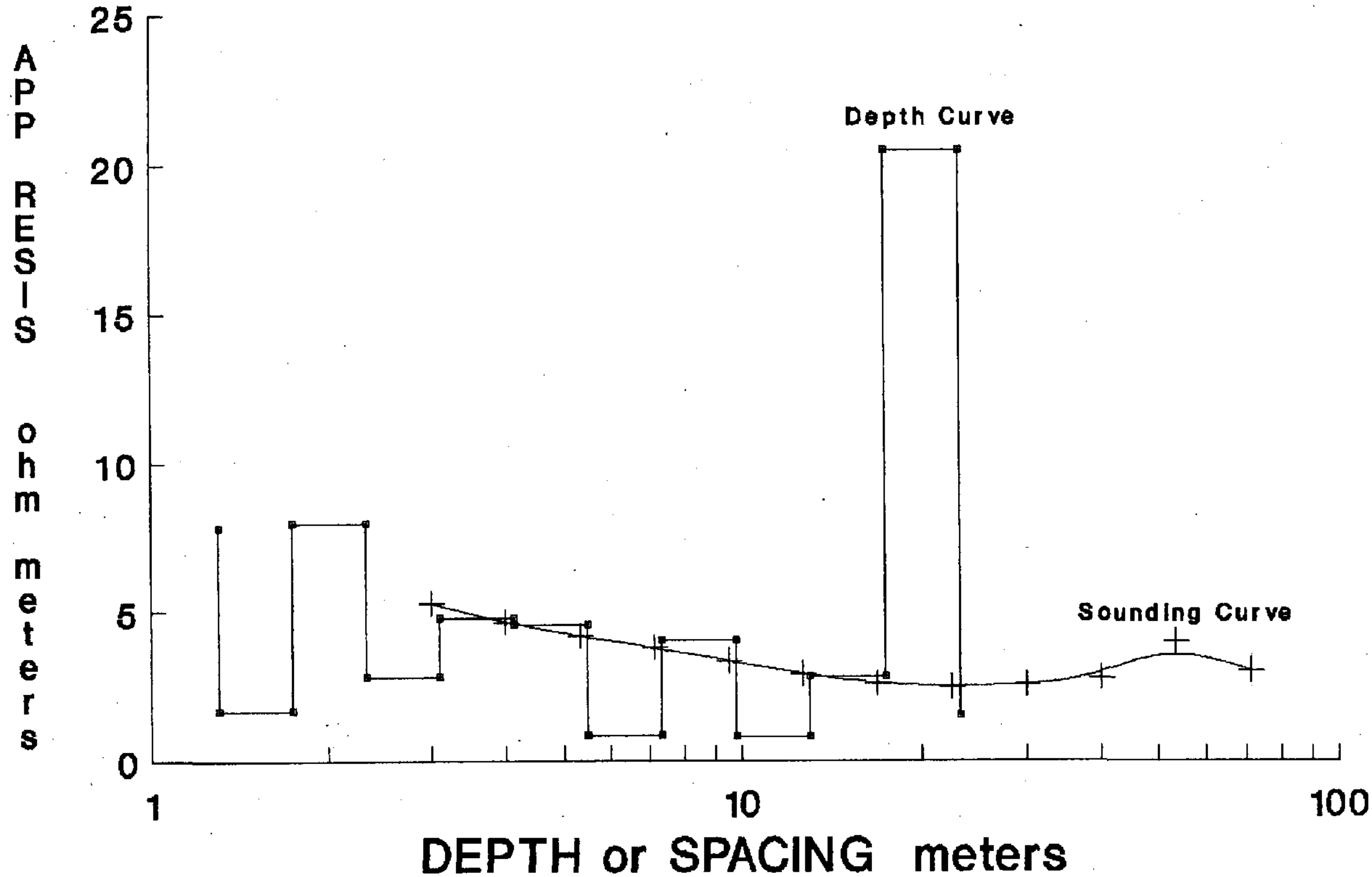
Figure 29. Earth resistivity plots measured along transect 8 of apparent resistivity versus depth or spacing. Refer to Figure 4 for location.


APP RESIS ohm meters
25
20
15
10
5
0
Depth Curve
Sounding Curve
1
10
100
DEPTH or SPACING meters

Transect 9

SPACING OF CURRENT ELECTRODES (m)	POTENTIAL DROP (mV) SPACING = 1.0 m	POTENTIAL DROP (mV) SPACING = 10.0 m
3.00	30.5	
4.00	14.20	
5.33	7.60	
7.11	3.82	
9.49	1.70	
12.65	0.97	
16.87	0.58	
22.50	0.35	
30.00	0.18	1.98
40.00		1.16
53.35		0.73
71.14		0.46

Figure 30. Earth resistivity plots measured along transect 9 of apparent resistivity versus depth or spacing. Refer to Figure 4 for location.



APP RESIS ohm meters
25
20
15
10
5
0
Depth Curve
Sounding Curve
1
10
100
DEPTH or SPACING meters

REFERENCES

Arndt, J.L. and Richardson, J.L., 1985, Winter effects on the salt balance of saline ponds in North Dakota: North Dakota Academy of Science, 36, p. 54.

Arndt, J.L. and Richardson, J.L., 1986, The effects of ground water hydrology on salinity in a recharge-flowthrough-discharge wetland system in North Dakota in G. Van der Kamp, and M. Makunicky [eds] Proc., Third Geohydrological Conference Saskatchewan Research Council Saskatoon. p. 269-278.

Arndt, J.L. and Richardson, J.L., 1988, Hydrology, salinity and hydric soil development in a North Dakota prairie pothole wetland system: Wetlands, v.8, p. 93-108.

Arndt, J.L. and Richardson, J.L., 1989, Geochemistry of hydric soil salinity in a recharge-throughflow-discharge prairie-pothole wetland system: Soil Science Society American Journal, v.53, p. 848-855.

ASTM, 1983, Classification of soils for engineering purposes: Annual Book of ASTM Standards, Section 4 - Construction, Volume 04.08 Soil and Rock; Building Stones, ASTM, Philadelphia, PA, p. 392-403.

Benz, L.C., Mickelson, R.H., Sandoval, F.M., and Carlson, C.W., 1961, Ground-water investigations in a saline area of the Red River Valley, North Dakota: Journal Geophysical Research, v. 66, no. 8, p. 2435-2443.

Benz, L.C., Sandoval, F.M., Mickelson, R.H., and George, E.J., 1964, Microrelief influences in a saline area of ancient glacial Lake Agassiz: II. On shallow ground water: Soil Science Society of America Proceedings, v. 28, p. 576-570.

Benz, L.C., Willis, W.O., Sandoval, F.M., and Mickelson, R.H., 1968, Soil water translocation in a high water area: Water Resources Research, v.4, no.1, p. 95-101.

Birkeland, P.W., 1984, Soils and Geomorphology: Oxford University Press, New York, NY, 372 p.

Bluemle, J.P., 1977, The face of North Dakota, the geologic story: North Dakota Geological Survey Educational Series 11, 73p.

Bouwer, H., 1989, The Bouwer and Rice slug test - an update: Ground Water, v. 27, p. 15-20.

Cowardin, L.M., Carter, V., Golet, F.C., and LoRoe, E.T., 1979, Classification of wetlands and deepwater habitats of the United States: U.S. Fish Wildlife Office of Biological Service Report 31. Washington, D.C.: Department of the Interior, 103 p.

Doering, E.J. and Sandoval, F.M., 1975, Hydrology of saline seeps in the Northern Great Plains: Transactions of the American Society of Agricultural Engineering, v. 19, no. 5, p. 856-865.

Doolittle, J.A., Heidt, C.J., Larson, S.J., Ryterske, T.P., and Ulmer, M.G., 1981, Soil survey of Grand Forks County: Soil Conservation Service, P.E. Wellman, North Dakota State Soil Conservation Committee, U.S. Department Office of Agriculture, Soil Conservation Service, 191 p.

Downey, J.S., 1969, Geology of northeastern North Dakota, Pederson, D.I. and Reid, J.T., eds., North Dakota Geological Survey Miscellaneous Series 39, 12 p.

Downey, J.S., 1973, Ground water resources, Nelson and Walsh Counties, North Dakota: North Dakota Geological Survey Bulletin 57, Part III, and North Dakota State Water Commission County Ground Water Studies 17, Part III, 69 p.

Downey, J.S., 1986, Geohydrology of bedrock aquifers in the northern Great Plains in parts of Montana, North Dakota, South Dakota, and Wyoming: U.S. Geological Survey Professional Paper 1402-E, 87 p.

Downey, J.S. and Dinwiddie, G.A., 1988, The regional Aquifer system underlying the northern great plains in parts of Montana, North Dakota, South Dakota, and Wyoming-summary: U.S. Geological Survey Professional Paper 1402-A.

Eisenlohr, W.S., Jr., 1972, Hydrologic investigations of prairie potholes in North Dakota, 1959-68: U.S. Geological Survey Professional Paper 585-A.

Fetter, C.W., 1988, Applied Hydrogeology: Merrill Publishing Company, Columbus, OH, 592 p.

Fulton, G.W., Richardson, J.L., and Barker, W.T., 1986, Wetland soils and vegetation: North Dakota Agricultural Experiment Station Research Report 106, 16 p.

Gerla, P.J., 1992a, The relationship of water table changes to the capillary fringe, evapotranspiration, and precipitation in intermittent wetlands: Wetlands, v. 12, p. 91-98.

Gerla, P.J., 1992b, Pathline and geochemical evolution of ground water in a regional discharge area, Red River Valley, North Dakota: Journal of Ground Water, v. 30, no. 5, p. 743-754.

Gillhan, R.W., 1984, The capillary fringe and its effect on water table response: Journal of Hydrology, v.67, p. 307-324

Goebel, D.G. and Gerla, P.J., 1992, Geochemistry of ground water in the lunby and stewart wetland, Grand Forks County, North Dakota: NDSU Extension, Third Biennial N.D. Water Quality Symposium, Bismarck, p. 48-59.

Grisak, G.E., Cherry, J.A., Vanhof, J.A., and Bluemle, J.P., 1976, Hydrogeologic and hydrogeochemical properties of fractured till in the Interior Plains region, in Glacial Till - An Interdisciplinary Study, ed. R.F. Legget. Royal Society Canadian Special Publications 12, p. 304-335.

Hansen, D.E. and Kume, J., 1970, Geology and ground water resources of Grand Forks County. Part I, Geology: North Dakota Geological Survey Bulletin 53 and North Dakota State Water Commission County Ground Water Studies 13, 76 p.

Hardie, L.A. and Eugster, H.P., 1970, The evolution of closed-basin brines: Mineral Society America Special Paper 3: p. 273-290.

Harris, K.L., Moran, S.R., and Clayton, L., 1974, Late Quaternary stratigraphic nomenclature Red River Valley, North Dakota and Minnesota: North Dakota Geological Survey Miscellaneous Series 52, 47 p.

Hendry, M.J., 1982, Hydraulic conductivity of a glacial till in Alberta: Ground Water, v. 20, p. 162-169.

Hendry, M.J., 1983, Ground water recharge through a heavy-textured soil: Journal of Hydrology, v. 63, p. 201-209.

McClune, W.F., ed., 1991, Powder Diffraction File, sets 1-41, International Centre for Diffraction Data, Swarthmore, PA.

Jensen, R.E., 1972, Climate of North Dakota: North Dakota National Weather Service, North Dakota State University, Fargo, North Dakota, 48 p.

Kantrud, H.A., Krapu, G.L., and Swanson, G.A., 1989, Prairie basin wetlands of the Dakotas: A community profile: U.S. Fish and Wildlife Service, Northern Prairie Wildlife Research Center, U.S. Department of the Interior Fish and Wildlife Service Research and Development, Biological Report 85(7.28), 111 p.

Kelly, T.E., 1968, Geology and ground water resources of Grand Forks county: Part 2. Ground water basic data: North Dakota Geological Survey Bull. 53, 117 p.

Laird, W.M., 1944, The geology and ground-water resources of the Emerado quadrangle: North Dakota Geological Survey Bulletin 53, 35 p.

LaBaugh, J.W., Winter, T.C., Adomaitis, V.A., and Swanson, G.A., 1987, Geohydrology and chemistry of prairie wetlands, Stutsman County, North Dakota: U.S. Geological Survey Professional Paper 1431, 26 p.

Lindorff, D.E., Feld, J., and Connelly, J., 1987, Groundwater sampling procedures guidelines: Wisconsin Department of Natural Resources, Madison, WI, 91 p.

Lissey, A., 1971, Depression-focused transient groundwater flow patterns in Manitoba: Ottawa, Ontario, Canada, The Queen's Printer, The Geological Association of Canada Special Paper 9, p. 333-341.

Meyboom, P., 1966, Unsteady groundwater flow near a willow ring in hummocky moraine: Journal of Hydrology, v. 4, p. 38-62.

Meyboom, P., 1967, Mass-transfer studies to determine the groundwater regime of permanent lakes in the hummocky moraine of western Canada: Journal of Hydrology, v.5 p. 117-142.

Millar, J.B., 1976, Wetland classification in western Canada: A guide to marshes and shallow open water wetlands in the grasslands and parklands of the prairie provinces: Canadian Wildlife Service Rep. Ser., No. 37, 38 p.

Parkhurst, D.L., Plummer, L.M., and Thorstenson, D.C., 1982, BALANCE - a computer program for calculation of chemical mass balance: U.S. Geological Survey Water-Resources Investigations 82-14, 33 p.

Remenda, V.H., Rudolph, D.L., Cherry, J.A., Kuhnel, V., and Woessner, W., 1992, Major and minor ions in Lake Agassiz clay near Manvel, ND: Implications for water quality and soil salinity: NDSU Extension, Third Biennial N.D. Water Quality Symposium, Bismarck, p. 302-310.

Richardson, J.L. and Arndt, J.L., 1989, What use prairie potholes? Hydrologic and soil factors come into play in determining the uses that can be made of wetlands in the prairie pothole region: Journal of Soil and Water Conservation, p. 196-198.

Rozkowska, A.D. and Rozkowski, A., 1969, Seasonal changes of slough and lake water chemistry in southern Saskatchewan (Canada): Journal of Hydrology, v. 7, p. 1-13.

Rozkowski, A., 1967, The origin of hydrochemical patterns in hummocky moraine: Canadian Journal of Earth Sciences, v. 5, p. 1065-1092.

Rozkowski, A., 1969, Chemistry of ground and surface waters in the Moose Mountain area, southern Saskatchewan: Ottawa, Ontario, Canada, Geological Survey of Canada Paper 67-9, 111 p.

Sandoval, F.M., Benz, L.C., and Mickelson, R.H., 1964, Chemical and physical properties of soils in a wet saline area in eastern North Dakota: Soil Science Society of America Proceedings, v. 28, p. 195-199.

Schwartz, F.W., Crowe, A.S., Hendry, M.J., and Chorley, C.W., 1987, A case study to assess the potential for saline soil development due to irrigation: Journal of Hydrology, v. 91, p. 1-27.

Skarie, R.L., Richardson, J.L., Maianu, A., and Clambey, C.K., 1986, Soil and groundwater salinity along drainage ditches in eastern North Dakota: Journal of Environmental Quality, v. 15, p. 335-340.

Sloan, C.E., 1972, Ground water hydrology of prairie potholes in North Dakota: U.S. Geological Survey Professional Paper 585-C, 28 p.

Soil Survey Staff, 1975, Soil taxonomy: U.S. Department of Agricultural Handbook No. 436, 754 p.

Stewart, R.E., and Kantrud, H.A., 1971, Classification of natural ponds and lakes in the glaciated prairie region: U.S. Fish and Wildlife Service Resource Publication, v.92, 57 p.

Stewart, R.E., and Kantrud, H.A., 1972, Vegetation of prairie potholes, North Dakota in relation to quality of water and other environmental factors: U.S. Geological Survey Professional Paper 585-D, 36 p.

Stein, R. and Schwartz, F.W., 1990, On the origin of saline soils at Blackspring Ridge, Alberta, Canada: Journal of Hydrology, v. 117, p. 99-131.

Strobel, M.L. and Gerla, P.J., 1992, Effects of saline ground-water discharge on water quality of the Red River of the North, northeastern North Dakota: Preliminary observations of the hydrogeology. NDSU Extension, Third Biennial N.D. Water Quality Symposium, Bismarck, p. 60-82.

Swanson, G.A., Winter, T.C., Adomaitis, V.A., and LaBaugh, J.W., 1988, Chemical Characteristics of prairie lakes in south-central North Dakota-Their potential for influencing use by fish and wildlife: United States Department of the Interior, Fish and Wildlife Service, Fish and Wildlife Technical Report 18, 44 p.

Uhlman, K., 1991, The geochemistry of boron in a landfill monitoring program: Ground Water Monitoring Review, v. 11, no. 4, p. 139-143.

U.S. EPA, 1989, MINTEQA2: Metal speciation model for surface and ground water, version 2.01. Center for Exposure Assessment Modeling, U.S. Environmental Protection Agency, Athens, GA.

U.S. Soil Conservation Service, 1985, Hydric soils of the United States: U.S. Department of Agriculture, Washington, D.C.

Winter, T.C., 1983, The interaction of lakes with variably saturated porous media: Water Resources Research, v.9, p. 1203-1218.

Winter, T.C., 1989, Hydrologic studies of wetlands in the northern prairie, <u>in</u> A.G. van der Valk, ed. Northern prairie wetlands. Iowa State University Press, Ames p. 16-54.

Winter, T.C. and Carr, M.R., 1980, Hydrologic setting of wetlands in the Cottonwood Lake area, Stutsman County, North Dakota: U.S. Geological Survey Water-Resource Investigation WRI 80-99, 42 p.

Zhody, A., 1989, A new method for the automatic interpretation of Schlumberger and Wenner sounding curves: Geophysics, v. 54, p. 245-253.