GEOHYDROLOGY AND HYDROGEOCHEMISTRY OF GROUNDWATER: STREAMFLOW SYSTEMS IN THE WILSON CREEK EXPERIMENTAL WATERSHED, MANITOBA.

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by
Franklin W. Schwartz
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ABSTRACT

Geohydrologic and hydrogeochemical investigations of groundwater-streamflow systems in Wilson Creek watershed make possible further development and refinement of the hydrochemical method of hydrograph separation.

During storm runoff periods, dilution behaviour of the major ions in the streamflow is dependent upon its concentration in each of the streamflow sources, direct runoff, channel precipitation, quick return flow and extended return flow. The ions chosen to characterize a particular component or group of hydrograph components relate closely to the physical system as described.

Groundwater flow patterns and hydrochemistry indicate that during periods with little or no precipitation streamflow is maintained by extended return flows discharging from local and intermediate, transverse flow systems principally in dissected reaches of the watershed. High hydraulic conductivity of the Riding Mountain formation coupled with large transient water table fluctuations during storm runoff periods result in increased extended return flow contribution to the streamflow.

Geohydrology and Hydrogeochemistry of Groundwater: Streamflow Systems in the Wilson Creek Experimental Watershed, Manitoba. Franklin W. Schwartz

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Contents

	Page
ABSTRACT	ii
INTRODUCTION	1
ACKNOWLEDGEMENTS	3
PHYSIOGRAPHY AND GEOHYDROLOGIC SETTING	4
METHODS OF INVESTIGATION	6
Precipitation	6
Streamflow	6
Hydraulic Head Distribution in the Groundwater Zone	7
Insitu Hydraulic Conductivity	8
Major Ion Chemistry	9
HYDROGEOLOGY	11
Alluvium	11
Upper Glacial Drift	12
Lacustrine sediments	13
Lower Till	13
Riding Mountain Formation	14
Lower Bedrock	15

Page

GROUNDWATER FLOW SYSTEMS 17

Conceptual Model 17

Longitudinal Flow Pattern Beneath Intervalley Uplands 17

Details of Flow Systems 18

GROUNDWATER GEOCHEMISTRY 23

Hydrochemical Facies 23

Controlling Parameters 24

HYDROCHEMISTRY OF STREAMFLOW 30

Source of Ions in Recession Flow 30

Geochemical Hydrographs 31

GEOCHEMICAL HYDROGRAPH SEPARATION 34

Idealization of Hydrograph Components 34

Hydrochemical Separation 36

SUMMARY OF CONCLUSIONS 41

REFERENCES CITED 44

APPENDICES 78

List of Figures

Page

1. Location of watershed and regional physiography . . 49
2. Topography and location of instrumentation. 50
3. Geologic cross-section through the watershed. . . . 51
4. Three detailed geologic cross-sections through the lower reaches of the watershed. 52
5. Conceptual groundwater model of an open watershed system. 53
6. Longitudinal flow pattern beneath uplands 54
7. Schematic interpretation of groundwater flow pattern in a section transverse to valley trends . . . 55
8. Three geohydrologic cross-sections through lower reaches of the watershed. 56
9. Water table fluctuations in upper glacial drift and Riding Mountain formation 57
10. Interpretation of water table contours and flow lines as basis of outflow computations. 58
11. Piper diagram of hydrochemical facies 59
12. Histogram summary of cation and anion concentrations in water types I-IV 60
13. Location of hydrochemical facies in cross-section . 61
14. Time variation of ionic concentration and conductivity of streamflow at Wilson Creek Weir 62
15. Time variation of major ion concentration and conductivity of streamflow at Packhorse Weir. . . . 63
16. Time variation of major ion concentration and conductivity for Wilson Creek during major storm. . 64
17. Time variation of major ion and conductivity dilution ratios for Wilson Creek (May 30 to June 10). . 65

Page

18. Time variation of major ion and conductivity dilution ratios for Wilson Creek (June 25 to July 1) . 66

19. Effect of Bald Hill reservoir on $SO_4^=$ concentration of Wilson Creek flow following major storm period 67

20. Annual variation of $SO_4^=$ and conductivity, 1969 . . 68

21. Time variation of $SO_4^=$ concentration and conductivity for McKinnon and Dead Ox Creeks 69

22. Time variation of $SO_4^=$ concentration and conductivity for Packhorse, Bald Hill, Dead Ox and McKinnon Creeks 70

23. Geochemical hydrograph separation for Wilson and Packhorse Creeks using Na^+, Ca^{++} and Mg^{++} average . 71

24. Detailed geochemical hydrograph separation for Wilson Creek using Na^+, Ca^{++} and Mg^{++} average . . . 72

25. Geochemical hydrograph separation for McKinnon and Dead Ox Creeks using $SO_4^=$ dilution 73

26. Detailed geochemical hydrograph separation for McKinnon and Dead Ox Creeks using $SO_4^=$ dilution . . 74

27. Piezometer design 75

28. Scatter diagram of total dissolved solids vs conductivity 76

List of Tables

Page

1. Summary of Hvorslev measurements 12

List of Appendices

Page

A. Description of stratigraphy and lithology of deposits in the lower reaches and east of the watershed 78

B. Piezometer locations, design and test hole logs . . 80

C. Hydraulic conductivity data: Results of Hvorslev Tests 99

D. Computer program for chemistry computations 101

E. Tabulation of chemical analyses including percent saturation and ion charge balance 106

F. Hydraulic head data for piezometers 121

G. Detailed description of the hydrograph separation technique 124

INTRODUCTION

Studies of groundwater-streamflow systems in Wilson Creek Experimental Watershed (Fig. 1) began in 1968 in order to determine the hydrochemical characteristics of the groundwater and surface water flow systems, and to refine the hydrochemical method of hydrograph separation (Newbury et al., 1969; Cox, 1969).

The present study was motivated in part by the need for more detailed geohydrologic and hydrogeochemical information to assist in the development of digital response models for Wilson Creek watershed and other similar watersheds along the Manitoba Escarpment. Four specific objectives of this study were:

1. to describe patterns of groundwater flow within and adjacent to Wilson Creek watershed
2. to characterize hydrochemistry of the groundwater surface water system
3. to develop further and refine the hydrochemical method for separation of a composite hydrograph within Wilson Creek watershed and apply the technique to Dead Ox and McKinnon Creeks, small creeks in a similar physical setting along the Manitoba Escarpment
4. to estimate the quantity of subsurface out-flow from Wilson Creek watershed.

Forty-five piezometer nests were utilized to investigate groundwater flow patterns and hydrochemistry as well as the spatial distribution of hydraulic conductivity. Stream hydrochemistry was monitored daily at five locations and often more frequently during storm runoff periods.

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PHYSIOGRAPHY AND GEOHYDROLOGIC SETTING

Wilson Creek watershed (Figs. 1 and 2) is typical of many small watersheds located on the eastward facing slope of the Manitoba Escarpment. Within a relatively short distance streams rising at the top of the escarpment descend more than 1000 feet in elevation.

Upper reaches of Wilson Creek watershed (Fig. 2) are characterized by hummocky topography with closed depressions, sloughs and lakes. Middle reaches of the watershed are deeply dissected. Accentuated valleys typically are bounded by high, steep and unstable walls formed of weathered shale bedrock. A meandering stream channel and gentle slopes characterize lower reaches of the watershed. The alluvial fan developed here merges with Lake Agassz plain 3 to 5 miles east and northeast of Wilson Creek watershed (Fig. 2). Lake Manitoba (Fig. 2), with average water surface 813 feet above sea level, is situated approximately 37 miles east of the watershed.

Annual air temperature cycle in the watershed ranges between -45°F (-42.7°C) and +110°F (43.3°C) with a mean of about 30°F (-1.1°C). Air-mass movement along the Manitoba Escarpment produces frequent and intense rainfall between May and September. Intensities as large as 6 inches per hour have been recorded. Total summer rainfall on the watershed over the last 12 years has averaged 14 inches, (Newbury et al., 1969).

Formation of an open, discontinuous tree layer of hardwoods and spruces in upper reaches of the watershed is attributed to browsing of shrubs and young trees. Young stands of deciduous trees dominated by white birch and aspen poplar occupy the middle and lower reaches. The lowland plain at the base of the escarpment forms a mixed forest with an assortment of conifers and hardwoods.

Total stream channel discharge from the watershed ranged from .1 to 700 cfs during 1969. Waterlevels in Bald Hill Reservoir, a headwater storage reservoir fluctuated from empty to a maximum stage of 15.5 feet.

Post-Paleozoic formations in the Riding Mountain area of the Manitoba Escarpment range in age from Jurassic to Upper Cretaceous (Fig. 3). Siliceous shale bedrock in upper reaches of the watershed is overlain by thick glacial drift deposits predominantly composed of till with minor sand and gravel interbeds. A thin discontinuous veneer of glacial till overlies bedrock in middle reaches. A thick glacial drift sequence at the base of the escarpment overlies the shale bedrock and is blanketed by thin alluvial fan deposits (Fig. 3).

METHODS OF INVESTIGATION

Precipitation

Precipitation is measured by a network of 32 standard raingauges and 8 recording raingauges distributed within and adjacent to the watershed (Fig. 2). Rainfall distribution is variable within the watershed but most often is greatest in the middle and upper reaches. In one rainfall period in 1969, precipitation ranged from a high of 5.35 inches to a low of 3.60 inches.

Average precipitation for the watershed was calculated using the recording raingauges and the Theisson Polygon method (Theissen, 1911). Precipitation measured at raingauge No. 10 has been used in this study to approximate average basin rainfall because it corresponds closely to the calculated values. Rainfall samples for chemical analysis were collected using a polyethylene sheet as a catchment.

Streamflow

Streamflow was measured by two stage recording weirs, one located on Packhorse Creek and a second located at the exit of Wilson Creek from the watershed. Rating curves were constantly updated throughout the 1969 field season. Discharge measurements made at these weirs are accurate to ± 5 percent (J.E. Thomlinson, Personal Communication, 1969). Stage recording installations at Bald Hill reservoir and Ridge dam also provided continuous outflow measurements.

Discharge measurements along lower reaches of Bald Hill Creek have been approximated. It is assumed that the discharge sum of Bald Hill and Packhorse Creeks at any time t is equal to the measured discharge at Wilson Creek weir at t + 1 1/2 hours. This assumption is based on a measured 1 1/2 hour water travel time from the confluence of Packhorse and Bald Hill Creeks to Wilson Creek weir and no measurably significant increase or decrease in discharge along this reach. (J.E. Thomlinson, Personal Communication, 1969)

Stream stages of Dead Ox and McKinnon Creeks were measured daily using staff gauges. Discharge measurements were approximated from rating curves established by 5 discharge meterings during the period of observation June 13 to September 2, 1969.

Hydraulic Head Distribution in the Groundwater Zone

The movement of groundwater is governed by the distribution of hydraulic head and permeability of the porous medium. For shallow, steady state and transient flow systems, the expression for hydraulic head can be written

$$h = Z + \frac{P}{\rho g}$$

where h is hydraulic head, Z is elevation of the point above some datum, P is pressure, ρ is fluid density and g is the gravitational acceleration constant (Hubbert, 1940). From consideration of this expression, it follows that the water-level in a piezometer or watertable observation well,

expressed in feet above sea level is a direct measure of hydraulic head at the termination point of the well or piezometer. Throughout this investigation, the open standpipe type of piezometer has been utilized which in its simplest form (Appendix B, Fig. 27) consists of a standpipe or lined borehole open to the atmosphere.

Piezometers and watertable observation wells were emplaced at 45 locations in and adjacent to the watershed (Fig. 2). They were constructed from semi-rigid polyvynlchloride (P.V.C.) piping with diameters ranging from .8 to 1.5 inches. Test holes up to 80 feet deep were drilled using a truck-mounted power auger. A portable power auger was used to drill shallow test holes less than 45 feet deep.

Five piezometer nests installed in 1965 by the Geological Survey of Canada are designated alphabetically A to E with individual piezometers and watertable wells bearing the prefix GS before each individual identification number (Fig. 2). Piezometer nests emplaced during the present study bear the prefix F before each identification number (Fig. 2). Pipe dimensions, top elevations and piezometer depths are listed in Appendix B.

Insitu Hydraulic Conductivity

Each piezometer was subjected to drawdown response tests. The detailed procedure is outlined by Hvorslev (1951). Because the duration of any response test is generally short, estimated values of hydraulic conductivity represent only the

water bearing material close to the piezometer. When the vertical hydraulic conductivity of a porous media is but a fraction of the horizontal component, as is often the case, the flow induced during the short period of observation is two dimensional. Consequently, the horizontal component of hydraulic conductivity is measured preferentially.

The time for complete recovery of water levels in a bailed piezometer ranged from several seconds to approximately 14 days. Measurements of the recovery rates indicated that all piezometers had stabilized after installation.

Major Ion Chemistry

By using a small diameter pipe with a one-way valve at its base, water samples were collected close to the inlet portion of the piezometer in order to obtain samples not in contact with the atmosphere. Stream samples were collected daily from locations D2, D4, D5, D6 and D7 (Fig. 2). During the storm runoff period June 24 to July 4, 1969, these locations were sampled much more frequently.

Measurements of pH were made at the piezometers and wells with a temperature controlled, null balance, Radiometer type PHM4, pH meter and combination glass electrodes standardized to two buffers in the manner outlined by Barnes (1964). Each groundwater or stream sample was divided into an acidified and non-acidified portion. Within one to two days, non-acidified samples were analysed at a field laboratory for HCO_3^-, Cl^- and $SO_4^=$ concentrations. Concentra-

tion of HCO_3^- was determined by potentiometric titration (Barnes, 1964). Turbidometric and volumetric procedures supplied by a commercial field chemistry kit (Hach Co.) were used to determine $SO_4^=$ and Cl^- concentrations respectively.

Concentrations of Ca^{++}, Mg^{++}, Na^+ and K^+ were determined at the University of Manitoba using a Perkin-Elmer 303 atomic absorption spectrophotometer. The detailed analytical procedures are given by Fishman (1966). Conductivity was measured for all samples and for comparison, results were standardized at 20°C.

Accuracy of the turbidometric procedure for $SO_4^=$ concentration was tested by preparing five different sulfate solutions in duplicate from a commercial standard solution and analysing them. Results indicate an accuracy of ± 9 percent at concentrations less than 100 mg. per litre and ± 15 percent at concentrations between 150-200 mg. per litre.

Quality of the analytical procedures for Ca^{++}, Mg^{++}, K^+, Na^+ as well as HCO_3^- concentration measurements was examined by duplicating these determinations for several samples. Results indicate that concentrations of the four cations in all cases were reproducible to within 2 percent and those of HCO_3^- were reproducible to within 4 percent. The average deviation of the samples from electrical balance was 8 percent.

HYDROGEOLOGY

Six hydrostratigraphic units have been identified within the watershed on the basis of their geohydrologic properties such as effective porosity and permeability. In general, hydrostratigraphic units need not have a specific relationship with the formal stratigraphic units (Maxey, 1964).

Alluvium

Following the last Pleistocene deglaciation approximately 12,000 years B.P., an alluvial fan has formed at the base of the escarpment. Alluvium overlies lacustrine sediments to a depth of approximately 20 feet (Fig. 4) and extends northeast five miles to McCreary. These non-indurated deposits are discontinuously stratified with variable sorting. Sub-rounded siliceous shale fragments are abundant in a silt-sized matrix. Coarse alluvial terrace deposits along stream channels within the watershed extend upward into middle reaches. They are comprised almost completely of shale fragments with some coarse till-derived material.

An intergranular permeability is dominant in the alluvium because the overburden pressures have not been sufficient to decrease the pore volume. Three Hvorslev values of hydraulic conductivity ranged from 1.6×10^{-4} to 2×10^{-4} ft. per sec. (Table 1). Hydraulic conductivity data are listed in Appendix C.

Table 1. Summary of Hvorslev Measurements

Hydrostratigraphic Unit	Number of Measure-ments	Horizontal Hydraulic Conductivity ft/sec.	
		Range	Median
Alluvium	3	$1.6x10^{-4}$-$2x10^{-4}$	$1.6x10^{-4}$
Upper Glacial Drift	5	$3x10^{-7}$-$7x10^{-8}$	$2x10^{-7}$
Lacustrine Sediments	12	$1.6x10^{-8}$-$1x10^{-4}$	$1x10^{-5}$
Lower Till	5	$7x10^{-9}$-$2x10^{-5}$	$1x10^{-8}$
Riding mountain formation	2	$1x10^{-4}$-$1.6x10^{-3}$	$8.5x10^{-4}$
Lower Bedrock	8	$7x10^{-9}$-$1x10^{-4}$	$1.6x10^{-6}$

Upper Glacial Drift

Shales of the Riding Mountain formation in the upper reaches of the watershed are blanketed by glacial drift deposits approximately 450 feet thick (Fig. 3). In sloping middle reaches, the upper glacial drift unit overlies shale bedrock as a discontinuous veneer 0 to 30 feet thick (Fig. 3).

The drift sequence is comprised mainly of calcareous glacial till with minor lenses of sand and gravel. The loosely compacted structure of the surficial till results in a dominant intergranular permeability with probably only minor secondary permeability. At depth, the changing stress

conditions caused by glacial loading and unloading probably produces significant joints and fractures (Westgate, 1969). Five Hvorslev values of hydraulic conductivity ranged from $3x10^{-7}$ to $7x10^{-8}$ ft. per sec. with a median of $2x10^{-7}$ ft. per sec. This wide range reflects textural inhomogeneities that were observed within the unit.

Lacustrine sediments

An interbedded sequence of lacustrine sediments consisting mainly of calcareous silts and clayey silts with occasional clay laminae underlies the alluvial unit in lower reaches of the watershed (Fig. 4).

A primary permeability is the result of relatively small overburden pressures. Twelve Hvorslev values of hydraulic conductivity range from $1x10^{-4}$ ft. per sec. to $1.6x10^{-8}$ ft. per sec. with a median value of $1x10^{-5}$ ft. per sec. The wide range in hydraulic conductivity results in part from the spatial variation of grain size within the unit. Tree root penetration observed in upper portions of this unit results in development of secondary, vertical permeability. Origin and correlation of nonindurated sedimentary deposits situated near the base of the escarpment are discussed in Appendix A.

Lower Till

In lower reaches of the Wilson Creek watershed a thin, compact, silty clay till overlies shale bedrock (Fig. 4).

This unit is discontinuous and no outcrops were observed. Lithologically the till resembles closely the underlying shale bedrock units. Five Hvorslev values for hydraulic conductivity ranged from $2x10^{-5}$ to $7x10^{-9}$ ft. per sec. with a median of $1x10^{-8}$ ft. per sec. The hard compact nature of the till and wide range of hydraulic conductivity values suggest that a joint permeability rather than intergranular permeability has developed as a result of differential glacial stress.

Riding Mountain Formation

This unit outcrops along stream valley walls in the middle reaches and underlies the upper glacial drift unit in the upper reaches and intervalley regions of the middle reach. It has a maximum thickness of approximately 500 feet and is composed of hard grey shale with minor interbeds of calcium montmorillonite bentonite (Bannatyne, 1963).

Measurements of hydraulic conductivity in two deep piezometers indicate values as high as $1.6x10^{-3}$ and $1x10^{-4}$ ft. per sec. These high values of hydraulic conductivity and the hard siliceous nature of the unit suggest that flow at depth in this unit is confined to joint and fracture zones. In the Brandon area of Manitoba, Halstead (1959) found that a deep well yielding 10 gallons per minute in the Riding Mountain formation may be only 100 feet away from a well of the same depth yielding only about 1 gallon per minute. The fissile nature of the Riding formation in the weathering

zone as evidenced in surface outcrop and shallow boreholes results in extensive, secondary permeability and values of hydraulic conductivity that in general are enhanced over values expected at depth.

Valley walls outcrops of the Riding Mountain formation are easily erodable. Frequent slumping or other mass movements commonly observed along the stream channels result in development of additional fracture permeability. In order to describe the flow pattern beneath the intervalley uplands (Fig. 6), the horizontal component of hydraulic conductivity is assumed to be twenty times larger than the vertical component. In the absence of suitable field measurements, the degree of anisotropy was estimated to take into account the interbedded nature of the shales as evidenced by drill logs and outcrops.

The water table in soil free portions of the middle reach is extremely responsive to precipitation events. Resulting short period fluctuations can have maximum amplitudes of from 5 to 7 feet.

Lower Bedrock

This unit comprises all Upper and Lower Cretaceous formations stratigraphically underlying the Riding Mountain formation (Fig. 3). In lower reaches, the lower bedrock unit underlies the lower till unit or in some cases lacustrine sediments (Fig. 4). It is composed almost exclusively of

shale with local accumulations of calcite and natural gas.

Eight Hvorslev measurements of hydraulic conductivity ranged four orders of magnitude from $1x10^{-4}$ to $7x10^{-9}$ ft. per sec. with a median of $1.6x10^{-6}$ ft. per sec. Bentonite and interbeds with low hydraulic conductivity produce large scale anisotropic behaviour and the large range in measured values of hydraulic conductivity. The horizontal component of hydraulic conductivity was again assumed to be twenty times more than the vertical component.

Overburden pressure and glacial stress conditions have reduced considerably the size of the intergranular pore spaces. Accordingly, auger samples had a low water content and appeared almost dry in some of the test holes. A secondary joint and fracture permeability resulting from glacial or tectonic stresses has developed within the unit.

GROUNDWATER FLOW SYSTEMS

Conceptual Model

Regional groundwater flow has been analysed by Toth (1963), Freeze and Witherspoon (1966, 1967), Meyboom (1966) and Freeze (1967) with the groundwater basin as the unit of geohydrologic study. In the context of watershed hydrology, the concept of the groundwater basin is often difficult or impossible to apply because often the groundwater basin boundaries do not correspond to the watershed boundaries.

The conceptual watershed model proposed here (Fig. 5) enables the watershed itself to remain the basic unit of study. Groundwater flux across imaginery, vertical boundaries coincident with surface water boundaries of the watershed is termed groundwater inflow or groundwater outflow. At some depth, the lower boundary is defined by groundwater flow which neither recharges nor discharges within the watershed (Fig. 5). Following the terminology of Toth (1963), a local flow system within the watershed has its recharge area at a topographic high and its discharge area at the adjacent topographic low. When one or more topographic highs or lows separate the recharge and discharge areas the flow system is termed intermediate.

Longitudinal Flow Pattern Beneath Intervalley Uplands

Two dimensional generalization of the flow pattern (Fig. 6) along section A-A^1 considers the upper glacial drift

to be isotropic. The effect of vertical exaggeration in the isotropic units has been accounted for using the procedure outlined by van Everdingen (1963). Because it is not possible to accurately construct flow lines in exaggerated, anisotropic sections, flow directions in the anisotropic Upper Cretaceous formation were estimated. The estimation procedure involved taking the mean flow vector after considering vertical exaggeration only, assuming isotropic behaviour and secondly anisotropic behaviour only, following the permeability ellipse procedure, assuming no exaggeration. The data indicate that the groundwater flow in the intervalley regions above the confluence of Bald Hill and Packhorse Creeks is characterized by a downward hydraulic gradient. Maximum downward gradient in recharge areas of the upper reaches was 0.2 ft. per ft.

Details of Flow Systems

Local and intermediate flow systems are situated transverse to the general longitudinal flow pattern. In intervalley regions (Fig. 7), recharge moves downward into deeper flow systems and local and intermediate flow systems discharge into the stream network. A hummocky water table configuration in upper reaches of the watershed and deeply dissected stream valleys in middle reaches control the flow patterns of these local and intermediate flow systems (Fig. 7).

To characterize in detail groundwater flow patterns

in lower reaches of the watershed, a series of three, two dimensional flow diagrams were constructed (Fig. 8). Alluvium,lacustrine sediment and lower till units were considered to be isotropic. Lower bedrock units were assigned an estimated anisotrpy of 20:1 (K_H:K_V). Again in the isotropic units flow vectors were constructed following the procedure outlined by van Everdingen (1963) and in the anisotropic unit flow vectors were estimated. Groundwater flow here is characterized by small vertical gradients and general lateral movement (Fig. 8) and is controlled by the relatively gentle water table slope in the alluvial fan material.

In middle reaches of the watershed, particularly in soil free areas, high values of hydraulic conductivity result in virtually no surface runoff and water table fluctuations are accentuated. The hydrograph of water table observation well GS 5, located in such a soil-free region demonstrates these short period, large amplitude fluctuations (Fig. 9).

In the upper reaches of the watershed, relatively low values of hydraulic conductivity coupled with steeply sloping land surfaces and a decadent vegitative cover result in large amounts of surface runoff. Fluctuations of the water table here as exemplified by GS 1 (Fig. 9) typically have longer periods and shorter amplitudes. A comparison of the time rates of change of waterlevels in GS 1 and GS 5

indicates that precipitation infiltrates and groundwater discharges much more rapidly in portions of the middle reach.

The single most important factor expediating rapid groundwater movement along these transverse, local flow systems is the high hydraulic conductivity of the Riding Mountain formation both insitu and in the slumped valley wall material. The hydraulic conductivity of the Riding Mountain formation at depth is more than two orders of magnitude higher than the upper glacial drift unit (Table 1).

Streamflow persists throughout cold winter months along lower reaches of Bald Hill and Packhorse Creeks as well as Wilson Creek, where the regime of these streams is controlled by groundwater seepage. Preceeding the spring snowmelt period, a two day survey (April 4 and 5, 1969) was made to measure stream and bottom sediment temperatures as well as to determine the distribution of ice cover. In the upper reaches, Bald Hill and Packhorse Creeks were completely frozen with ice thicknesses from 12 to 18 inches. Along lower reaches of Bald Hill Creek water flowed under an ice cover greater than 12 inches thick. The first small discontinuous stretches of open water were observed near the junction with Packhorse Creek. Streambed temperatures in the ice free portions ranged from 2.0 to 3.1 degrees centigrade and were consistently higher than the water temperature which ranged from 1.6 to 1.9 degrees centigrade. Downstream from Beer Bottle Park, Wilson Creek generally had

few continuously frozen reaches.

Groundwater outflow from the basin was calculated using the Darcy equation to be .004 cfs. The flow net constructed (Fig. 10) tacitly assumes that the water table gradient over the entire outflow depth remains constant. For this calculation, an outflow depth of 100 feet was chosen to extend downward and include 50 to 60 feet of the lower bedrock unit. From Figure 10, the hydraulic gradient is .02 ft. per ft. and maximum possible outflow width from the flow net was estimated to be 6,500 feet. Sufficient data was not available to extend the flow net southward to include the total outflow width but available data has been extrapolated to include this additional area of suspected outflow. A value of $3x10^{-7}$ ft. per sec. was calculated for the hydraulic conductivity by taking the mean of the hydraulic conductivities for the units involved.

A liberal estimate of groundwater outflow calculated using the Darcy equation with the highest measured hydraulic conductivity of $1.6x10^{-4}$ ft. per sec. and an assumed outflow depth of 200 feet, was 5 cfs. A conservative estimate of groundwater outflow of .00004 cfs was calculated using the lowest measured hydraulic conductivity of $3x10^{-9}$ ft. per sec. and an outflow depth of 100 feet. Because the highest and lowest values of hydraulic conductivity are representative of only a small fraction of the total outflow depth, the most probable estimate of outflow, calculated using the mean value

of hydraulic conductivity, is .004 cfs.

GROUNDWATER GEOCHEMISTRY

The chemical characteristics of natural waters result from direct solution and chemical reaction with solids, liquids and gases with which they have come into contact during various portions of the hydrologic cycle. The nature of the dissolved constituents in groundwater depends upon several important geochemical processes: a) chemical composition of precipitation b) gas generation in the soil zones of recharge areas c) dissolution of the porous media d) precipitation of mineral phases within the porous media e) ion exchanges between pore solutions and minerals of the porous media f) oxidation reduction reactions. These intimately related processes are strongly influenced by several environmental and dynamic parameters such as i) pressure ii) temperature iii) rate of fluid flow iv) chemical and structural variability of the solid phases in the porous media v) the order in which pore fluids come in contact with the porous media. Objectives of this geochemical investigation are to describe some of the specific geochemical processes operating in the groundwater system and to utilize major ion concentration to determine the source of ions in the streamflow.

Hydrochemical Facies

A six variable graphical representation (Piper, 1944) of the major ions in the groundwater (Fig. 11) shows

the general hydrochemical variation within and adjacent to Wilson Creek Watershed. On the basis of the similarity in the proportion of anion constituents (Fig. 11), four distinct hydrochemical facies have been recognized. Each facies type is designated by an identification number. Figure 12 is a histogram summary of the hydrochemistry of each facies.

The spatial distribution of the four facies are shown in figure 13. Type I water, a calcium-magnesium, bicarbonate facies (Back, 1966) is found in the upper reaches predominantly in the upper drift unit. Type II water, a calcium-sodium, bicarbonate-sulfate facies, is found in portions of the Riding Mountain formation as well as the alluvium, lacustrine sediment, and lower till units. Type III water, a sodium, chloride or sodium, chloride-bicarbonate facies, appears confined to the lower bedrock unit. Type IV water, a calcium-sodium or sodium calcium, sulfate-chloride-bicarbonate facies, is found east of the watershed (Fig. 13) in the alluvium, lacustrine sediment and lower till units.

Controlling Parameters

A dominant influence in determining the composition of subsurface waters is the mineralogy of the solid phases with which they come into contact. Field observation indicates that the coarse fraction of the upper glacial drift unit is composed of dolostone, limestone and Precambrian

boulders. Dolomite, calcite, feldspar and clay minerals comprise the matrix material of this unit as well fine grained fraction of the drift derived alluvium and lacustrine sediment units. By analogy with the surface till described by Rozkowski (1967) in the Moose Mountain area of south-eastern Saskatchewan, the probable dominant fine grained minerals are successively quartz, plagioclase, dolomite and calcite with montmorillonite predominating among the clay minerals. Because several Devonian evaporite members must have been eroded and material incorporated, the upper glacial drift probably contains minor amounts of gypsum, halite and other easily soluble salts. Rozkowski (1967) identified minor or trace quantities of hexahydrate, epsomite, halite and gypsum in the tills of the Moose Mountain area.

The following dissolution reactions indicate the ionic species associated with several of these minerals when in contact with an aqueous solution,

calcite: $CaCO_3 \rightleftarrows Ca^{++} + CO_3^{=}$ . . . . . (1)

dolomite: $(CaMg)(CO_3)_2 \rightleftarrows Ca^{++} + Mg^{++} + 2CO_3^{=}$ (2)

gypsum: $CaSO_4 \cdot 2H_2O \rightleftarrows Ca^{++} + SO_4^{=} + 2H_2O$ . . (3)

halite: $NaCl \rightleftarrows Na^{+} + Cl^{-}$ . . . . . (4)

The Riding Mountain formation, lower bedrock unit and lower till unit derived from the bedrock are composed almost

exclusively of montmorillonite and illite (J. Eades, Personal Communication, 1970). Bannatyne (1963) describes minor occurences of calcium montmorillonite bentionite within the Riding Mountain formation. Type II water has $SO_4^=$ concentrations that vary from 50 to 150 mg. per litre. Water flowing through the Riding Mountain formation and alluvium unit, which contains abundant shale fragments, derives $SO_4^=$ from disseminated gypsum that is common found in marine sediments of this kind (J. Eades, Personal Communication, 1970). Wickenden (1945) has described the occurence of pyrite in cores from the Vermillion River, Riding Mountain and other upper Cretaceous formations. Minor contributions of $SO_4^=$ could result from the oxidation of pyrite by the following reaction (Singer and Stumm, 1970).

$$\text{pyrite:}\quad FeS_2 + 2O_2 \rightleftarrows Fe^{++} + 2SO_4^= \quad \ldots\ldots\ldots (5)$$

Solubility constraints play an important role in determining the chemical evolution of groundwater (Schoeller, 1956; Back, 1961). The condition of chemical equilibrium is governed by the law of mass action and is described for equations 1, 2, 3, 4, by rewriting them in terms of dissociation constants,

$$\text{calcite:}\quad K^t_{CaCO_3} = \frac{A_{Ca^{++}} \cdot A_{CO_3^=}}{A_{CaCO_{3_c}}} \quad \ldots\ldots\ldots\ldots (6)$$

$$\text{dolomite:}\quad K^{t}_{CaMg(CO_3)_2} = \frac{A_{Ca^{++}} \cdot A_{Mg^{++}} \cdot A^{2}_{CO_3^{=}}}{A_{CaMg(CO_3)_2 c}} \quad \ldots \quad (7)$$

$$\text{gypsum:}\quad K^{t}_{CaSO_4 \cdot 2H_2O} = \frac{A_{Ca^{++}} \cdot A_{SO_4^{=}}}{A_{CaSO_4 c}} \quad \ldots\ldots \quad (8)$$

$$\text{halite:}\quad K^{t}_{NaCl} = \frac{A_{Na^{+}} A_{Cl^{-}}}{A_{NaCl_c}} \quad \ldots\ldots\ldots \quad (9)$$

where t is the temperature of the solution. In general, nearly all groundwater samples were saturated with respect to calcite, dolomite and aragonite but undersaturated with respect to gypsum (Appendix E). The computer procedure and solubility constants utilized to calculate percent saturation with respect to calcite, dolomite, gypsum and aragonite are listed in Appendix D. Cursory inspection of the relatively low concentrations of Na^{+} and Cl^{-} in the groundwater samples was sufficient to dismiss this reaction as a solibility constraint on the groundwater. Percent saturation values calculated for some metastable phases of the carbonate mineral--$CaSO_4$ - NaCl - H_2O systems (Appendix E), nesquehonite, $MgCO_3 \cdot 3H_2O$; hydromagnesite, $Mg_4(CO_3)_3(OH)_2 \cdot 3H_2O$; magnesite, $MgCO_3$; huntite, $Mg_3Ca(CO_3)_4$ and landsfordite $MgCO_3 \cdot 5H_2O$ were consistently less than 1 percent also dismissing them as solubility constraints on the groundwater.

High partial pressures of CO_2 are produced in the soil zones by decaying vegetation and respiration of plant roots. Calculated values of CO_2 partial pessures for shallow groundwater ranged between $10^{-2.30}$ and $10^{-1.30}$ atm., considerably higher than $10^{-3.5}$ atm., the atmospheric value (Garrels and Christ, 1965). Recharge infiltrating through these zones acquires high concentrations of HCO_3^-, Ca^{++} and Mg^{++} through leaching of carbonate minerals by carbonic acid. Kinetically this reaction is very rapid (Weyl, 1958).

Contribution of Ca^{++} derived from the dissolution of gypsum would tend to shift the carbonate equilibria toward precipitation of calcite, dolomite or aragonite. However, these precipitation reactions are kinetically slow (Hostetler, 1963) and therefore causes supersaturation of the groundwater with respect to calcite, dolomite and aragonite (Appendix E). The observed supersaturations cannot be completely explained by the common ion effect. For example, type I water generally containing less than 10 mg. per litre of $SO_4^=$ is supersaturated with respect to calcite and dolomite (Appendix E). The saturation data (Appendix E) indicates supersaturation of calcite and dolomite is not the result of equilibrium of the groundwater with the metastable carbonates, including aragonite. Bricker and Garrels (1967) indicate that the detailed chemical and structural variability of the solid phases are most important in the interpretation of chemical equilibria in natural water systems containing Ca and Mg carbonate com-

pounds. Observation of the mineral characteristics of the surfaces of the pore network was not feasible in this investigation.

The diminishing concentration of $SO_4^=$ and increasing concentration of HCO_3^- in type III water as compared to type II water is explainable in terms of sulfate reduction by aneorobic bacteria. Natural gas present in the lower bedrock unit could serve as a donor of organic hydrogen for the bacteria (Hvid-Hansen, 1951). The following equations modified from Hvid-Hansen (1951) and Hem (1959) provide an explanation of the high HCO_3^- content combined with low $SO_4^=$ content in the presence of bacteria and methane, a common constituent of natural gas,

$$SO_4^= + CH_4 = S^= + CO_2 + 2H_2O \quad \ldots\ldots\ldots\ldots (10)$$

$$S^= + 2H_2O + 2CO_2 = H_2S + 2HCO_3^- \quad \ldots\ldots\ldots\ldots (11)$$

HYDROCHEMISTRY OF STREAMFLOW

Source of Ions in Recession Flow

During extended periods with little or no precipitation, streamflow is maintained by extended return flows into the stream channels. Hydrochemistry of Wilson Creek and lower reaches of Packhorse and Bald Hill Creeks during these recession flows closely resembles type II groundwater (Figs. 14, 15; Appendix E). Chemistry data from all springs and apparent concentration of seepage along Bald Hill and Packhorse Creeks in the middle and lower portions of the upper reaches (Newbury et al., 1969) indicated ionic concentrations also comparable to type II water and the streamflow. Water table observation wells, F34, F35 and F36 along the Bald Hill Creek channel in the lower portion of the middle reach also possessed water of a similar chemical character (Appendix E). Type II water is therefore the dominant source of recession discharge for Bald Hill, Packhorse and Wilson Creeks. Low Cl^- concentrations in the streamflow and in groundwater types I and II as well as piezometric data presented in Figure 6 indicate that water from large, regional flow systems is not entering the surface water system within the watershed. These systems apparently discharge east of the escarpment.

Stream water during the recession periods was highly supersaturated with respect to calcite, aragonite and dolomite and undersaturated with respect to gypsum (Appendix E). When

discharging groundwater comes into contact with the atmosphere the partial pressure of CO_2 gas is reduced but the concentration of $CO_3^=$ increases. Because streamflow precipitation reactions for calcite and dolomite are kinetically slow (Barnes, 1964), supersaturation with respect to calcite, aragonite and dolomite was observed in Wilson and Packhorse Creeks.

Geochemical Hydrographs

Time variation (May to September, 1969) of major ions, Ca^{++}, Mg^{++}, Na^+, K^+, $HCO_3^- + CO_3^=$ and $SO_4^=$ as well as electrical conductivity is depicted for Wilson and Packhorse Creeks (Figs. 14, 15). More detailed major ion and conductivity variation with time for Wilson Creek during a storm runoff period (June 24 to July 2, 1969) is presented in Figure 16.

To compare the concentration behaviour of individual ions, the dilution ratio of each was calculated and plotted versus time for two storm runoff periods (Figs. 17, 18). In general, Na^+ and $SO_4^=$ concentrations are reduced considerably; while, Ca^{++} and Mg^{++}, behaving almost identically, are diluted substantially less.

Precipitation falling in the watershed contains only minimal concentrations of dissolved material. Analysis of three rainfall samples determined maximum concentrations of Ca^{++}, Mg^{++}, Na^+ and K^+ to be 1.5, .45, 2.46 and 1.49 mg. per

litre respectively with total dissolved solids less than 15 mg. per litre.

Sulfate dilution behaviour as influenced by Bald Hill detention reservoir indicates the sensitivity of the geochemical hydrographs. At any reservoir stage except overflow, maximum discharge is 5 to 6 cfs. During periods with little or no precipitation, the reservoir is normally empty. Water is however ponded during the snowmelt period or heavy rainfall periods. Following the rainfall period of June 25 to July 8, the detention reservoir contained water for 14 days (Fig. 19).

During this time, $SO_4^=$ concentrations of Bald Hill Creek remained at a stable, low level because the higher than normal discharges from Bald Hill Reservoir had $SO_4^=$ concentrations only as high as 3-4 mg. per litre (Fig. 19). Concentrations returned to pre-storm, recession levels only after the reservoir had drained completely (Fig. 19). In contrast, concentration of $SO_4^=$ in Packhorse Creek rebounded quickly to its pre-storm, recession level (Fig. 19). Concentrations of $SO_4^=$ at Wilson Creek weir increased slowly reflecting the direct combination of Bald Hill and Packhorse Creek discharges (Fig. 19).

Annual variation of conductivity and $SO_4^=$ concentration at Wilson Creek weir (Fig. 20) shows an excellent negative correlation with discharge. Highest conductivity values and $SO_4^=$ concentrations were measured during the

winter months when Wilson Creek discharge was low.

Conductivity and $SO_4^=$ concentration behaviour as monitored at Dead Ox and McKinnon Creeks followed dilution trends quite similar to other creeks investigated (Fig. 21). However, for the entire period of observation, Dead Ox Creek consistently had the lowest $SO_4^=$ concentrations of all.

More detailed measurements of $SO_4^=$ concentration and conductivity variation of Dead Ox and McKinnon Creeks revealed dilution behaviour comparable to Packhorse and Bald Hill Creeks (Fig. 22). However, the magnitude of the $SO_4^=$ concentration dilution at a given time tended to be unique for each creek, controlled by several intimately related variables. The chemical comparison of Bald Hill, Packhorse and Wilson Creeks (Fig. 19) indicates that the relative effectiveness of headwater storage and the amount of streamflow combination are two important variables.

GEOCHEMICAL HYDROGRAPH SEPARATION

Idealization of Hydrograph Components

An important hydrologic problem is separation of the composite hydrograph into components and interpretation of these components. Traditionally, it has been recognized (Meyboom, 1961; Hall, 1968; Pinder and Jones, 1969) that streamflow during storm runoff periods consists of three main components: direct runoff, interflow and baseflow.

Processes contributing to the formation of the composite hydrograph are intimately related and depend upon several independent variables. Betson and Marius (1969) found that storm runoff originates from but a small portion of the total drainge area. Location and extent of the source area are dependent upon several parameters including rainfall intensity, hydraulic conductivity in the unsaturated zone and antecedent moisture conditions. Jameson and Amerman (1969) recognize two interflow components, quick return flow, defined as rapid lateral flow in the uppermost soil horizons and delayed return flow, defined as long term lateral flow in the remaining unsaturated portion of the soil.

During recession flow, streamflow is sustained by extended return flows, made up of a groundwater discharge component and a delayed return flow component. Hall (1968) concluded that baseflow as traditionally defined probably exists only in arid regions where there is negligible con-

tribution to the streamflow from prolonged non-linear drainage of the unsaturated zone.

The major ion concentration of Wilson and Packhorse Creeks during periods with little or no precipitation characteristically remains stable. However, during storm runoff periods additional discharge components, direct surface runoff, channel precipitation, and quick return flow are added to the streamflow. Each component possesses a unique ionic concentration determined according to the various modes of interaction with solids, liquids and gases with which they have come into contact.

Delayed return flow and quick return flow having flowed through a soil zone with high CO_2 partial pressures contain relatively high concentrations of Ca^{++}, Mg^{++}, and HCO_3^-. Direct surface runoff and quick return flow that have not passed through a soil zone do not contain appreciable concentrations of these ions because the partial pressure of CO_2 gas in the atmosphere is low. Both surface runoff and quick return flow could be expected to possess negligible concentrations of Na^+, $SO_4^=$ and Cl^- because of the slow solution rates of sulfate and sodium silicate minerals, the short contact times involved and the general unavailability of the soluble sodium, sulfate and chloride salts on the ground surface and in leached upper soil horizons.

During recession flow, the hydrochemistry of Wilson Creek and lower reaches of Bald Hill and Packhorse Creeks

closely approximate Type II groundwater. Geochemical hydrographs from these creeks indicate that during rainfall periods contributions of direct runoff, channel precipitation, and quick return flow tend to chemically dilute the streamflow. Much of the surface runoff is contributed from the upper reaches where infiltration is restricted (MacKay and Stanton, 1964). Rapid infiltration into the highly permeable Riding Mountain formation results in large, transient increments in water table gradients as evidenced by the water table hydrograph of GS 5. Extended return flow contributions to the streamflow from transverse flow systems in the middle reach increase in response to increased gradients. Quick return flow probably originates in the greatest quantity under large hydraulic gradients from along the very steep valley walls of the middle reach. Direct runoff contribution to the streamflow ends quickly after the precipitation ceases.

Hydrochemical Separation

The hydrochemical method for hydrograph separation (Voronkov, 1963; Zektser, 1963) has been used frequently to yield separations more closely related to the physical system. Kunkle (1965) used conductivity to estimate the groundwater contribution to baseflow. Toler (1965a, 1965b) has distinguished two components of baseflow and estimated total contribution by means of conductivity. Pinder and

Jones (1969) determined the groundwater component of total storm discharge using the dilution behaviour of several representative ions. In Wilson Creek Watershed, hydrochemical characteristics of the system were used to identify the baseflow component of storm runoff hydrographs (Newbury et al., 1969).

Extended return flows and quick return flows that have passed through a humic soil zone possess high Ca^{++} and Mg^{++} concentrations. Dilution of these ions in the streamflow results from the addition of direct runoff and channel precipitation as well as a portion of the quick return flow that infiltrates in soil-free shale bank areas and is chemically similar to direct runoff. Because the dilution behaviour of Ca^{++} and Mg^{++} in the streamflow are very nearly identical (Figs. 17, 18), the average of Ca^{++} and Mg^{++} dilution ratios has been utilized to separate a combined extended return flow and partial quick return flow component from the composite hydrograph.

Because only minor concentrations of $SO_4^{=}$ and Na^{+} are contributed by quick return flow and because the dilution behaviour of Na^{+} closely approximates that of $SO_4^{=}$ (Figs. 17, 18), direct surface runoff and channel precipitation, the dilution of $SO_4^{=}$ and Na^{+} can separate the extended return flow contribution to the streamflow.

In general, the extent to which $SO_4^{=}$ and Na^{+} are present in aqueous solution depends upon the availability

of sulfate and sodium containing minerals for dissolution and the length of time groundwater has been in contact with these minerals. Hydrochemical measurements of groundwater and streamflow indicate that during storm runoff periods the increases in the extended return flows must result from rapid, transient flow in the Riding Mountain formation. The expected pattern with $SO_4^=$ and Na^+ concentration dilution greater than the average of Ca^{++} + Mg^{++} dilution results from the dual source of Ca^{++} and Mg^{++} in quick return flow and extended return flow as compared to a single, extended return flow source for $SO_4^=$ and Na^+. A dilution pattern of this kind was observed for Wilson and Packhorse Creek during all storm runoff periods.

Three hydrograph components were separated in the composite hydrographs of Wilson and Packhorse Creeks (Figs. 23, 24). A single ratio characterizing dilution of Ca^{++} and Mg^{++} at a particular time was determined by averaging Ca^{++} and Mg^{++} concentrations, to separate from the total discharge hydrograph a combined extended return flow and partial quick return flow component as well as a combined channel precipitation and direct runoff component that includes some quick return flow. Because atomic absorption spectrophotometer determinations of Na^+ concentrations are considerably more accurate than the field turbidometric procedure for $SO_4^=$ concentration, Na^+ has been utilized in this study to separate an extended return flow component.

Subtle concentration changes obvious in Wilson and Packhorse Creeks were not apparent with respect to $SO_4^=$ concentration.

The extended return flow component was separated for Dead Ox and McKinnon Creeks using $SO_4^=$ dilution (Figs. 25, 26). The detailed procedure for the hydrochemical method of hydrograph separation is outlined in Appendix G.

The ions chosen to characterize a particular component or group of hydrograph components at Wilson Creek watershed relate closely to the physical system. The characteristic ions for any watershed tend to be unique depending in part upon the geohydrologic setting.

On the basis of information derived from this study, the hydrochemical hydrograph separation as developed at Wilson Creek watershed could be applied to many similar watersheds along the Manitoba Escarpment utilizing easily obtainable data. Rapid accurate analyses of Ca^{++}, Mg^{++} and Na^+ concentration can be made using atomic absorption spectrophotometer techniques. Stream discharge can be measured relatively easily using staff gauges and rating curves.

Investigators (Kunkle, 1965; Toler, 1965a, 1965b; Newbury et al., 1969) have utilized conductivity dilution to obtain hydrograph separations in part because of the ease with which these measurements may be made. Conductivity dilution as determined at Wilson Creek (Figs. 17, 18) and Packhorse Creek represents an average of the ion dilutions weighted according to the mass concentration of the individual

ions. Because the conductivity dilution is consistently 5 to 15 percent lower than the average of Ca^{++} and Mg^{++} (Figs. 17, 18), separations resulting are a combination of extended return flow plus a small proportion of quick return flow.

SUMMARY OF CONCLUSIONS

Six hydrostratigraphic units have been distinguished in the Wilson Creek watershed, a surficial alluvium unit, an upper till unit, a lacustrine silt-clay unit, a lower till unit, the Riding Mountain formation and a unit comprising the Cretaceous bedrock formations underlying the Riding Mountain formation.

In general, groundwater flow in the Wilson Creek watershed above the confluence of Bald Hill and Packhorse Creeks is characterized by a downward hydraulic gradient. Transverse, local and intermediate flow systems develop in the deeply dissected middle and hummocky upper reaches of the watershed and discharge into the surface water system. Recharge to deeper flow systems predominates in the inter-valley regions of the middle and upper reaches. In lower reaches of the watershed, the gentle, relatively constant water table slope results principally in lateral flow with only minor vertical flow. Groundwater outflow from the watershed was estimated to be between 5 and .00004 cfs., with a best estimate of .004 cfs.

Four distinct hydrochemical facies occur in and adjacent to the watershed. The chemical character of the natural water evolves as a result of direct solution and chemical reactions with solids, liquids and gases with which it has come into contact. Hydrochemical comparisons of the

groundwater and streamflow reveals that extended return flows from the upper glacial drift unit and the Riding Mountain formation in middle reaches of the watershed as well as from the glacial drift at the base of the escarpment are the major sources of recession stream flow. Groundwater flow patterns and hydrochemical measurements indicate that deep groundwater does not enter the surface water system within the watershed but rather discharges east of the escarpment.

The time variation of conductivity and major ions, Ca^{++}, Mg^{++}, Na^{+}, K^{+}, $HCO_3^{-} + CO_3^{=}$ and $SO_4^{=}$ in Packhorse and Wilson Creeks displayed a distinct, negative correlation with stream discharge. Dilution behaviour of the major ions in the stream flow during storm runoff periods is dependent upon its concentration in each of the streamflow sources, direct runoff, channel precipitation, quick return flow and extended return flow. Conductivity and concentration of $SO_4^{=}$ in Dead Ox and McKinnon Creeks also correlate well with stream discharge.

Average dilution of Ca^{++} and Mg^{++} was utilized to separate from the composite hydrograph an extended return flow and partial quick return flow component as well as a combined channel precipitation and direct runoff component that includes some quick return flow. Dilution of Na^{+} and $SO_4^{=}$ was indicative of the extended return flow contribution

to the streamflow. The hydrochemical method of hydrograph separation as developed in Wilson Creek watershed was applied to Dead Ox and McKinnon Creeks situated in a similar physical setting along the Manitoba Escarpment.

With a few simple and readily obtainable measurements of chemistry and discharge, the hydrochemical method of hydrograph separation can be applied to numerous streams along the Manitoba Escarpment. These techniques may better represent the physical system than more arbitrary graphical methods.

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F I G U R E S

1 - 28

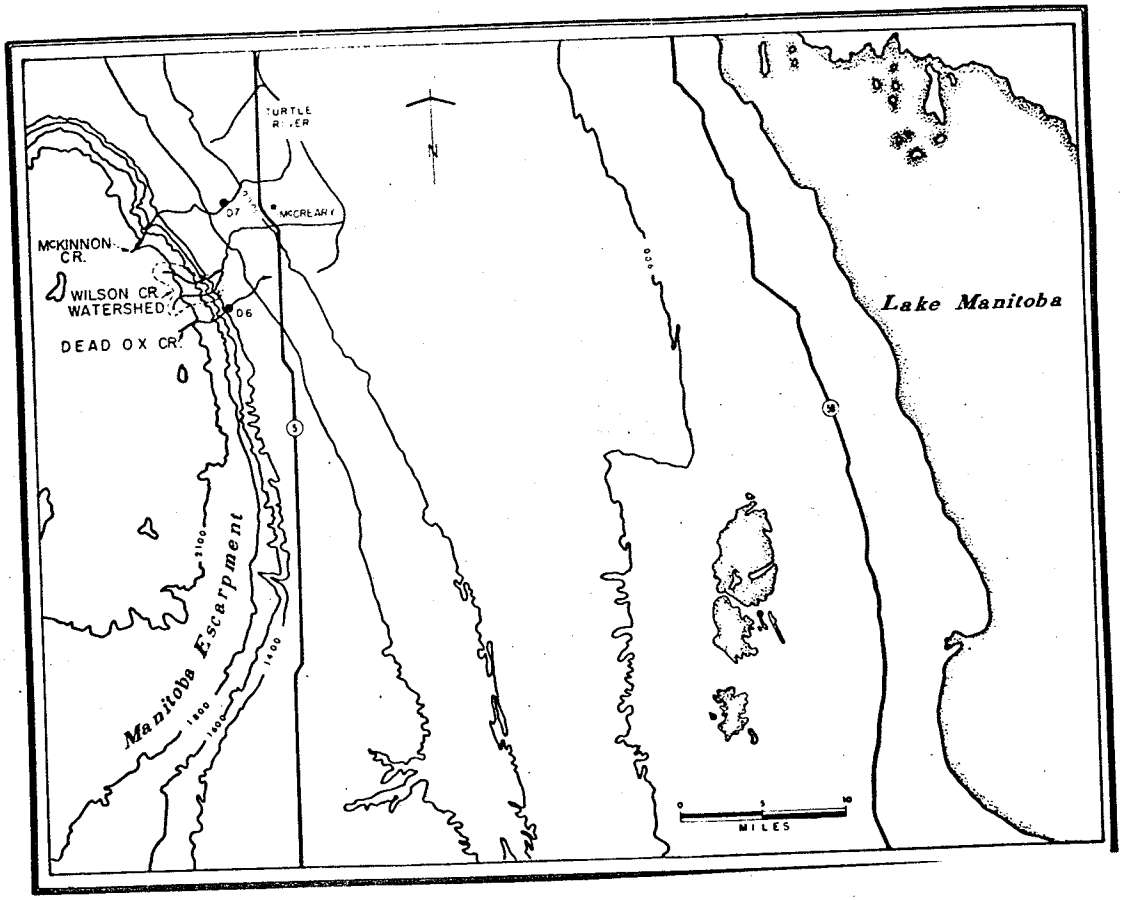

Fig. 1 Location of watershed and regional physiography.

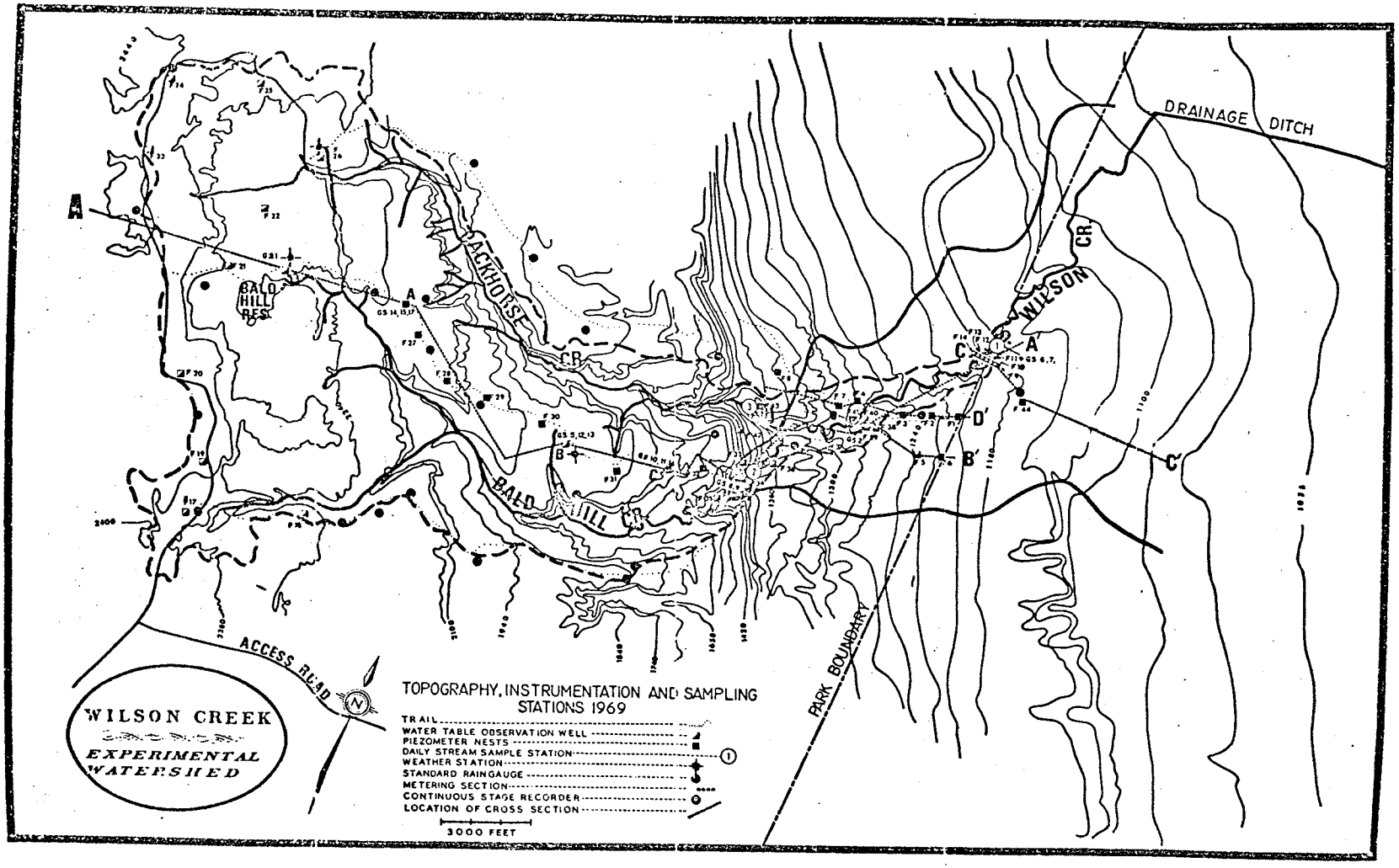

Fig. 2 Topography and location of instrumentation.

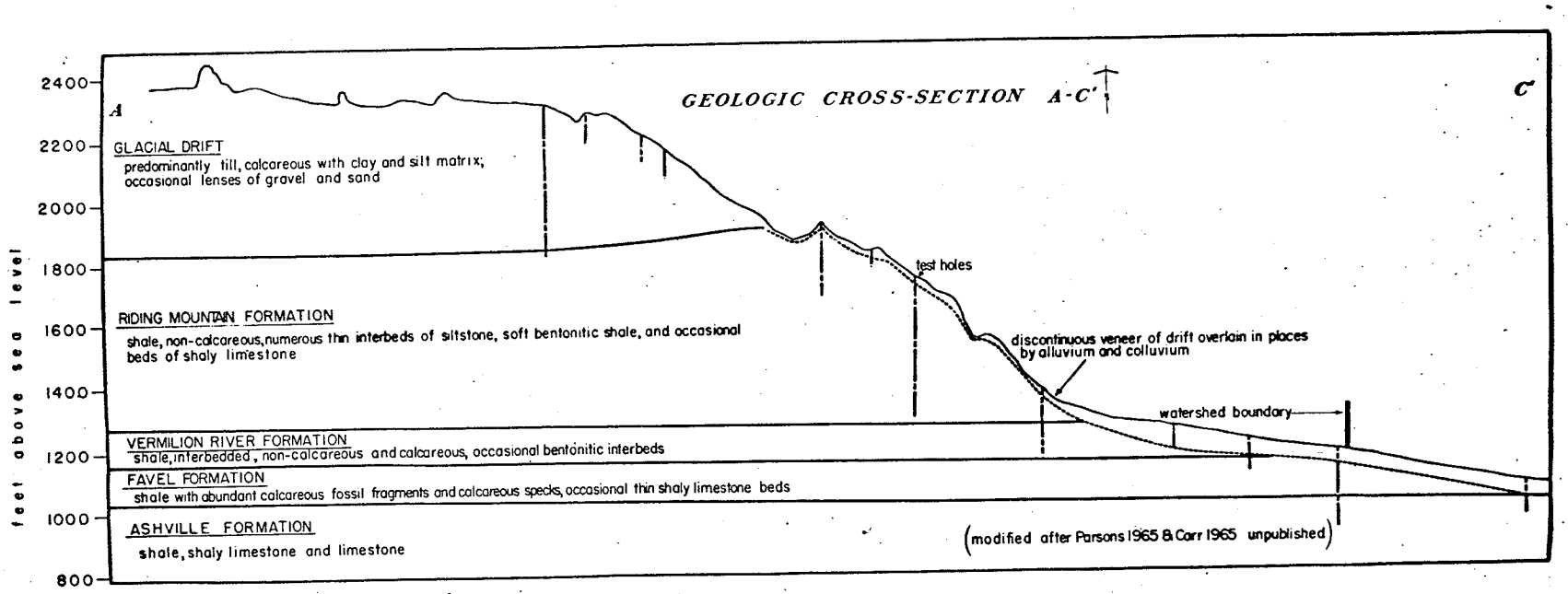

Fig. 3 Geologic cross-section through the watershed.

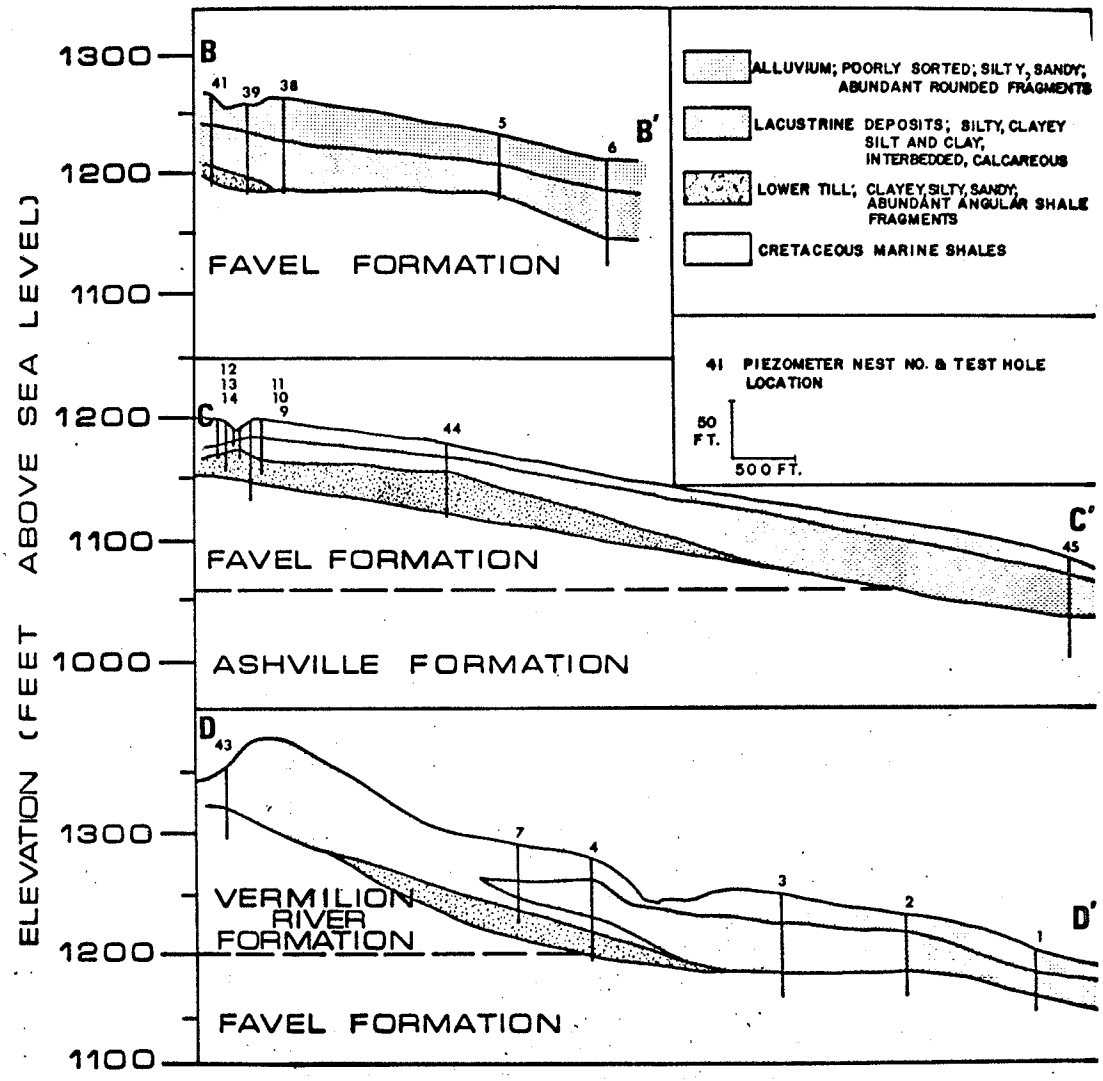

Fig. 4 Three detailed geologic cross-sections through the lower reaches of the watershed.

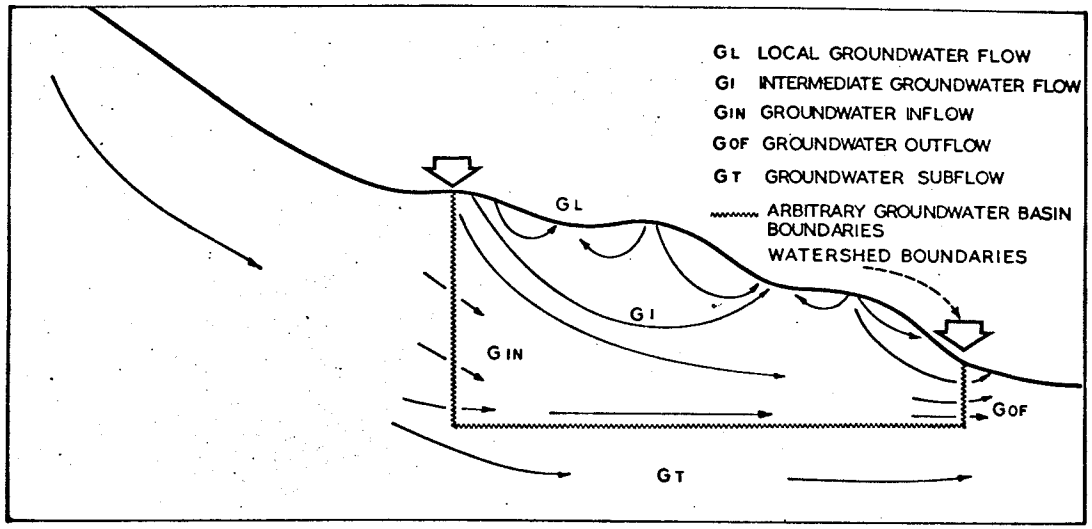

Fig. 5 Conceptual groundwater model of an open watershed system.

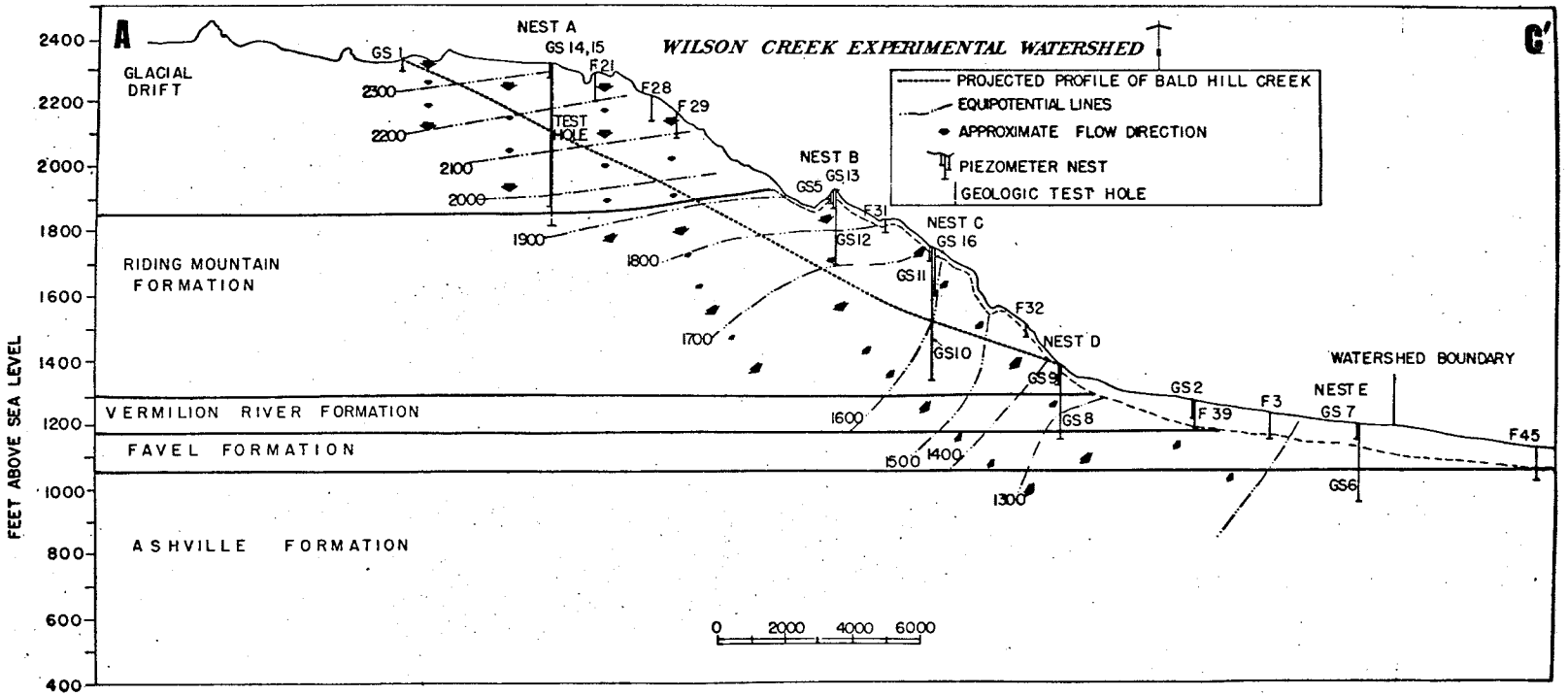

Fig. 6 Longitudinal flow pattern beneath uplands.

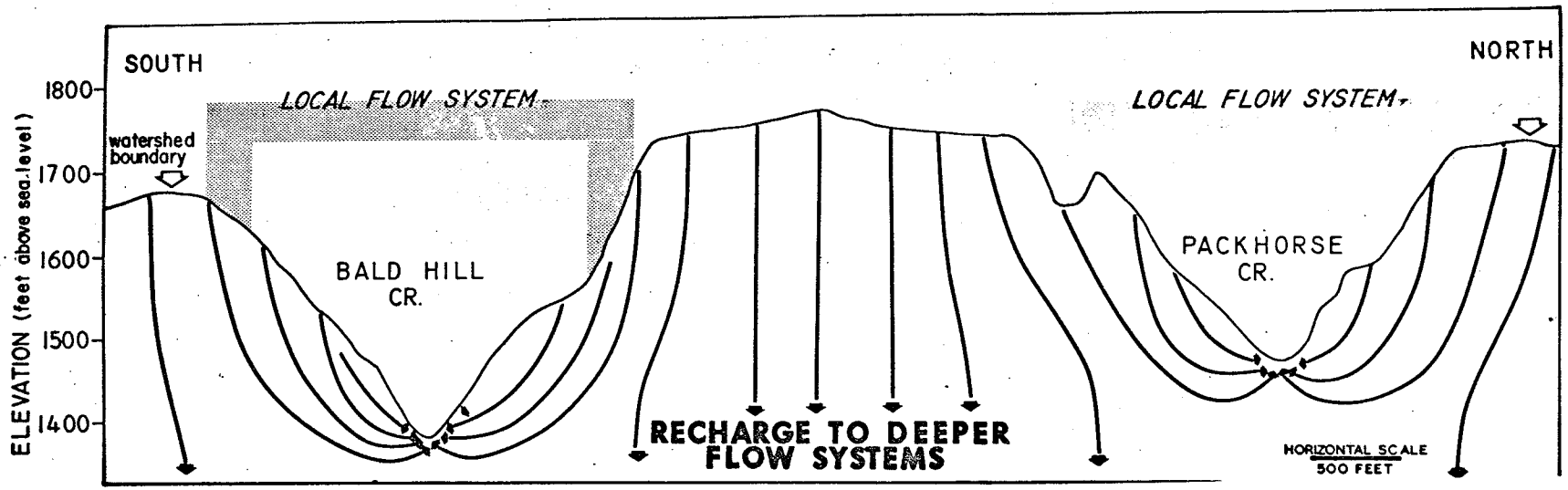

Fig. 7 Schematic interpretation of groundwater flow pattern in a section transverse to valley trends.

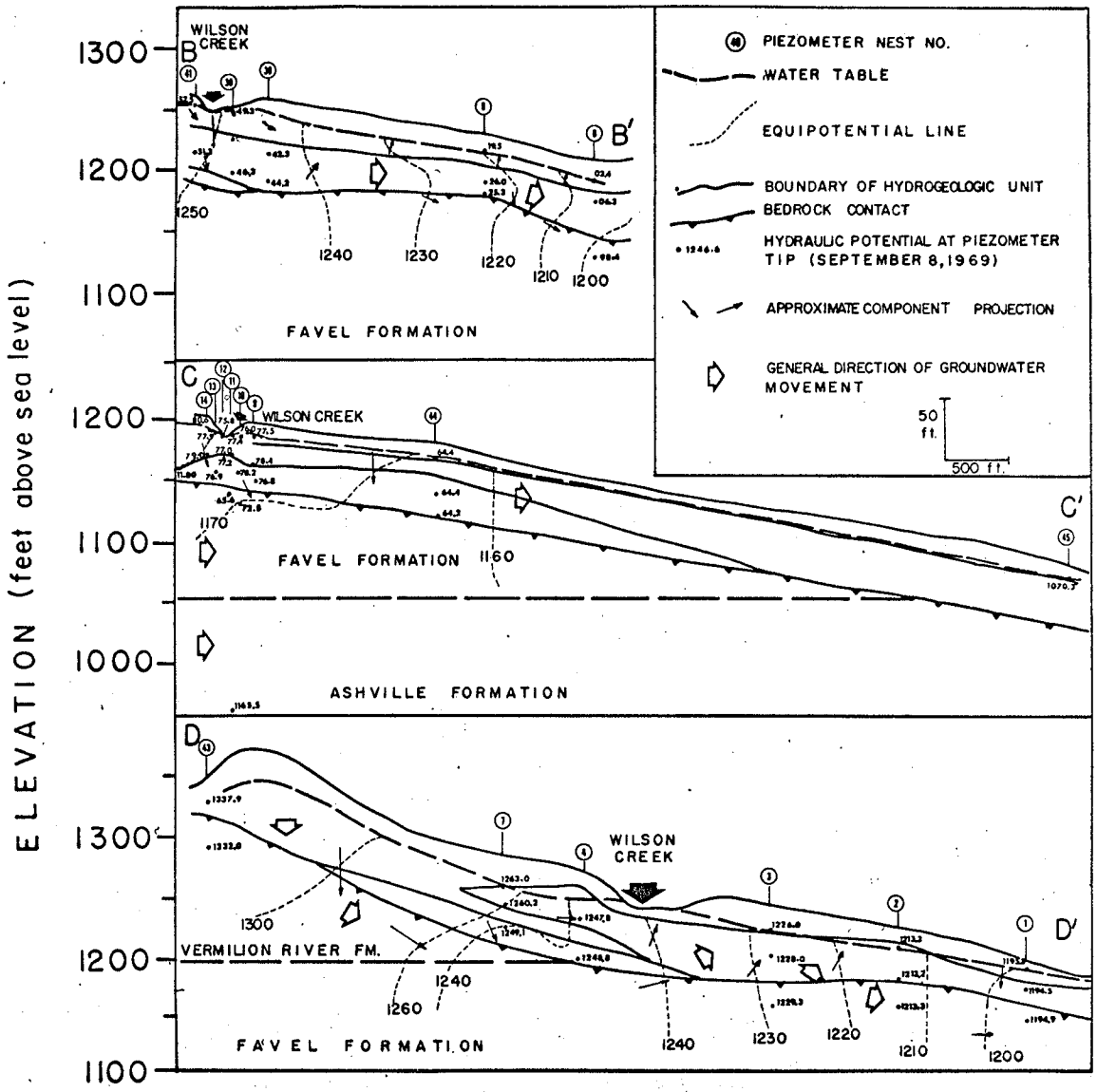

Fig. 8 Three geohydrologic cross-sections through lower reaches of the watershed.

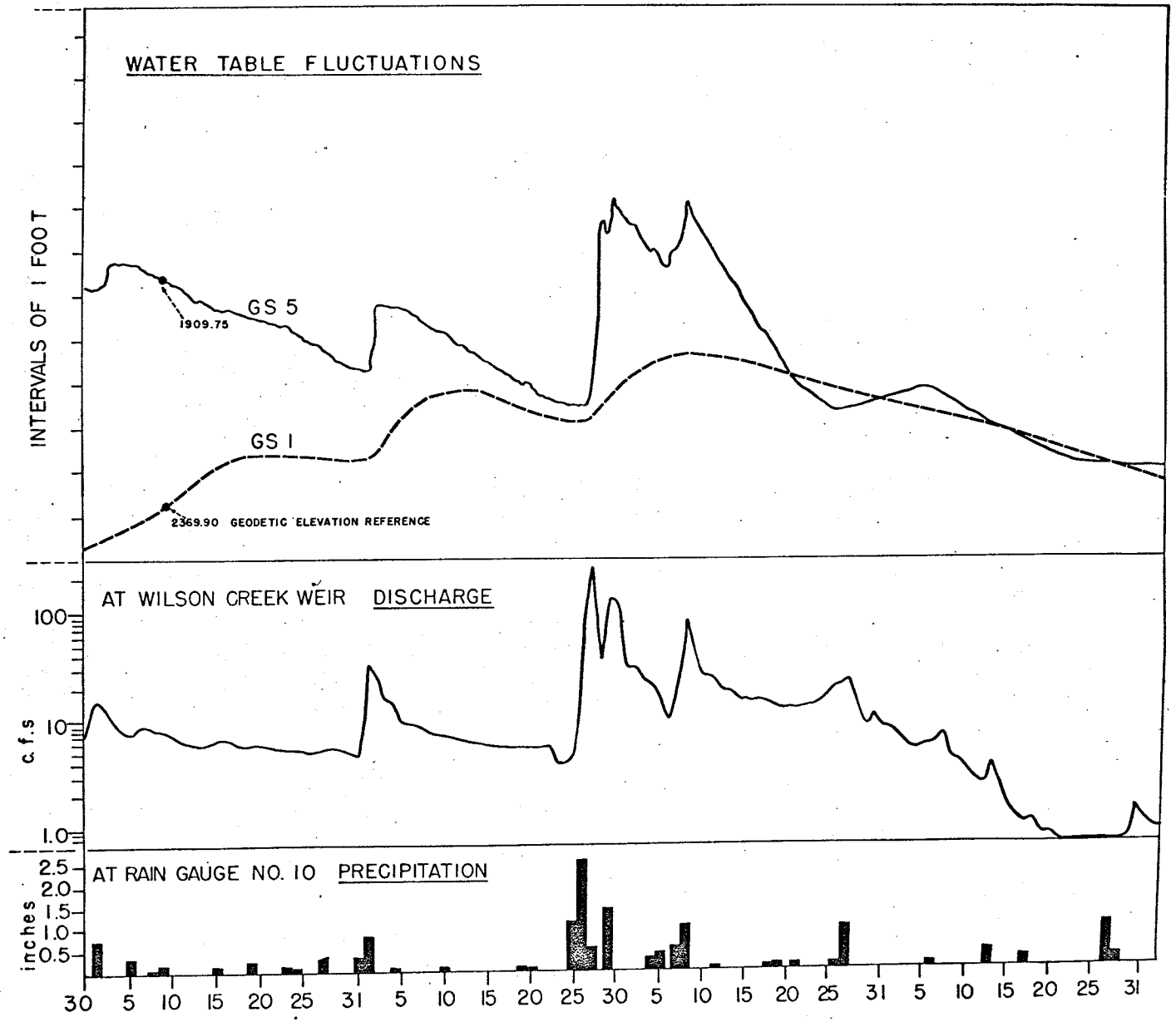

Fig. 9 Water table fluctuations in upper glacial drift and Riding Mountain formation.

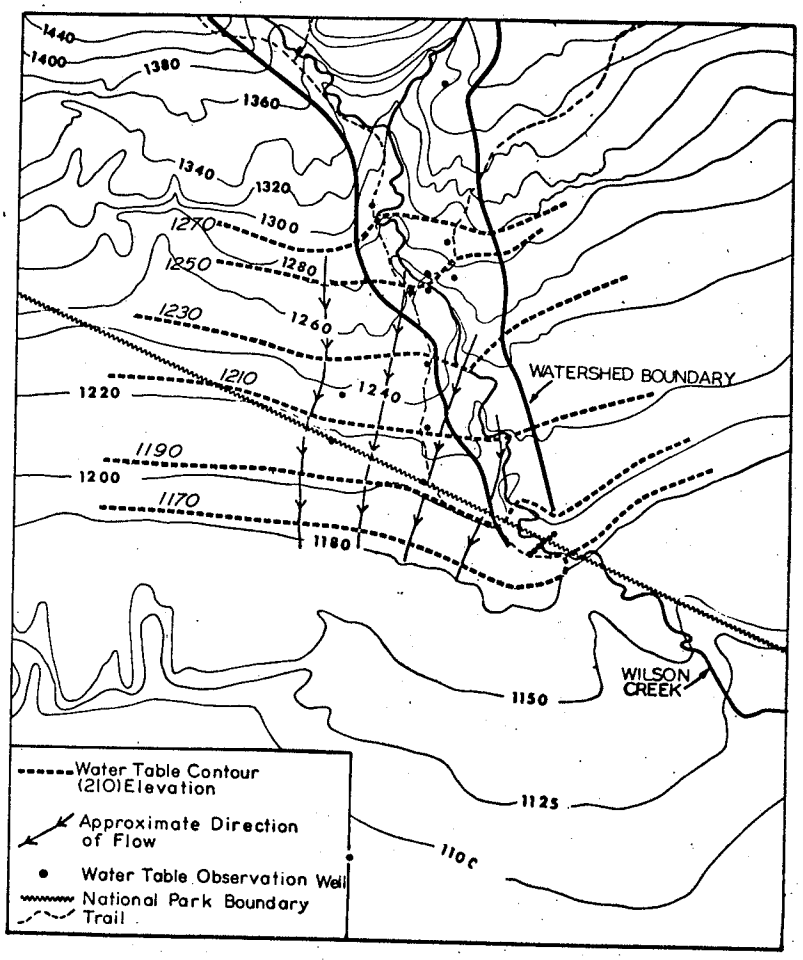

Fig. 10 Interpretation of water table contours and flow lines as basis of outflow computations.

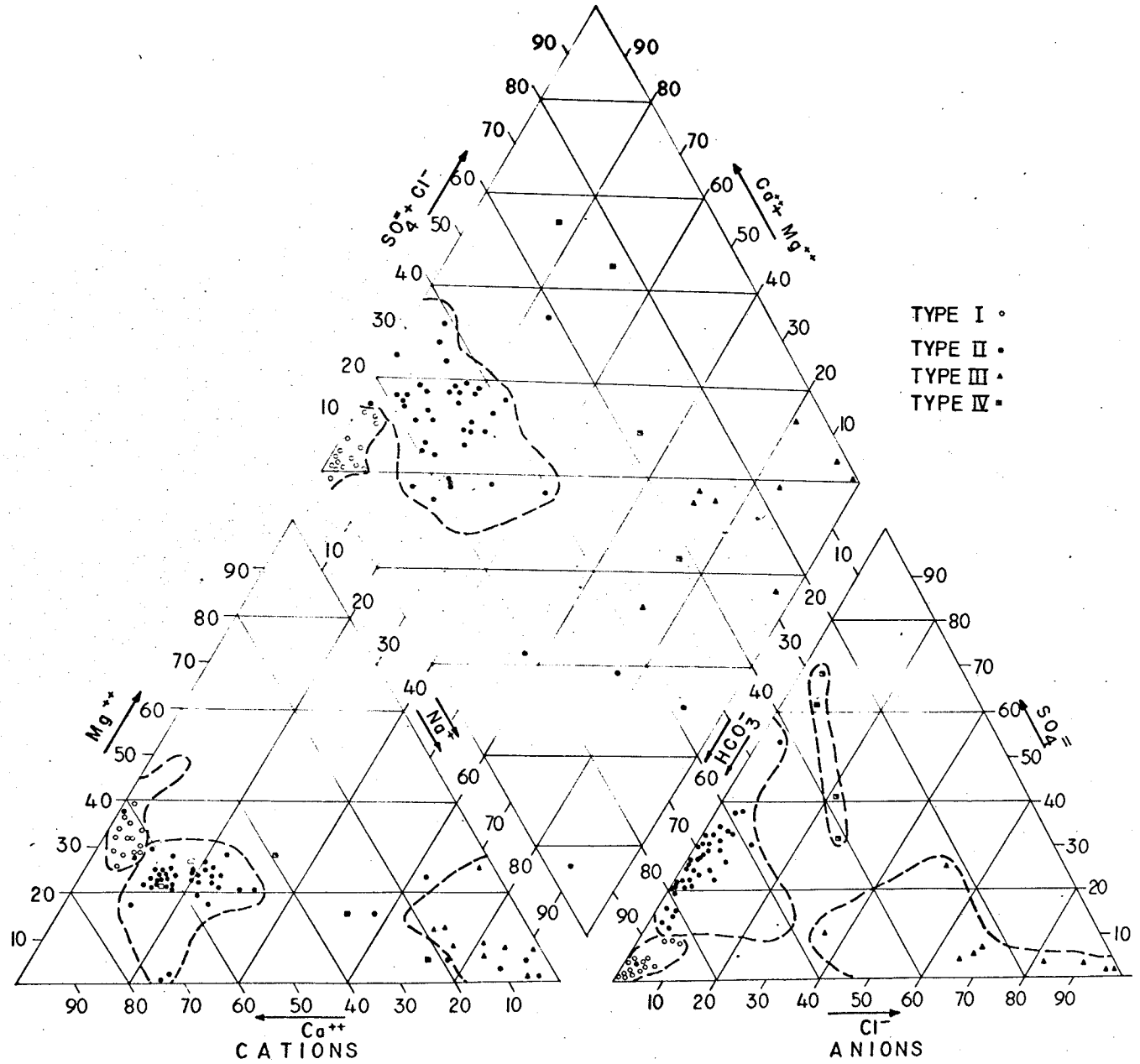

Fig. 11 Piper diagram of hydrochemical facies

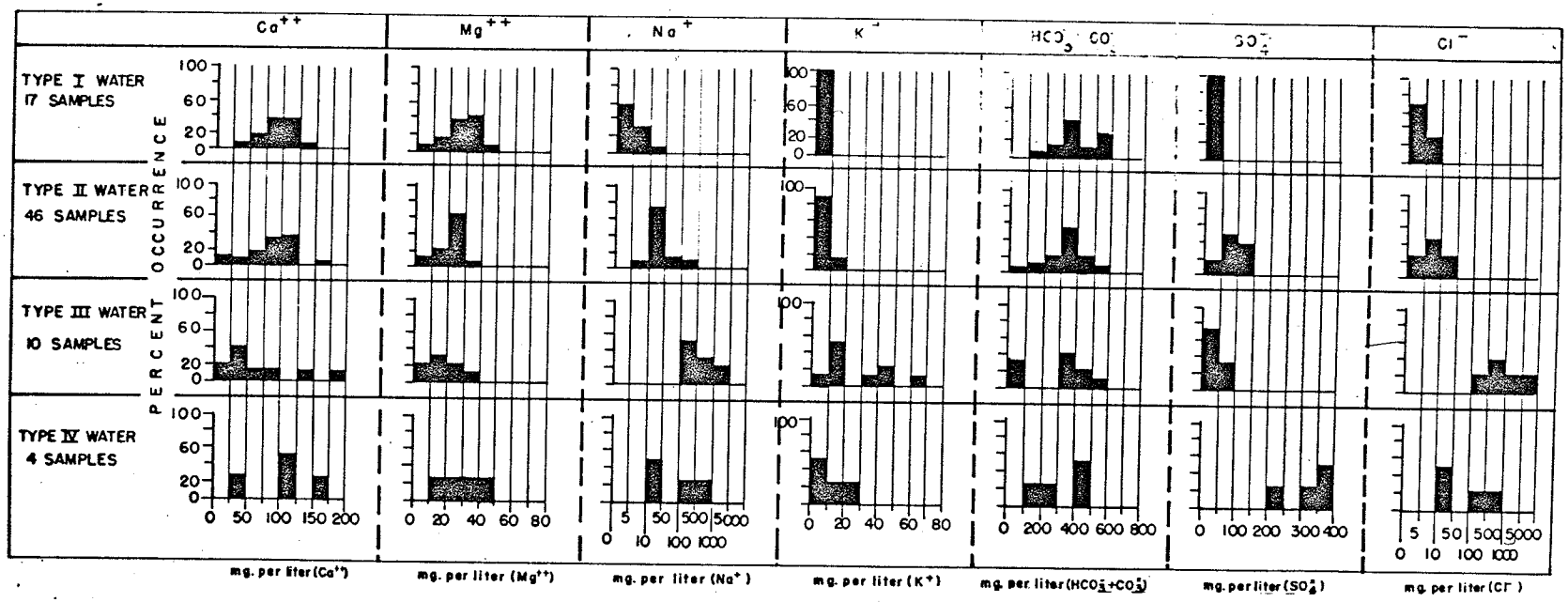

Fig. 12 Histogram summary of cation and anion concentrations in water types I-IV.

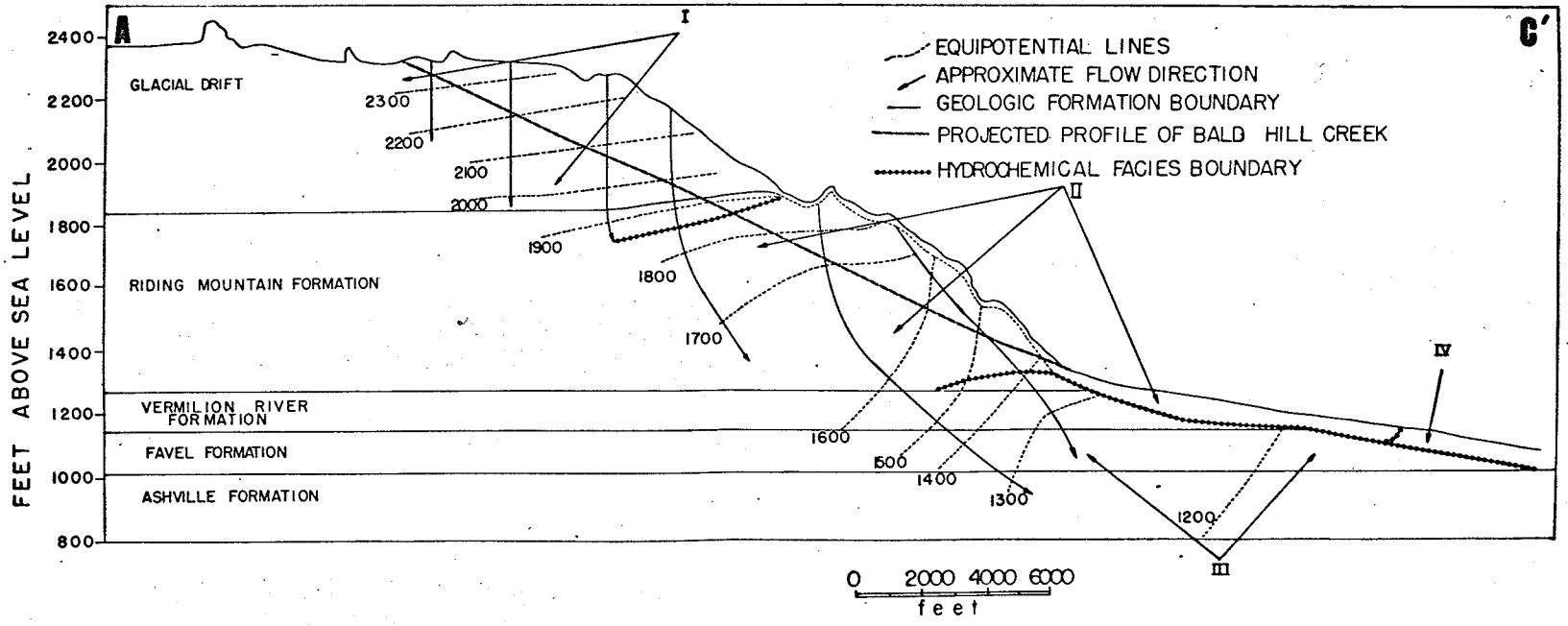

Fig. 13 Location of hydrochemical facies in cross-section

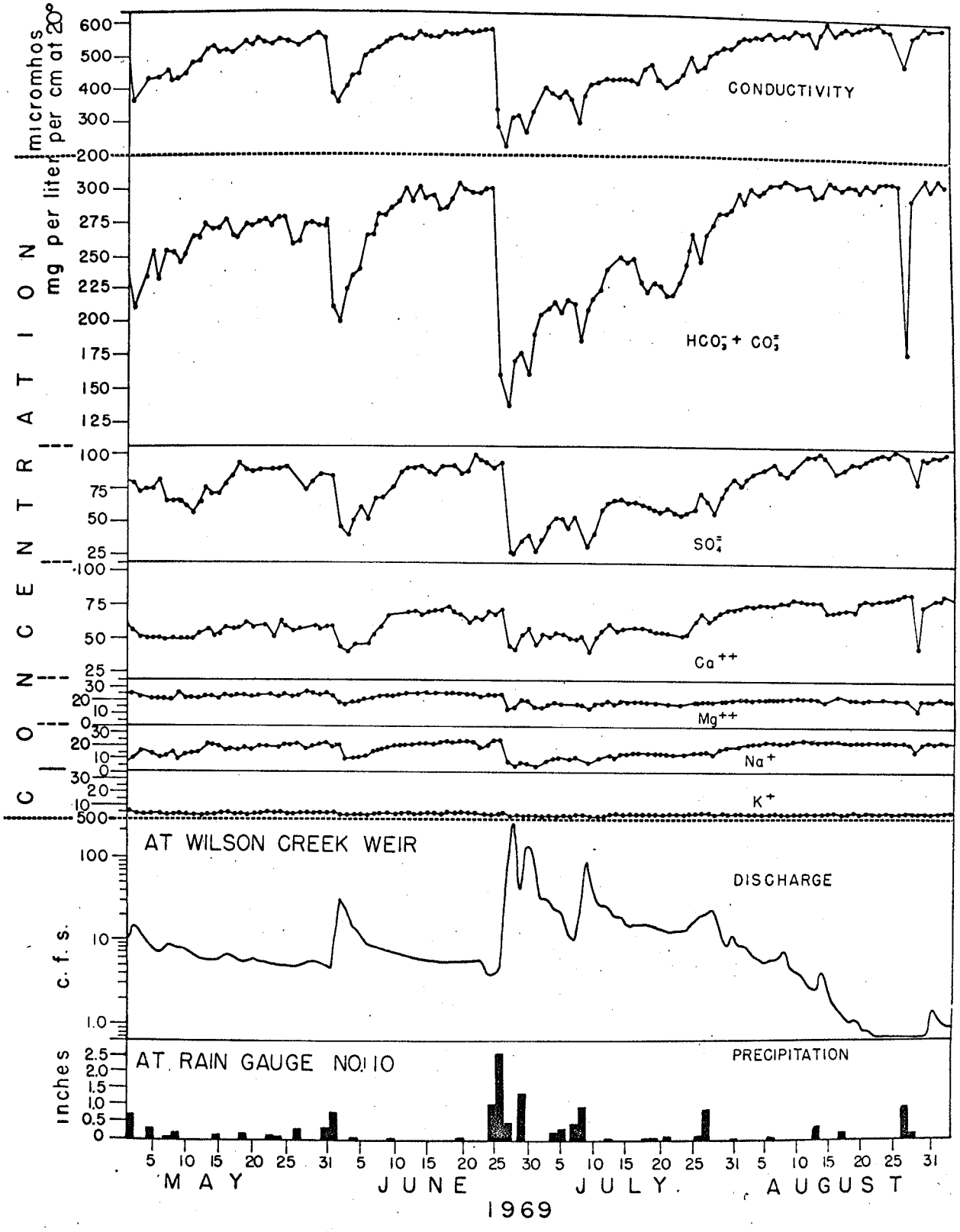

Fig. 14 Time variation of ionic concentration and conductivity of streamflow at Wilson Creek Weir.

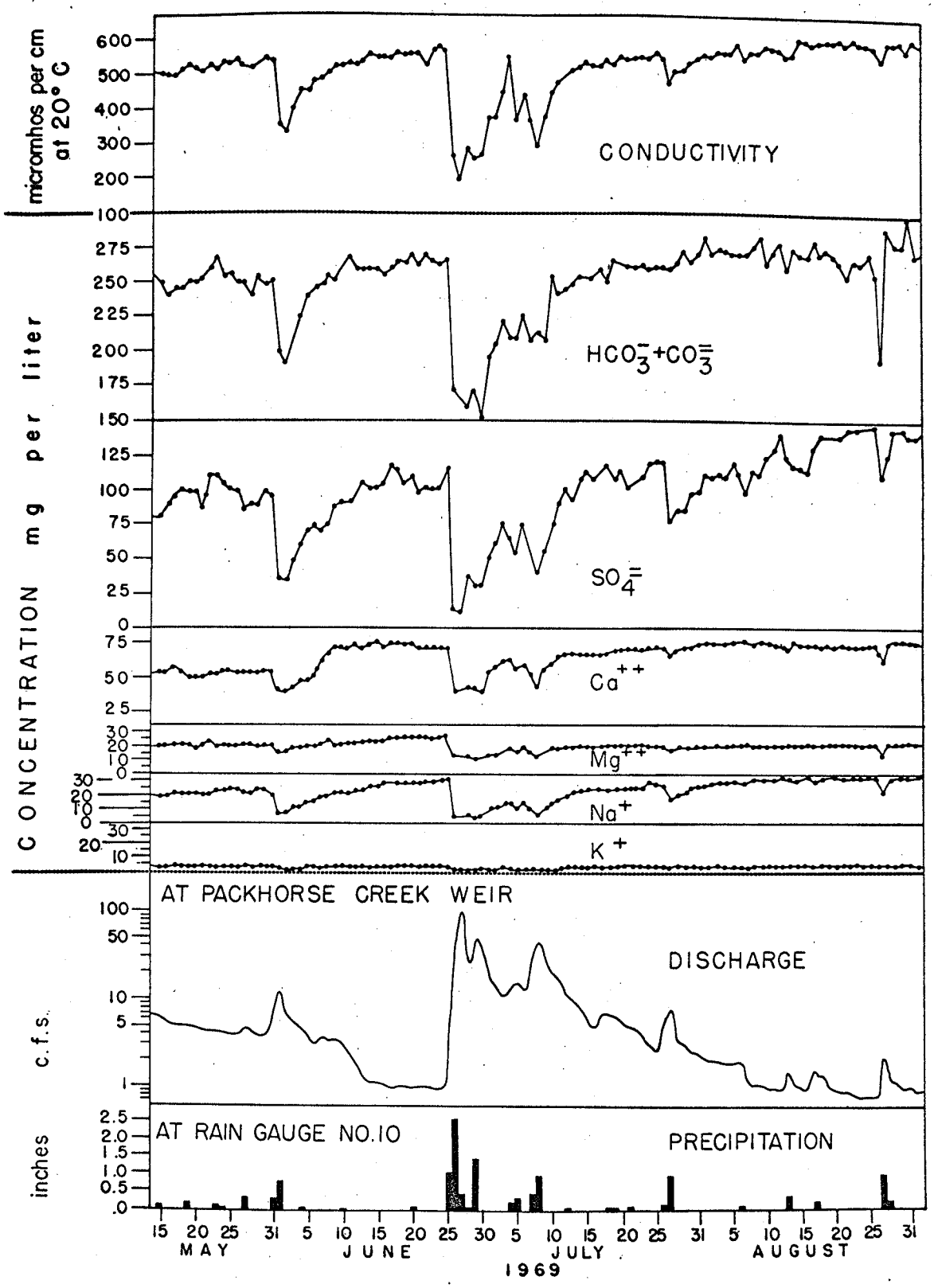

Fig. 15 Time variation of major ion concentration and conductivity of streamflow at Packhorse Weir

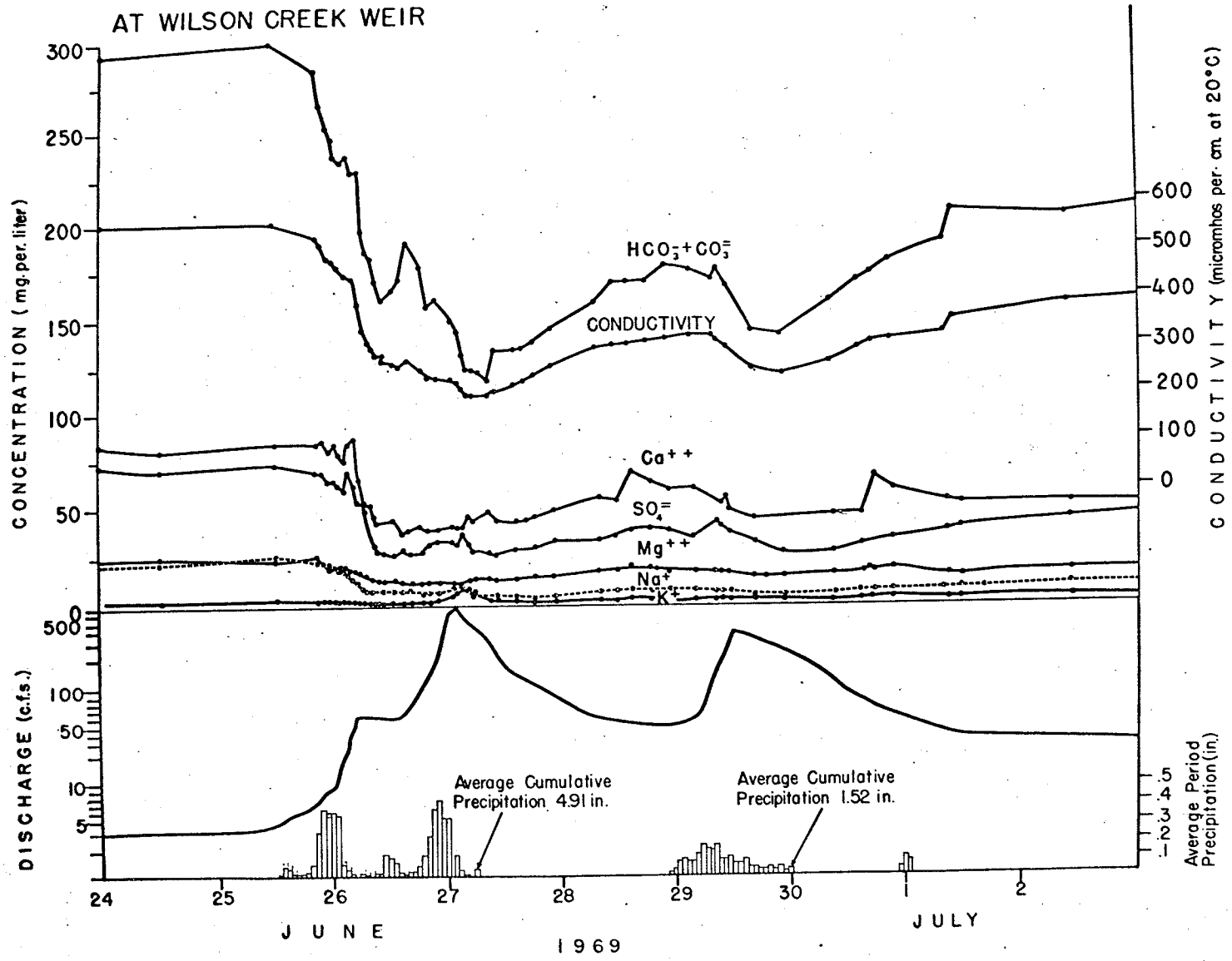

Fig. 16 Time variation of major ion concentration and conductivity for Wilson Creek during major storm.

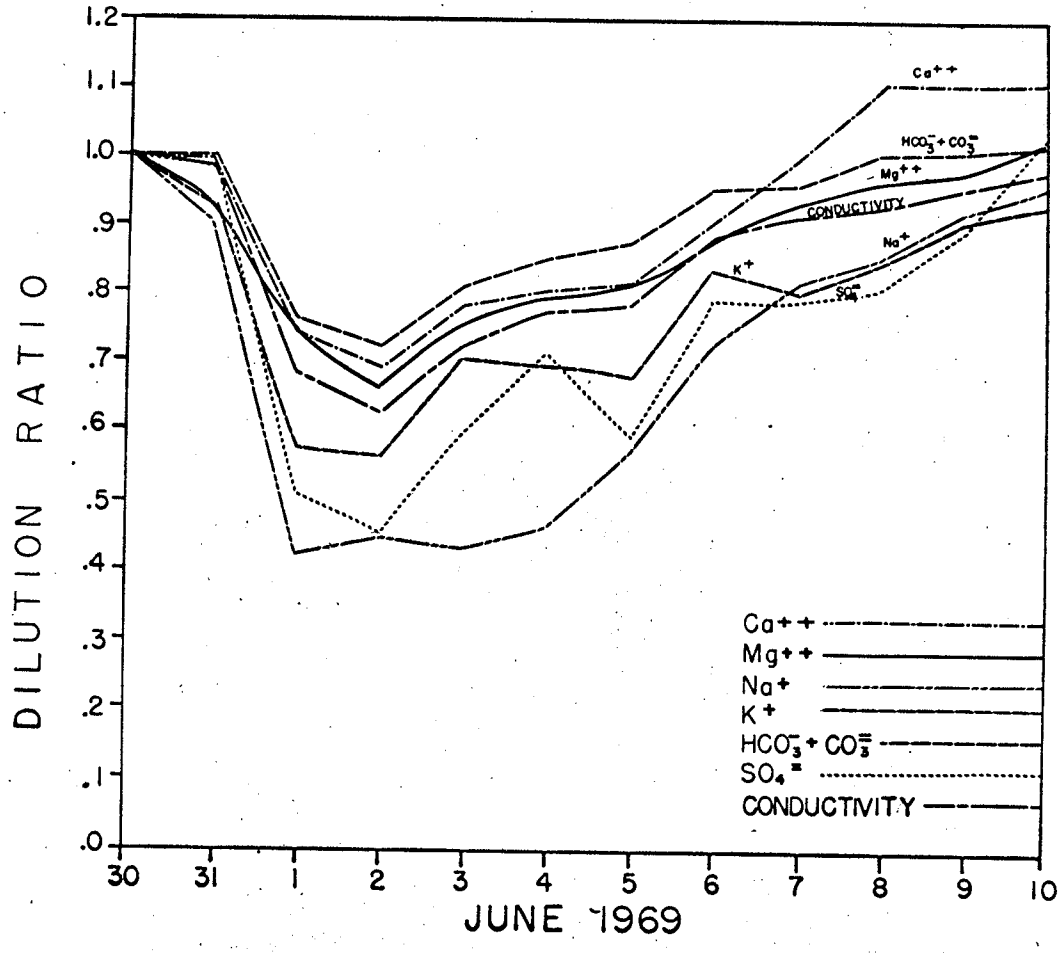

Fig. 17 Time variation of major ion and conductivity dilution ratios for Wilson Creek (May 30 to June 10).

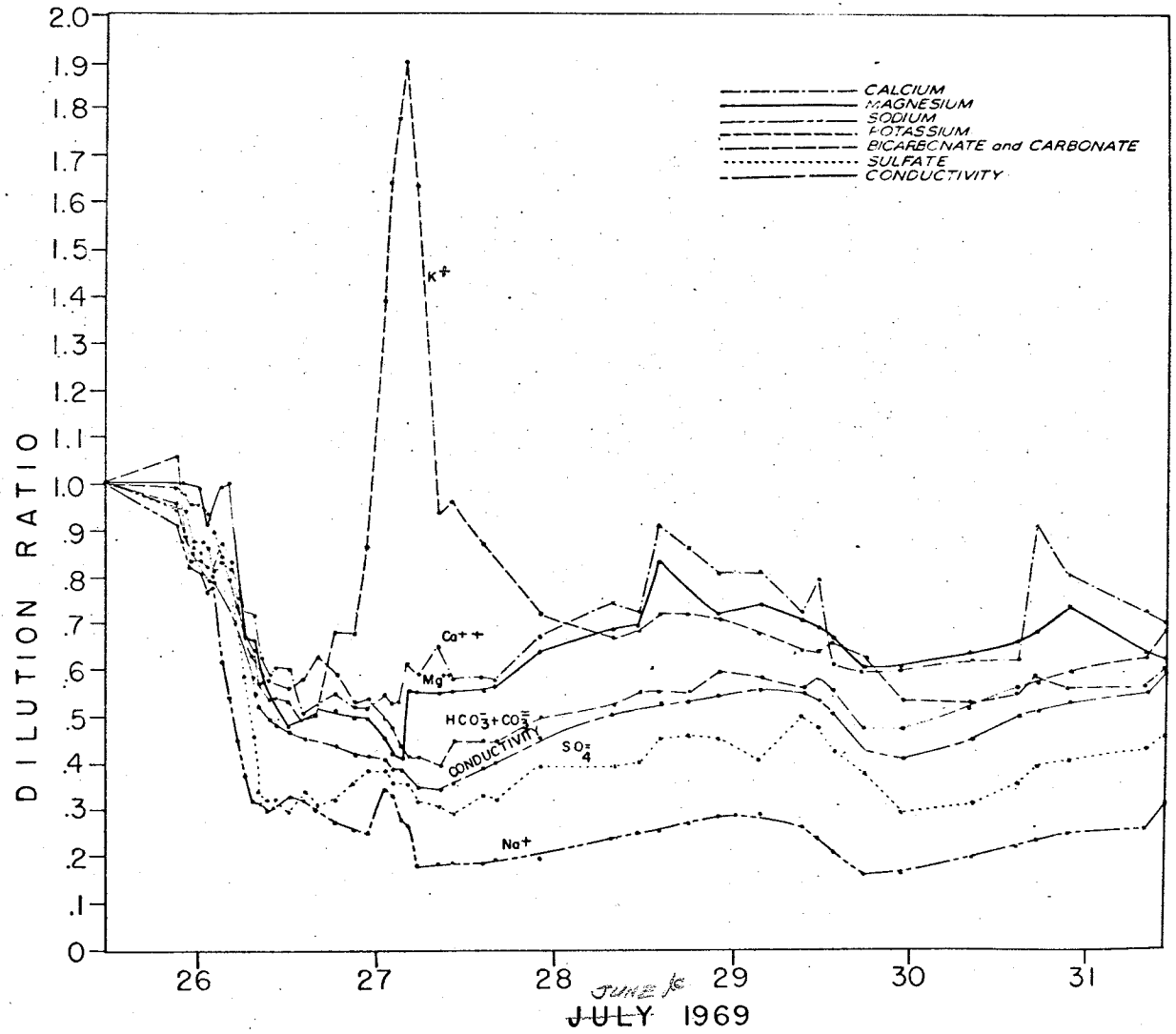

Fig. 18 Time variation of major ion and conductivity dilution ratios for Wilson Creek (June 25 to July 1).

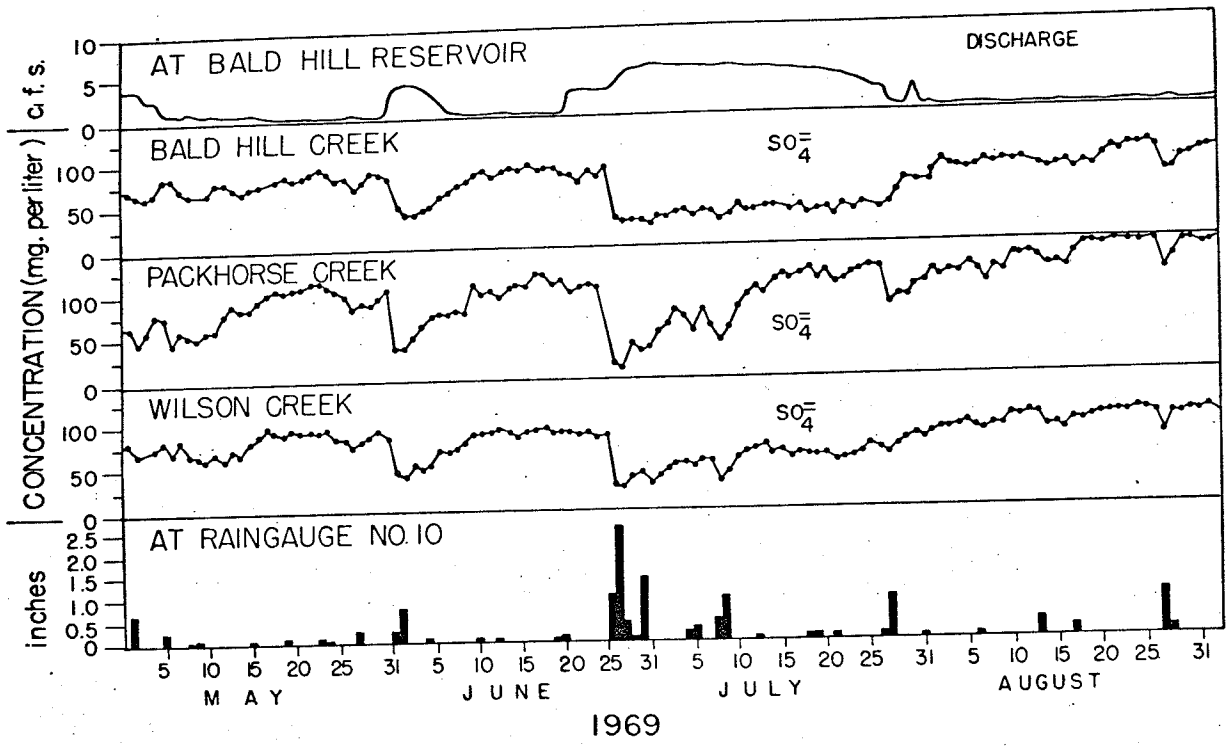

Fig. 19 Effect of Bald Hill reservoir on $SO_4^=$ concentration of Wilson Creek flow following major storm period.

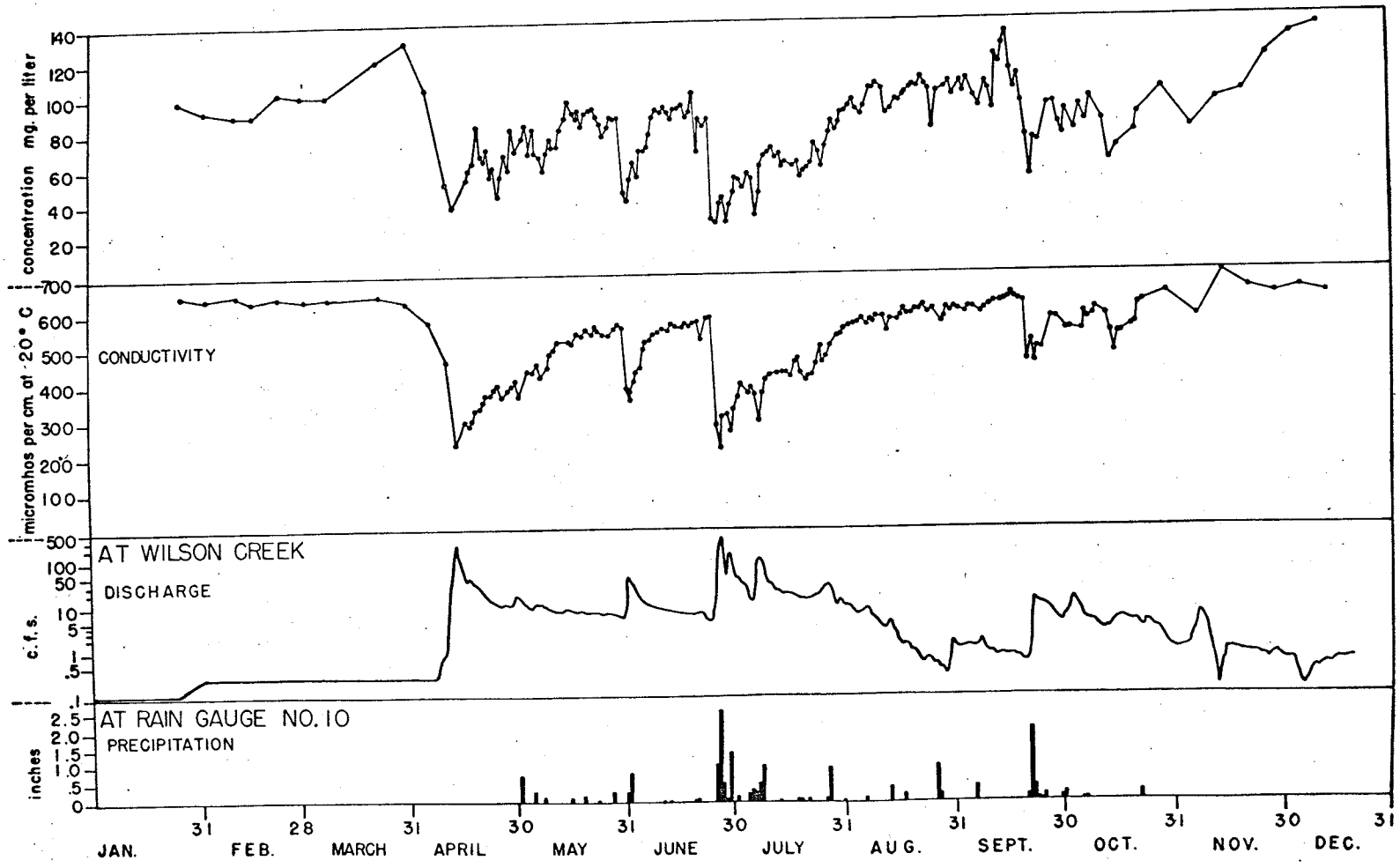

Fig. 20 Annual variation of $SO_4^=$ and conductivity, 1969.

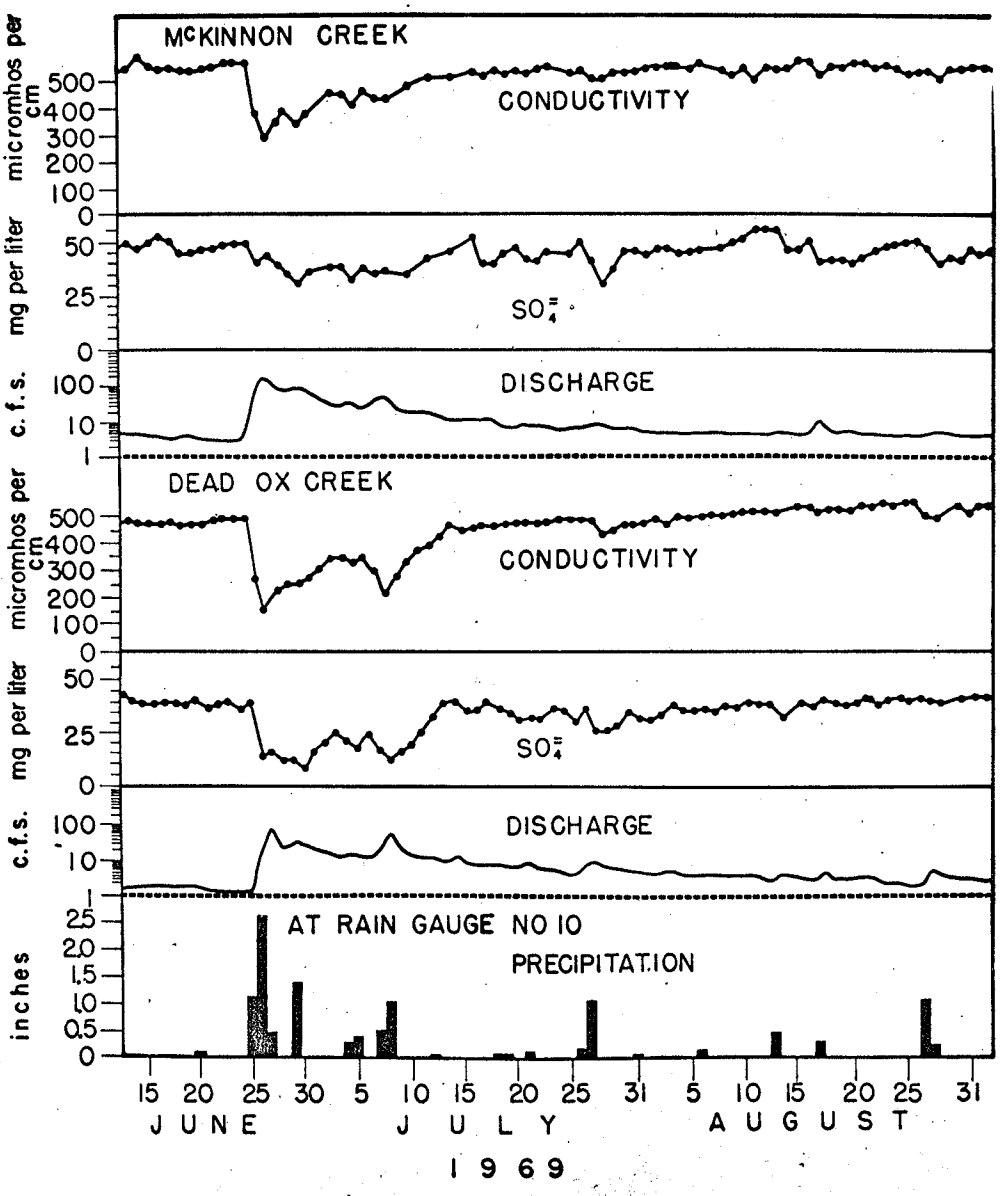

Fig. 21 Time variation of $SO_4^=$ concentration and conductivity for McKinnon and Dead Ox Creeks

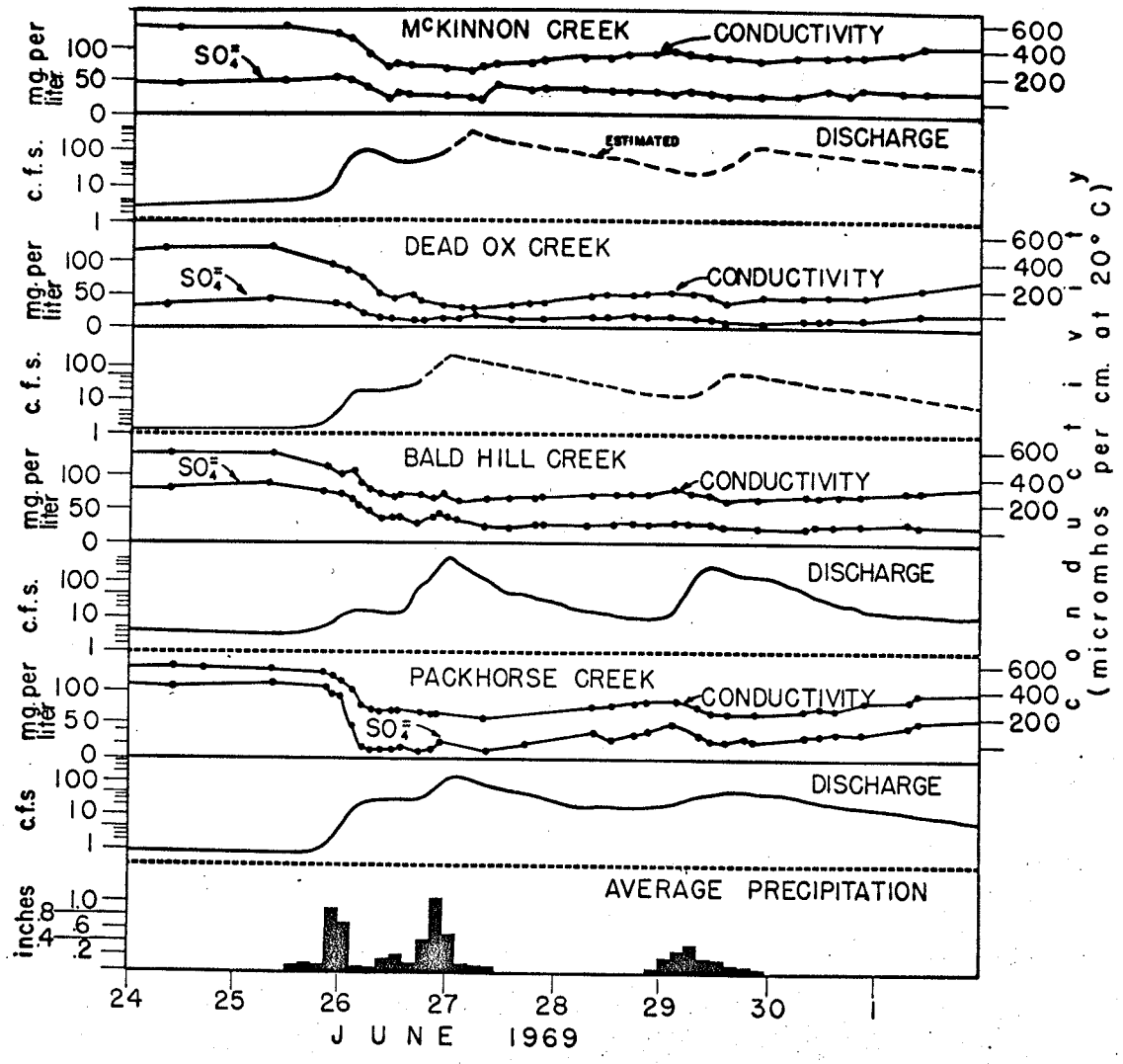

Fig. 22 Time variation of $SO_4^=$ concentration and conductivity for Packhorse, Bald Hill, Dead Ox and McKinnon Creeks.

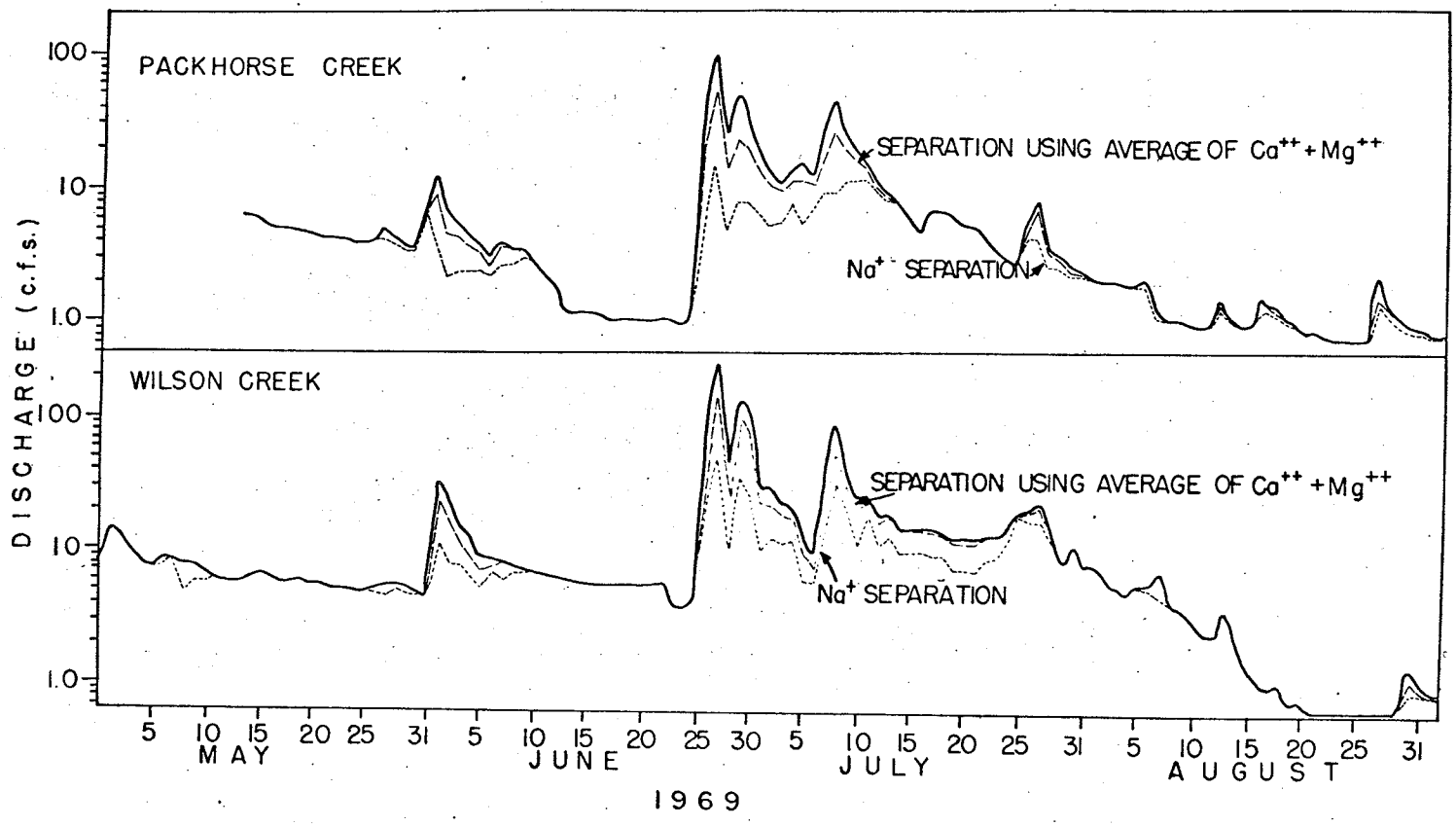

Fig. 23 Geochemical hydrograph separation for Wilson and Packhorse Creeks using Na^+, Ca^{++} and Mg^{++} average.

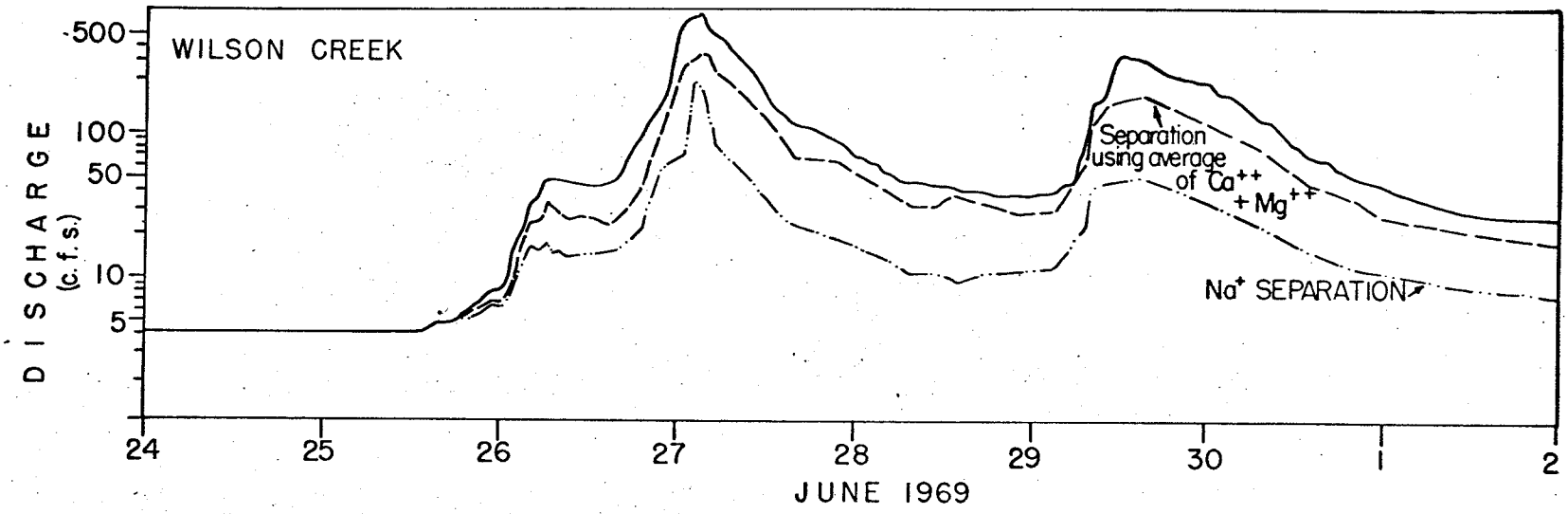

Fig. 24 Detailed geochemical hydrograph separation for Wilson Creek using Na^{+}, Ca^{++} and Mg^{++} average.

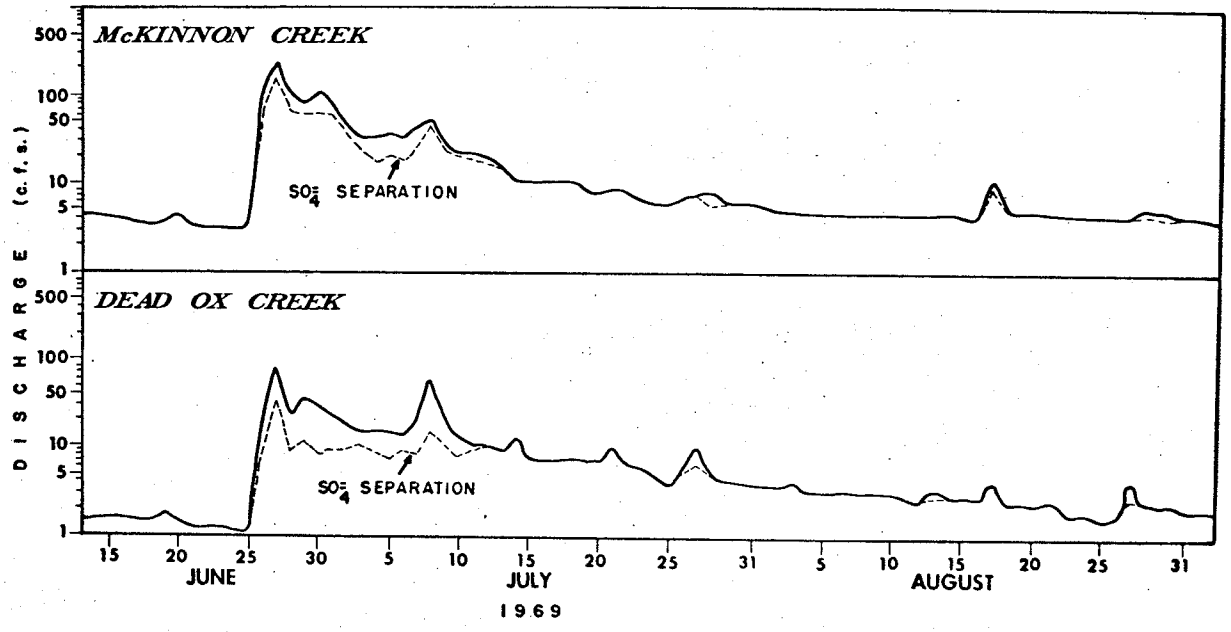

Fig. 25 Geochemical hydrograph separation for McKinnon and Dead Ox Creeks using $SO_4^=$ dilution.

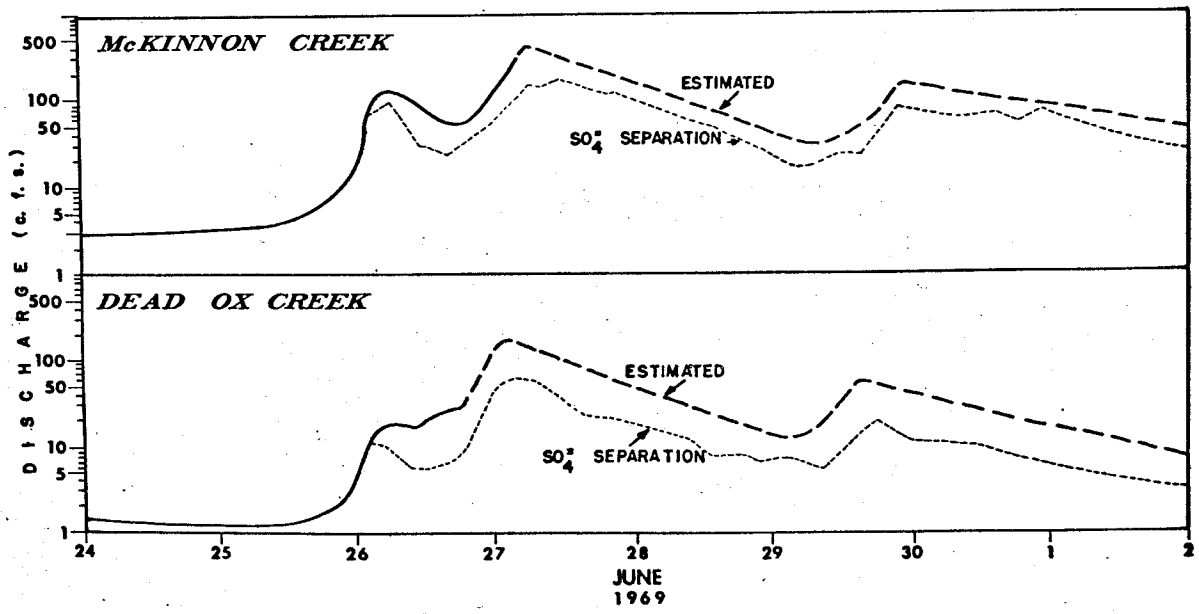

Fig. 26 Detailed geochemical hydrograph separation for McKinnon and Dead Ox Creeks using $SO_4^=$ dilution.

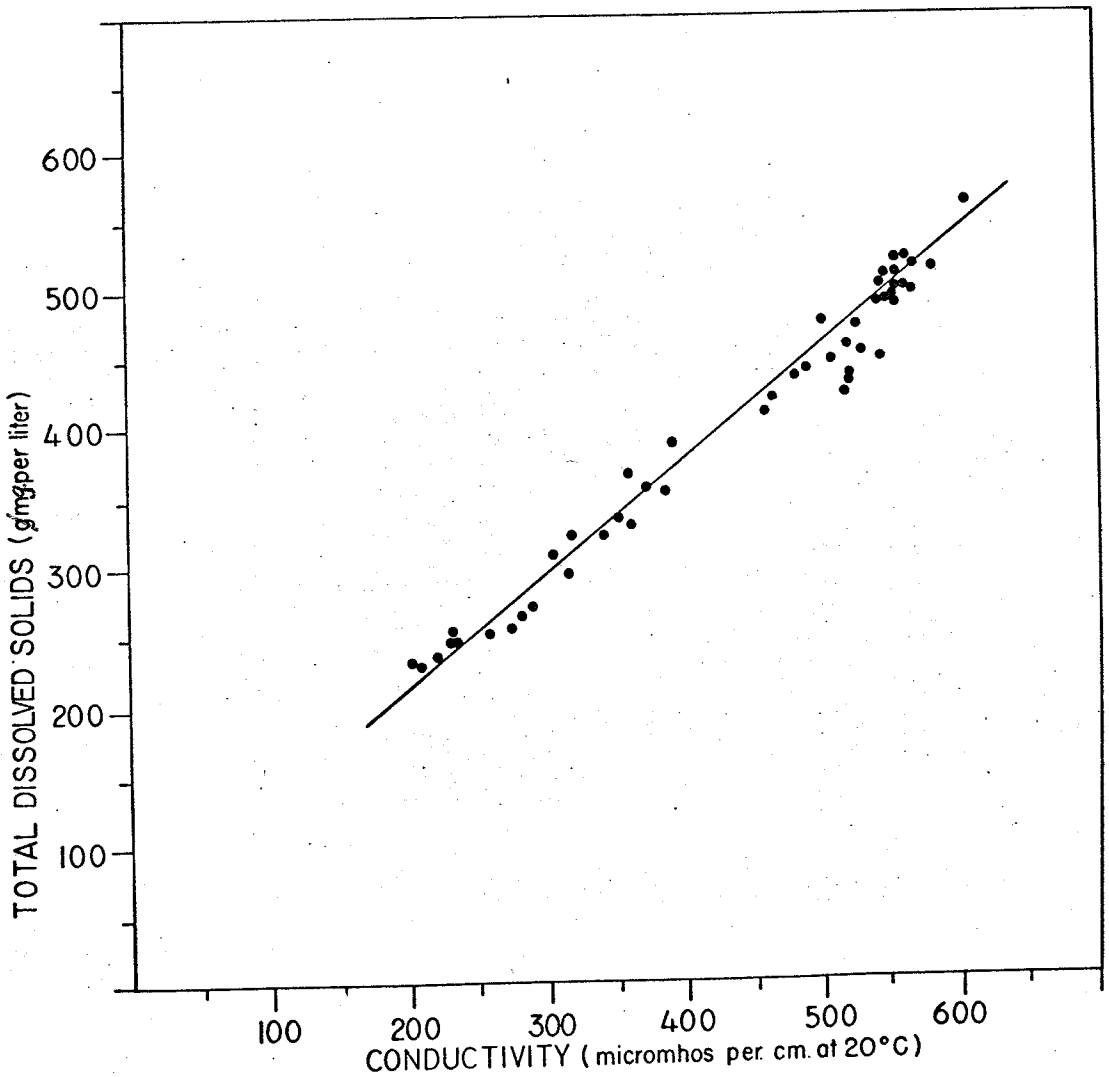

Fig. 27 Piezometer design.

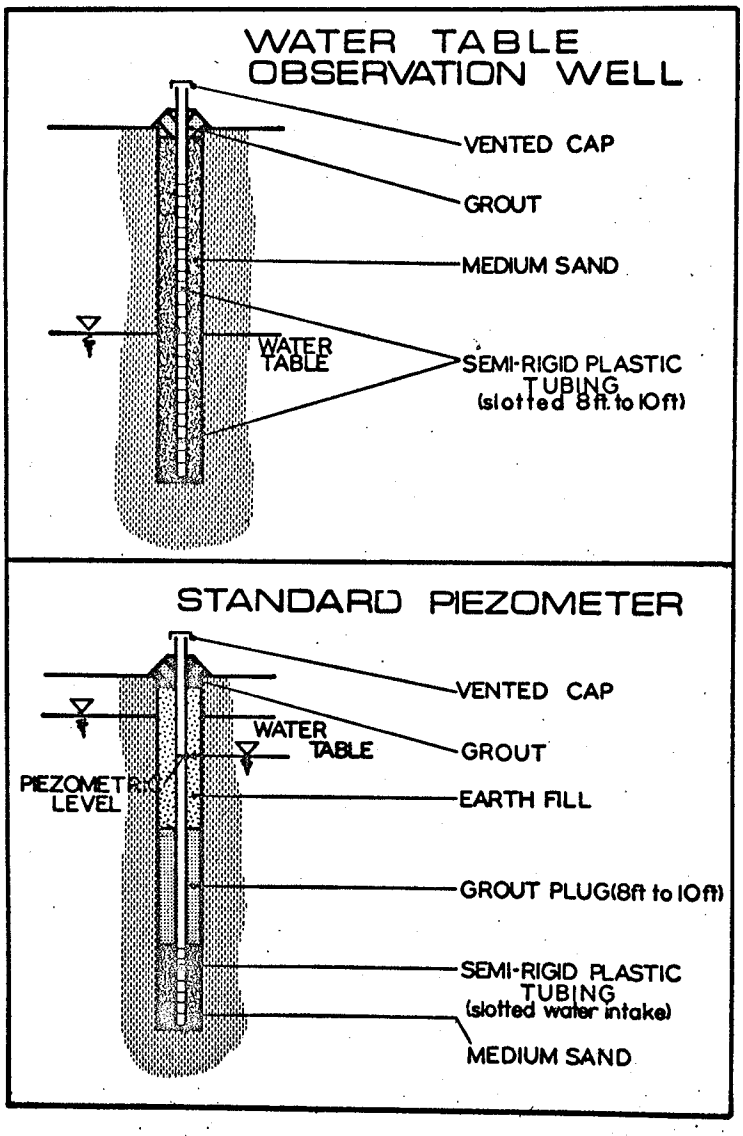

Fig. 28 Scatter diagram of total dissolved solids vs conductivity.

APPENDICES

A - G

APPENDIX A

Description of the stratigraphy and lithology of deposits in the lower reaches and east of the watershed

Oldest Pleistocene deposits in western Manitoba are Wisonsinan in age and consist of one to two tills overlying bedrock (Elson, 1967). Gradual retreat of the ice sheet and blockage of northward drainage resulted in formation of Glacial Lake Agassiz. Although evidenced in an area of nearly 200,000 square miles, the surface extent of any one phase of Lake Agassiz did not exceed 80,000 square miles (Elson, 1967).

Along the Manitoba Escarpment, near McCreary, Lake Agassiz strandlines are preserved. The Campbell beach is the highest found at a present elevation of 1120 feet above sea level in the vicinity of Wilson Creek watershed (Johnston, 1946). The Lower Campbell beach has an elevation of approximately 1080 feet above sea level in the same area (Johnston, 1946).

At the base of the escarpment a black (5 YR,2/1) compact silty clay till overlies shale bedrock. This unit sampled close to bedrock surface had a strong petroliferous odour. Overlying the till and underlying the alluvial deposits (Fig. 4), a thick sequence of waterlaid sediments was described consisting of well bedded silts with minor thinly interbedded clays. In general, the colour is a dark grey (5Y 3/1) but variations included olive grey (5Y 4/2), dark

grey (5Y 4/1) and dark greyish brown (10 YR 4/2). Because of their thickness, appearance and stratigraphic position, they appear to be lacustrine deposits of Glacial Lake Agassiz.

The thickness of Lake Agassiz sediments in the lower reaches of Wilson Creek is much greater than anticipated by Elson (1967) who described the near shore deposits along the base of the Manitoba Escarpment as an apron of silt a few feet thick and a dozen miles wide occuring downslope from the areas of wave action as indicated by terraces. Within Wilson Creek watershed, all sediments attributed to deposition in Lake Agassiz are found 10 to 110 feet above the elevation of the highest known beach. However, these deposits nowhere outcrop.

A process of alluvial fan formation has persisted, at least since the deposition of Lake Agassiz sediments, blanketing them to a maximum depth of approximately 35 feet (Fig. 4). In general, the alluvium is variably sorted with silt-size material predominating. Sub-rounded, silicerus shale fragments are common.

Appendix B

Piezometer locations, design and test hole logs

Piezometer No.	Elevation	Length of pipe feet	# of feet slotted	diam. of hole inches
F1-1	1204.25	23	3	3
F1-2	1204.01	13	7	3
F1-3	1203.46	50.	5	6
F2-1	1230.57	18	9	3
F2-2	1230.59	23	3	3
F2-3	1230.61	42	3	3
F2-4	1230.31	66.7	5	6
F3-1	1247.07	40	3	3
F3-2	1247.45	32	15	3
F3-3	1247.74	80	5	6
F4-1	1276.53	40	3	3
F4-2	1274.85	72.2	3	6
F5-1	1231.00	40	3	3
F5-2	1231.00	21	15	3
F5-3	1231.42	31	11	6
F5-4	1232.02	49	5	6
F6-1	1213.17	30	3	3
F6-2	1213.45	16.5	11	3
F6-3	1213.66	80	5	6
F7-1	1290.35	42.5	3	3
F7-2	1289.56	28	6	3
F7-3	1289.86	59	5	6
F8-1	1347.76	34.6	3	6
F8-2	1347.76	20	10	6
F8-3	1347.90	56.8	5	6
F9-1	1193.44	40	3	3
F9-2	1193.35	32	10	3
F9-3	1193.55	51.6	5	6
F10-1	1186.86	39	3	3
F10-2	1186.86	19.9	10	3
F10-3	1186.85	65.	5	6
F11-1	1179.38	11	7	3
F11-2	1180.19	20	3	6
F12-1	1179.64	24.3	3	3
F12-2	1180.02	14.5	10	3

Piezometer No.	Elevation	Length of pipe feet	# of feet slotted	diam. of hole inches
F13-1	1183.53	39.80	3	3
F13-2	1183.48	20	10	3
F14-1	1194.61	31.9	3	3
F14-2	1194.61	21.5	13	3
F17-1	2395.91	27	15	3
F18-1	2368.14	23	15	3
F19-1	2426.95	31	15	3
F20-1	2455.09	28	12	3
F21-1	2387.73	28	10	3
F22-1	2356.61	31	15	3
F23-1	2420.94	14.1	9	3
F24-1	2484.70	25.5	17	3
F25-1	2389.75	23.3	19.9	3
F26-1	2348.84	26.3	12.5	3
F27-1	2270.19	9	6	3
F27-2	2268.67	25.5	3	6
F27-3	2289.99	65.3	5	6
F27-4	2302.05	29.6	3	6
F28-1	2188.47	20	10	6
F28-2	2188.41	40	3	6
F28-3	2188.19	81.4	5	6
F29-1	2013.34	20	10	6
F29-2	2013.63	40	3	6
F29-3	2014.90	47.6	5	6
F30-1	1901.90	38	3	6
F30-2	1901.80	20	10	6
F31-1	1865.15	-	3'	6
F31-2	1865.80	-	3	6
F32-1	1585.47	25.2	3	6
F32-2	1585.47	9	3	6
F32-3	1585.18	17	3	6
F33-1	1432.20	19.7	15	3
F34-1	1362.97	20	20	6
F35-1	1402.52	20	20	6
F36-1	1328.31	20	20	6
F39-1	1257.13	18.1	15.2	6
F39-2	1257.29	58.2	5	6
F39-3	1257.27	20	3	6

Piezometer No.	Elevation	Length of Pipe Feet	# of feet slotted	diam. of hole inches
F37-1	1288.06	20	8	6
F38-3	1260.79	68.4	5	6
F38-1	1261.15	18	9	6
F38-2	1261.13	45.2	3	6
F40-1	1254.12	20	20	6
F41-1	1261.70	20	15	6
F41-2	1261.65	41.8	5	6
F42-1E	1373.11	27	3	3
F42-2W	1373.05	30.8	5	6
F43-1	1350.07	20	14	6
F43-2	1350.07	55.6	5	6
F44-1	1176.00	19	10	6
F44-2	1176.00	40	3	6
F44-3	1176.00	59	5	6
F45-1	1080.00	25	5	6

TEST HOLE LOGS

Monday, July 7, 1969
1:50

F10-3

0-13' sandy, gravely, alluvium, abundant stones, poorly sorted.

13-23' grey, silty clay, lacustrine

23-36' stoney, silty till becoming at 27' very clayey and stone free COLOR (5 YR 2/1) looks very impermeable.
10 YR 3/1

36-40' possible bedrock clay or silt lens

40-46 (sample taken here) -48' glacial till, very stiff, fairly stoney, w. clay & silt same color 5 YR 2/1 slightly more stones.
SMALL & LARGE SAMPLE
sample @ 46' has a dry appearance, very stiff, brittle when broken, fine-med. pebbles abundant.

[48-53-65' drilling is very stiff, could be very hard day,
[no stones.
[bedrock, no stones, clay rich, appears to be
[fossilate petroliferous
[
[53' Drilling slightly softer, no stones
[
[56' softer material, drilling easier, no stones
[
[65' depth of hole piez is slotted 5'

very dry in appearance looks like calcareous bonds of shale Favel Formation? SMALL SAMPLE

length of pipe in the hole 64.8'

Monday, July 7, 1969
11:35

F9-3

0-24' sandy, stoney alluvium, gravel size

24' lacustrine silt, greenish, occasional grits gerogenous, becoming less green - more grey, calcareous, less iron.
LARGE SAMPLE COLOR 5 Y 4/2 - but slightly more blueish

33-51' till? grey-black COLOR 10 YR 3/1
abundant coarse sand-sized pebbles, clayey, silty (clay rich.

45-50' lower portion of the till is sandy, with small pebbles, very little silt & clayey.

51-65' probably bedrock, very hard drilling
no! till instead.

1:30 p.m. - 2:20 p.m.

hole caved in about 10'
hole dug 65'
re drill hole to 65'
pipe slit 5'
pipe was 80'
cut off 28.4
length
of pipe 51.6'

2:30 By the Farm

F6-1	30' West
F6-2	16 1/2' East
F6-3	E.E.

F6-3

0-15' sandy, gravely, alluvium

15-33' grey-blue lacustrine silt with twigs of wood etc.
SMALL SAMPLE no stones, towards the last 10' very greasy & sticky, very fine, no stones, no plant material.

15-50' lake silt still LARGE SAMPLE (Bottom pieces of sample polluted)

July 7, 1969
2:30 By the Farm (Continued)

50 or 60' bedrock, possibly layered, hard and soft layers fine grained, non consolidated, petroliferous with calcite, carbonate spots and spotting, very dry. LARGE SAMPLE.

Hole dug 80'
pipe in just about 80'
pipe silt at bottom for 5'

5:00

F3-3 (close to the road)

0-25 stoney 1/2 - 1 inch, sandy, alluvium

25-63' grey, silty lacustrine material. there is some shale fragments tending to become gritty.

63' till? no! its missing, didn't observe any till, therefore bedrock.

Hole drilled 80'
pipe silt for 5' at bottom

Upper layers of bedrock very clay rich, unconsolidated with sand bands.

65'
65 = 130
20 well
80
80
375

July 8, 1969
11:00

F2-4 at Rain Gauge 7

0-12' stoney, sandy alluvium

12' - silty, lacustrine sediments, iron staining, no stones, oxidized near the surface becomes grey and unoxidized farther down, possible organic material

July 8, 1969
11:00 (Continued)

43' - hit hard material with the drill, bedrock petroliferous, dark, grey-black, with white calcareous material.

hole dug 65'
length of pipe 66.7

11:40 Beer Bottle Park

Nest #1 F38

0-22' very sandy, alluvium, with gravel sized pebbles, seems poorly sorted

23-63' blue-grey silt, fragments of organic material trees-wood

hole drilled to 40'
pipe silt 3'
till 12:30 -30' of pipe in the hole.

1:00 Beer Bottle Park

0-22' same as previous

22-63' " " "

72' - very hard drilling, probably bedrock. LARGE SAMPLE

hole dug to 73' (hard drilling, therefore stop)
no sand in the bottom of this piez, therefore hole caved in.

length of pipe in the hole: 80
- 21.8
58.2' pipe in the hole
pipe silt for 5' at the bottom.

WATER TABLE pipe slit 15.2' at the bottom
total length 18.1

3:00 South of Beer Bottle Park

Dug 25', hit rock & stop.

July 8, 1969
3:30 Turn-Around Spot on Bald Hill. Trail vicinity rain gauge 8

Dug 15', hit rock.

4:10

F1-3

0-17' sandy, gravely, alluvium

17-38' lacustrine silts COLOR 5Y 3/1
possible plant material

38-50' bedrock COLOR 10 YR 2/1 LARGE SAMPLE

hole dug to 50'
pipe cut off at 50.6'
pipe sliced for 5'

5:15 - 6:20

F5-4

0-25' buff brown, gravely alluvium, shale fragments possibly 1" in diam.

25-46' lacustrine silt, mottled grey-brown color, fairly uniform COLOR 5Y 3/1

46-47' bedrock, some fine grained shale, unconsolidated rest is petroliferous, dry, fine grained bedrock material.

hole dug to 47'
pipe length 49'
pipe slotted 5' at bottom

F5-3 Water table well

pipe 31' long driller hit water at 15'?
hole dug 30'
pipe slotted 11' at the bottom

July 8, 1969
6:35 By Rain Gauge 21

F44

0-9' buff, silty alluvium, hit H_2O at 7'

9-22' blue, green, buff, lacustrine silt

22' - stoney, gritty, clayey silt till LARGE SAMPLE

at 35' the till becomes very stoney, approx. coarse sand size!

Pipe slit for 5'

after 35' till resembles the 1st variety, less stones, very clayey, and silty, occasional gritts and small pebbles. Color 2.5Y 3/0

56' approx. start of bedrock

59' hit bedrock

Some portions of the till contain medium sized sand pebbles
length of pipe put in = approx. 59.6
Pipe slit for 5' at bottom
hole dug 59'

Thursday, July 10, 1969
9:00 By Rain Gauge 21

F44

Hole dug to 40' (redug the hole)

Pipe 40' long
Pipe sit 3 ft. at bottom
1/2 of a 5 gal. pail of sand

10:00 by the 2 GS piez near Weir

hole dug 25'

0-9' poorly sorted, stoney alluvium, gravel size stones

9-17' blue lacustrine silt Color 5Y 4/1

Thursday, July 10, 1969
10:00 (Continued)

17-24' harder drilling, probably till?

24' hit bedrock

hole caved in 6'
- put in 1/2 bucket of sand

length of pipe 40
-20
20, Pipe slit 3' from bottom

10:50 - 11:00

well hole - 20'

11:10 - 12:15

Measurement		
F4-1	29.1	
	4.7	
	24.4	depth to H_2O

F4-2

0-16' brown, very silty alluvial material, stones not abundant.

18-36' brown, lacustrine silt, no stones, a few gritts
LARGE SAMPLE. Color 10 YR 4/2

shale fragments become abundant towards the bottom of the lake sediments sequence.

75' now encountering stones

end of hole in bedrock at 80'
bedrock encountered 77'

60' - till - grey, unweathered, stoney - silty till

hole dug 80'
pipe was 80'

80'
cut off 7.8
72.2 = final length of pipe

Pipe silt 3' at bottom

Thursday, July 10, 1969
12:55 - 2:15 Up Packhorse Trail before

F7-3

0-32' sandy, silty alluvium, abundant shale fragments, poorly sorted, soft and not very stiff. Color 2.5Y 5/2

20-25' LARGE SAMPLE

32-54' brown, silty, lacustrine deposit, occasional shale fragments, continue down
COLOR 2.5Y 5/2
to 54' - this could be an alluvial type deposit have red iron staining in the lacustrine sediments.

54' possible till

lacustrine silt becomes blue and unweathered or unoxidized as you go down. COLOR 2.5Y 4/0

Hole dug 65 feet
hole caved in so about 58' left

Pipe 80' long, cut off at 59'
Pipe slit for 5' at bottom

5 gal. of sand and 1/2 of a small bucket and fine sand

2:20 Down the Right Fork on Bald Hill Trail

F8-1

0-11' Bluff brown stoney, silty alluvium, mostly shale pebbles.

11-35' brown lacustrine silt with shale pebbles

35' COLOR 2.5Y 4/2, a brown silty, very shaley alluvial type of material
material coming from the auger at times looks like a shaley gravel.

45-50' apparently alluvial material, very stoney and silty.
COLOR 10 YR 4/2 LARGE SAMPLE

55-60' apparently gravely material

60-65' sand and gravel

Thursday, July 10, 1969
2:20 (continued)

at 65' just penetrated into bedrock. COLOR 7.5 YR 2/0
black-grey unconsolidated clay
the bottom 15' was a till fairly stoney grey, unoxidized.

Hole dug to 65'
Used a pipe 80' cut off 23.2'
Final length of pipe - 56.8'
Pipe slit at bottom for 5'

5 gal. of sand and 1/2 of sand and fine sand.

3:20 - 3:45

F8-2 & 3

Hole dug to 38' - hole caved in some

Pipe was 40' Depth to H_2O approx 12'
Cut off 5.4'
length of pipe left 34.6'
Pipe slit for 3' at bottom

1/2 of 5 gal. of coarse sand

Going to add an H_2O table one.

4:00 Packhorse Weir

10' Stop

4:30 Move down to side of old trail across from Rain Gauge #34

F43

Hole dug 15' - stone hit, stop 4:50

Start again

0-23' coarse very stoney alluvium material, cobble & pebble size, very difficult drilling almost like gravel.

23' the alluvium seems to be giving away to a silty, lacustrine deposit.

Thursday, July 10, 1969
4:30 (continued)

27-35' blue, - hit bedrock at 27' (porous shale?)
COLOR 7.5 YR 2/0 2 LARGE SAMPLES
(1 sample 27-35'
another 35-40')
black, unconsolidated shale bedrock, very fine grained.

35-40' In the upper 10' of the bedrock is more moist
lower stretch or samples become drier and petroliferous
final 10' of bedrock is becoming very dry

Pipe was 60'
cut off 4.4'
length of pipe 55.6'
pipe slit 5' at bottom

Hole Dug 55'

Going to add a H_2O table one
H_2O pipe = 20' long
slit 14'

5 gal. of coarse sand and
fine sand.

7:00 - 8:20 Near Packhorse Crossing

F41

0-24' interbedded sands and other materials alluvial sequence

24' - grey, lacustrine silt very occasional grits
the bedding is very obvious
COLOR 5Y 4/1 LARGE SAMPLE from 45'

at 62' till COLOR 10 YR 2/1
a few pebbles & grits, very silty, grades into bedrock at 70'

70' bedrock

Hole dug 70'
Caved in
length of pipe 41.8'
slit 5' at bottom

H_2O table pipe slit ten feet at bottom
Length of pipe = 20'

Friday, July 11, 1969
9:40 Ridge Dam Location

F27

Hole dug 25', some seepage H_2O in the hole
length of pipe 25.5'

2 1/2 gal. coarse sand
1/2 gal. fine sand.

Dug a hole 25' - hit rocks & stop.

0-20' light brown COLOR 10 YR 4/4 stoney, sandy, silty till (quite moist)

20-25' get till, slightly darker than above COLOR 2.5 YR 4/2 (LARGE SAMPLE TAKEN)

The tills are the same, but there's color changes going downwards.

25-35' greyer looking till COLOR 2.5 YR 3/2 LARGE SAMPLE

Color of Tills:
0-20' 10 YR 4/4
20-25' 2.5 YR 4/2
25-35' 2.5 YR 3/2

Around 48' the till is grading into very soft, grey, COLOR 5Y 4/1, till was encountered very moist, only fine stones in it.

50-60' LARGE SAMPLE COLOR 2.5Y 4/2 a light brown very silty till. pebbles are abundant.

Hole caved in
Put in small pail of coarse sand
pushed pipe about 7' in mud

Hole dug 80'
length of pipe in hole = 80 - 14.7 = 65.3'

Pipe slit 5' at bottom

Friday, July 11, 1969
12:50 - 1:25

3' hole, little blue pipe slit for 1'

length of pipe in hole = 4.7'
Length of pipe slit 1' at bottom

9' hole
length of pipe in hole = 10'
length of pipe slit 2'

15' hole
Shove pipe 18' long
3' of holes

Move farther up the hill

Hole dug 30' and caved in

Pipe length 40'
cut off 10.4
Length of pipe in the hole = 29.6'
Pipe slit for 3'

1/2 of a 5 gal. pail of sand.

2:45 - 3:45 Tried by Rain Gauge 33

3:45 - 5:20 Top of the Big Hill on Jet Trail down from Rain Gauge 33

F28

0-15; yellowish-orange-brown stoney silty till
abundant water COLOR 2.5 Y 5/4

15' - grey, unweathered, stiff stoney till, does not appear as permeable COLOR 2.5 Y 4/0

Approx 45' the till is silty, very compact COLOR 2.5 Y 4/0
LARGE SAMPLE

Hole dug to 80'
Pipe 100' long, final length of pipe: 81.4'
Pipe slit ____ ft.

5 gal. and 1 small bucket of sand.

Friday, July 11, 1969
5:20 - 6:00 On top of Big Hill on Jet Trail (same as previous one) - move up closer to the road.

length of hole = 40'
pipe length = 40'
pipe slit = 3'

5 gal. and small pail of coarse sand

Move down a bit closer to the road - make a 20' H_2O table well.

Pipe 20' long
slit for 10'

6:35 At the Bottom of the Big Hill on the Jet Trail Hole near Rain Gauge 11

F29

0-11' brown color 2.5 Y 5/4 silty till

11' COLOR 5 Y 3/1

50-60' till LARGE SAMPLE, grey, stoney silty till, fairly compact.

Redug hole to 80'. 1st time only 25' open
Pipe 80-32.4 = 47.6 feet of pipe in the hole

Use 1 small bucket of coarse sand and some fine sand

3 feet of the pipe = in mud

5 gal. and 1 small bucket of coarse sand.

Saturday, July 12, 1969
9:29-10:05 Bottom of Big Hill on Jet Trail by Gauge 11

Hole dug 40'
approx. pipe length 40' slit for 3'
pipe length 20', slit for 10'

1/2 of a 5 gal. pail of sand and some fine sand.

Saturday, July 12, 1969
10:25 - 11:05 Further down Jet Trail, West of Rain Gauge 10

F30

0-15' brown iron stained till?
COLOR 10 YR 4/3
pebbles fairly abundant, sandy & silty.

15-37' COLOR 2.5 Y 4/0 grey, clay - till? pebbles are only occasional and small,very clay rich, at about 33' the till is becoming very stiff, cobble sized boulders are being encountered.

30-37' LARGE SAMPLE till COLOR 2.5 Y 4/0

Hole dug 37'
Pipe 40'
Slit for 3'

11:20 Hole #2 At Location West of Rain Gauge 10.

F30

Very coarse cobbles - stopped drilling at 40', unable to penetrate, had to cover in the 40' to 20' and then put in an H_2O table piezometer.

20' pipe
Silt for 10'

1:40 - 2:20 Along the Jet Trail.

F31

0-16' brown very silty shale, pebbles COLOR 10 YR 4/4
alluvium or till?

16' COLOR 2.5 Y 3/2 hard, shale bedrock, dry.

Hole dug 35', unable to drill, therefore very dry.

LEFT OPEN

Saturday, July 12, 1969
2:20 - 3:05 Mulligan's Creek, along the Jet Trail.

F32

10-16' LARGE SAMPLE

0-17' brown COLOR 10 YR 4/4 silty, fairly stoney till, near saturated with H_2O.

20' hard, dry shale bedrock

Hole dug 25'
Pipe 33' long, cut off 7.8 = 25.2' long

LEFT OPEN

3:05 2nd hole, same place as before.

F32

Hole dug for 17'
Length of pipe = 20' - 3.1' = 16.9' long
Pipe slit for 3'

LEFT OPEN

In the last hole which was before Mulligan's Creek on the Jet Trail the till was fairly moist but shale was dry.

Down Jet Trail Bet. B. Bottle Park and Gauge 8.

F37

0-13' very coarse gravel alluvium

13' -

Hole dug 20'
An H_2O table piez. put in 21' long
pipe slit for 10 feet.

Saturday, July 12, 1969
4:50 Above Beer Bottle Park on Acces Trail

F38

10-15' LARGE SAMPLE COLOR 3 10 YR 4/2

0-37' stoney, silty, alluvium material lower portions becoming blue unoxidized.

- 37' grey-blue lacustrine silt with clay
COLOR 5 Y 3/1

45-50' LARGE SAMPLE going downwards, the lacustrine sediments become nearly pure silt with occasional fine stones.

74' Bedrock LARGE SAMPLE

about 60' the lacustrine becomes very silty and clayey again, bedding obvious COLOR 5 Y 4/1

60' LARGE SAMPLE

74' LARGE SAMPLE bedrock with calcite crystals

Hole dug 75', cut off 10.6 - final length of pipe - 69.4
Pipe slit 5'

5 gal. and a small bucket of coarse sand and some fine sand.

6:30 2nd hole here

Hole dug 45'

Lake clay at 37' instead of 44'

Pipe length 50.3
$-\underline{5.1}$
45.2 feet long (H_2O not in yet) 40' & 10' of slit.

Pipe slit for 3'

7:10

Water table piez. 20' long sawed for 15' across the creek at Beer Bottle Park beside the other one already there.

Tuesday, July 22, 1969
12:00 - 6:15 By the 40' piezometer. Dee's Trail #A

F33

Hole dug 90'
pipe slit 5'
length of pipe 100'

0-16' silty brown COLOR 2.5 Y 5/2 alluvium, abundant shale pebbles 1/2 inch and smaller.

16-38' probable lacustrine sediments, sandy and silty brown and unweathered.
becomes grey and unweathered, COLOR 5 Y 4/1
of the occasional bands of clay up to 2" thick, grey, might be present.

38-50' grey-brown, silty alluvium, shale fragments present, very difficult to decide what it exactly is.

50-90' black, clay bedrock, unconsolidated, gas smell
LARGE SAMPLE
Occasional white calcareous? specks.

Hole caved in, re-dug

- no sand, therefore piez in the mud

length of pipe in the hole = 30.8'.

F45 Hole at Yakumchuk's Farm

0-13' brown pebbly (shale) alluvium

13-51' lacastrine sandy silt - blueish green in color brownish grey in color for the most part - bands of 2" of dark green clayey silt - occasional grits present approx. med. sand size, lower down - grey with purple tint lacustrine silty clay stiffer than upper units.

51-80' black clay bedrock, pale yellow
x line veins present, bands of light blue material

75-80' bedrock appears to be layered, hard and soft bands 2-3".

Piezometer depth 25'

APPENDIX C

Hydraulic Conductivity Data:
Results of Hvorslev tests

Piezometer location	Hydraulic Conductivity (ft./sec.)
F1-3	2.5×10^{-5}
F2-1	7×10^{-8}
F2-2	1×10^{-5}
F2-4	1.6×10^{-7}
F3-1	1×10^{-6}
F3-3	7×10^{-9}
F4-2	3×10^{-6}
F5-4	3×10^{-6}
F6-1	3×10^{-6}
F6-3	2×10^{-7}
F7-1	1×10^{-8}
F8-1	2×10^{-4}
F9-3	1×10^{-6}
F10-1	1.6×10^{-8}
F10-3	7×10^{-9}
F11-2	3×10^{-6}
F12-1	3×10^{-8}
F13-1	7×10^{-9}
F14-1	1.6×10^{-4}

Piezometer location	Hydraulic Conductivity (ft./sec.)
F27-2	3×10^{-7}
F27-3	3×10^{-7}
F28-3	7×10^{-8}
F29-2	1×10^{-7}
F29-3	2×10^{-7}
F38-2	1×10^{-4}
F38-3	2×10^{-6}
F39-2	2×10^{-7}
F39-3	3×10^{-4}
F41-3	1.6×10^{-5}
F44-2	1×10^{-7}
F44-3	2×10^{-5}
GS5	1.6×10^{-6}
GS7	1×10^{-4}
GS9	1.6×10^{-6}
GS12	1×10^{-4}
GS14	1.6×10^{-8}
F43-2	7×10^{-9}

APPENDIX D

Computer program for chemistry computations

The chemistry program was developed to facilitate rapid evaluation of hydrochemical data. The program output includes the following

1) total parts per million
2) major ion concentration in molality
3) comparison of cation and anion equivalents per million
4) ionic strength
5) calculation of pertinent ion ratios
6) determination of activity coefficients
7) determination of equilibrium constants for a given temperature
8) percent saturation, calcite, dolomite, gypsum aragonite, neglecting ion complexing
9) calculation of concentrations of complex ions
10) percent saturation including ion complexing

Input Format

Results of a single, complete analysis requires one data card. The following data is typed on the card in this order

a) sample number - F 5.1 format
b) concentration in parts per million of Ca^{++}, Mg^{++}, Na^{+}, K^{+}, HCO_3^{-}, $SO_4^{=}$ and Cl^{-} in that order - F 7.1 format

c) pH measurement - F 6.2 format

d) temperature in degrees centigrade between 0.0 and 25.0 - F 4.1 format

e) concentration in parts per million $CO_3^{=}$ - F 7.1 format

The total number of data cards to a maximum of 90 is also required imput, on a data separate card, I6 format. This information is the first data card preceding the chemistry data cards.

Calculation Procedures

Comparison of cation and anion total is presented as a percentage, epm cations/epm anions X 100.

Ratios calculated by the program are as follows.

$RA = (Ca^{++} + Mg^{++})/Na^{+}$

$RB = Ca^{++}/Mg^{++}$

$RC = SO_4^{=}/Cl^{-}$

$RD = SO_4^{=}/HCO_3^{-}$

$RF = Ca^{++}/Na^{+}$

$RG = HCO_3^{-}/(Cl^{-} + SO_4^{=})$

$RH = HCO_3^{-}/Cl^{-}$

Percent saturation, the ratio of the ion activity product and the dissolution constant expressed as a percent, are calculated for calcite, dolomite, gypsum and aragonite. Activity coefficients for all equilibria reactions are linearly interpolated from graphical relationships of ionic strength versus activity coefficient given by Garrels and

Christ (1965) for Ca^{++}, Mg^{++}, HCO_3^-, $SO_4^=$ and Na^+ for 1 atmosphere total pressure and 25°C.

Dissociation constants varying with temperatures are as follows:

Temp. °C.	0.0	5.0	10.0	15.0	20.0	25.0
pK calcite (Langmuir, 1970 written communication)	8.31	8.31	8.32	8.34	8.37	8.40
pK dolomite (Langmuir, 1970 written communication)	16.57	16.63	16.71	16.79	16.89	17.00
pK gypsum (Cherry, 1968)	4.71	4.69	4.66	4.65	4.64	4.62
pK aragonite (Berner, 1967)	8.11	8.11	8.17			8.20
pK bicarbonate (Back, 1961, 1963)	10.615	10.566	10.488	10.429	10.376	10.329

The following reactions involving several metastable carbonates were also considered

Magnesite: $MgCO_3 \rightleftarrows Mg^{++} + CO_3^=$

Huntite: $Mg_3\,Ca(CO_3)_4 \rightleftarrows 3Mg^{++} + Ca^{++} + 4CO_3^=$

Landsfordite: $MgCO_3 \cdot 5H_2O \rightleftarrows Mg^{++} + CO_3^= + 5H_2O$

Nesquehonite: $MgCO_3 \cdot 3H_2O \rightleftarrows Mg^{++} + CO_3^= + 3H_2O$

Hydromagnesite: $Mg_4(CO_3)_3\,OH_2 \cdot 3H_2O \rightleftarrows 4Mg^{++} + 3CO_3^= + 2OH^- + 3H_2O$

To obtain saturation percentages of groundwater solutions with respect to the above mineral species, ion activity products computed from chemical analyses of each sample were compared to the following dissociation constants at 25°C. obtained from Langmuir (1965),

pK @ 25°C

magnesite: 5.10

Landsfordite: 5.46

mesquehonite: 5.59

hydromagnesite: 30.2

huntite: 7.80

In all of these equilibria calculations, the effects of pressure greather than 1 atm. has been neglected. Sippel and Glover, (1964) have shown that variations in hydrostatic fluid pressures between 0 and 6000 feet cause calcite solubility changes less than 1 percent at CO_2 partial pressures of 0.1 and 0.3 atm.

Concentrations of complex ions were calculated following an interative procedure again outlined by Garrels and Christ (1965). The solution was found to converge within the ten interations specified. Percent saturation based on the concentration of uncomplexed ions is recalculated for a revised saturation value.

List of variables:

PSUM	total parts per million	
CCAL	concentration in molality	Ca^{++}
CMAG	" " "	Mg^{++}
CSOD	" " "	Na^{+}
CPOT	" " "	K^{+}
CBIC	" " "	HCO_3^{-}
CSUL	" " "	SO_4^{-}
CCHL	" " "	Cl^{-}
CCAB	" " "	$CO_3^{=}$
ACTCA	activity coefficient	Ca^{++}

ACTBIC	activity coefficient	HCO_3^-
ACTMG	" "	Mg^{++}
ACTSUL	" "	$SO_4^=$
ACTNA	" "	Na^+
BKA	equilibrium constants ranging from 0.0 & 25.0°C -	calcite
BKB	" " " " "	bicarbonate
BKC	" " " " "	dolomite
BKD	" " " " "	gypsum
BKE	" " " " "	aragonite
BKF	" " " " "	H_2CO_3
BKG	" " " " "	CO_2
BKT	temperature range 0.0 to 25.0°C	
BKS	" " " " "	
EQCAL	interpolated equilibrium constant -	calcite
EQBIC	" " "	bicarbonate
EQDOL	" " "	dolomite
EQGYP	" " "	gypsum
EQARG	" " "	aragonite
SATCAL	percent saturation (IAP/K)	calcite
SATDOL	" " "	dolomite
SATARG	" " "	aragonite
SATGYP	" " "	gypsum
FCAL	concentration in molality of free	Ca^{++}
FMAG	" " " " "	Mg^{++}
FSOD	" " " " "	Na^+
FBIC	" " " " "	HCO_3^-
FSUL	" " " " "	$SO_4^=$
FCAB	" " " " "	$CO_3^=$
BD	13 values of activity coefficients	
BA	13 corresponding activity coefficients for	Ca^{++}
BB	" " " "	" HCO_3^-
BC	" " " "	" Mg^{++}
BE	" " " "	" $SO_4^=$
BF	" " " "	" Na^+
SMAG	percent saturation (IAP/K)	magnesite
SNESQ	" " "	nesquehonite
SLANS	" " "	landsfordite
SHYD	" " "	hydromagnesite

Appendix E

Tabulation of chemical analyses including saturation and ion charge balance

DATE	SAMPLE NO.	Ca^{++}	Mg^{++}	Na^{+}	K^{+}	HCO_3^-	$SO_4^=$	Cl^-	pH	TEMP. °C	$CO_3^=$	$HCO_3^- + CO_3^=$	LOCATION OF SAMPLE
MAY													
1	215	57.3	21.4	8.6	2.84	228.0	79.0	2.5	7.971	15	0	228.0	D-5 Wilson Cr
2	104	51.3	18.6	14.8	2.29	208.0	67.0	3.5	8.061	15	0	208.0	D-5
4	134	164.0	17.8	12.4	2.69	228.0	74.0	2.5	8.191	15	0	228.0	D-5
5	186	50.2	18.9	9.8	2.42	250.0	82.0	3.0	8.310	17.5	0	250.0	D-5
6	19	50.2	18.0	10.4	2.19	228.0	65.0	2.5	8.253	15	0	228.0	D-5
7	164	50.25	18.6	14.8	2.44	252.0	79.0	2.5	8.381	15	0	252	D-5
8	149	36.0	23.6	9.2	2.35	220	64	2.5	8.360	15	4	224	D-5
9	12	50.1	19.1	11.4	2.19	232	62	2.5	8.32	12	8	240	D-5
10	152	50.3	19.2	12.4	2.22	242	56	3.5	8.331	6	3	247	D-5
11	46	53.6	19.4	13.9	2.39	250	65	3.5	8.372	5	10	260	D-5
12	W-1	57.1	20.3	18.5	2.53	249	74	3.0	8.359	14	10	259	D-5
13	W-2	52.5	20.6	19.7	2.54	268	68	2.5	8.226	15	2	270	D-5
14	W3	53.6	19.7	19.1	2.72	260	68	3.0	8.322	17	6	266	D-5
15	W4	57.6	21.4	15.1	2.90	266	78	2.5	8.171	10	0	266	D-5
16	W5	57.1	21.4	16.0	2.72	268	85	2.5	8.379	11.4	6	274	D-5
17	W6	57.9	22.0	21.4	2.80	255	94	2.5	8.340	11	5	260	D-5
18	W7	61.9	22.4	22.8	2.80	257	88	2.5	8.405	11	5	262	D-5
19	W8	57.7	21.1	16.4	2.80	270	84	3.0	8.110	13	0	270	D-5
20	W9	58.6	21.8	22.8	2.71	268	89	3.0	8.209	9.9	0	268	D-5
21	W10	59.4	21.7	17.6	2.98	272	79	3.0	8.055	12.5	0	272	D-5
22	W11	52.0	22.2	17.8	3.29	270	88	2.5	8.296	12.5	4	274	D-5
23	W12	64.4	21.2	17.5	3.07	256	89	2.7	8.633	16.2	12	268	D-5
24	W13	58.4	21.8	19.2	2.86	269	90	3.0	8.352	9.2	5	274	D-5
25	W14	55.9	20.9	19.4	2.98	270	85	3.0	8.431	20.0	4	274	D-5
26	W15	57.4	22.1	18.3	3.43	246	80	3.0	8.66	25	8	254	D-5
27	W16	58.6	22.9	16.5	3.15	232	74	3.0	8.647	11	24	256	D-5
28	W17	60.1	23.1	18.1	3.07	262	79	3.0	8.401	12.5	6	268	D-5
29	W18	57.4	21.9	19.5	3.06	265	85		8.395	14.5	5	270	D-5
30	W19	58.4	22.7	20.3	3.17	261	84		8.415	12.2	6	267	D-5
31	W20	58.4	21.1	18.3	2.94	272	84		8.210	12	0	272	D-5
JUNE													
1	W21	53.0	16.4	18.6	1.93	207	43		8.225	14.5	0	207	D-5
2	W22	40.5	15.4	9.0	1.81	196	38		8.112	21	0	196	D-5
3	W23	45.5	17.2	8.77	2.25	220	50		8.132	21	0	220	D-5
4	W24	46.9	17.8	9.4	2.20	230	60		8.270	21.5	2	237	D-5

TE	SAMPLE NO.	Ca^{++}	Mg^{++}	Na^{+}	K^{+}	HCO_3^{-}	$SO_4^{=}$	Cl^{-}	pH	TEMP °C	$CO_3^{=}$	$HCO_3^{-} + CO_3^{=}$	LOCATION OF SAMPLE
NE	W25	46.5	18.2	11.5	2.16	232	51		8.303	22	4	236	D-5
;	W26	53.1	19.7	14.5	2.64	256	66		8.319	23.2	4	260	D-5
1	W27	58.5	21.5	16.6	2.52	260	66		7.992	20.	0	260	D-5
3	W28	67.0	21.6	17.3	2.68	275	68		8.130	19.7	0	275	D-5
7	W29	67.0	22.1	18.6	2.87	276	75		8.223	20.5	0	276	D-5
0	W30	68.6	20.6	19.4	2.92	280	85		8.182	20.5	0	280	D-5
1	W31	70.4	22.9	19.7	2.87	286	89		8.206	19.0	0	286	D-5
2	W32	70.7	22.8	20.1	2.82	290	88		8.166	17.0	0	290	D-5
3	W33	68.5	22.9	20.8	2.90	280	91		8.221	15.5	0	280	D-5
4	W34	70.4	23.4	21.2	2.98	294	87		8.298	22.5	0	294	D-5
5	W35	71.4	22.7	21.7	3.19	278	83		8.441	22.0	8	286	D-5
6	W36	72.1	22.9	22.1	3.29	288	89	3.0	8.291	20.5	2	290	D-5
7	W37	74.0	22.9	22.5	3.19	278	89		8.228	21.2	2	280	D-5
8	W38	70.5	23.3	22.8	3.27	277	91		8.293	18.	3	280	D-5
9	W39	69.1	22.6	22.6	3.16	285	84		8.252	10.5	3	288	D-5
0	W40	61.4	23.5	22.8	3.18	298	87		8.153	14	0	298	D-5
1	W41	67.1	23.9	23.1	3.27	288	98		8.301	22	6	294	D-5
2	W42	64.9	22.0	18.5	2.88	266	66		8.300	21.5	4	270	D-5
3	W43	73.2	23.2	24.2	3.44	290	83		8.244	24.0	2	292	D-5
4	W44	69.0	23.2	22.8	3.45	294	80		8.161	23.0	0	294	D-5
5	W45	73.5	23.1	24.7	3.35	297	84		8.239	19.0	0	297	D-5
;	W46	44.4	12.5	7.45	1.76	160	27		7.922	21.0	0	160	D-5
1	W47	42.5	12.8	4.39	2.93	132	25		7.850	22.2	0	132	D-5
3	W48	53.1	16.1	6.25	2.14	166	35		7.979	21.0	0	166	D-5
7	W49	58.5	16.1	5.87	2.14	172	40		8.010	19.0	0	172	D-5
0	W50	45.5	14.8	4.84	1.76	156	26		8.015	21.0	0	156	D-5
													D-5
LY	W51	53.3	14.7	6.4	1.90	186	36		8.101	19.5	0	186	D-5
,	W52	51.8	15.8	8.5	1.73	200	44		8.116	21.2	0	200	D-5
,	W53	54.5	17.1	9.5	1.92	204	51		8.118	23	0	204	D-5
:	W54	54.0	16.5	10.0	1.83	210	50		8.194	22.2	0	210	D-5
-	W55	50.8	16.7	8.8	1.71	202	45		8.161	19.1	0	202	D-5
	W56	50.4	16.8	10.3	2.25	211	53		8.176	24.8	0	211	D-5
	W57	50.9	15.85	8.6	2.05	208	50		8.120	24.5	0	208	D-5
	W58	40.9	12.9	6.1	1.49	180	30		8.178	24.5	0	180	D-5
	W59	51.5	16.0	8.6	2.06	207	41		7.981	24	0	207	D-5
)	W60	56.5	17.1	10.3	2.24	266	57		8.442	20.8	8	274	D-5
	W61	61.0	17.9	11.7	2.49	220	63		8.266	24.8	2	222	D-5
,	W62	56.7	17.3	11.7	2.50	233	65		8.241	24.2	1	234	D-5

DATE	SAMPLE NO.	Ca^{++}	Mg^{++}	Na^{+}	K^{+}	HCO_3^-	$SO_4^=$	Cl^-	pH	TEMP. °C	$CO_3^=$	$HCO_3^- + CO_3^=$	LOCATION OF SAMPLE
JULY 13	W63	58.7	17.8	13.2	2.53	238	66		8.207	24.8	0	238	D-5
14	W64	58.9	17.8	13.3	2.54	243	62		8.135	24.3	0	243	D-5
15	W65	58.7	17.8	13.5	2.68	239	64		8.246	24.3	1	240	D-5
16	W66	58.7	17.8	13.8	2.69	244	56		8.187	24.3	0	244	D-5
17	W67	57.6	17.8	13.9	2.66	226	59		8.131	19	0	226	D-5
18	W68	55.1	17.6	13.7	2.65	218	57		8.231	24.2	0	218	D-5
19	W69	55.1	17.1	13.1	2.68	221	57		8.284	23.2	4	225	D-5
20	W70	55.2	16.9	13.2	2.70	222	59		8.140	22.0	0	222	D-5
21	W71	54.5	16.5	12.9	2.61	216	51		8.122	20	0	216	D-5
22	W72	54.3	17.4	13.4	2.73	214	54		8.290	21.5	2	216	D-5
23	W73	54.3	17.4	13.6	2.74	226	56		8.230	21.4	0	226	D-5
24	W74	62.6	17.7	14.4	2.69	240	59		8.015	22.0	0	240	D-5
25	W75	69.1	19.2	18.2	3.23	260	69		8.241	22.0	2	262	D-5
26	W76	63.1	18.0	15.2	3.79	242	64		8.168	22.0	0	242	D-5
27	W77	67.4	18.6	13.0	2.74	260	56		8.243	21.5	0	260	D-5
28	W78	70.0	19.4	17.6	2.91	268	67		8.198	21.4	0	268	D-5
29	W79	72.4	20.0	18.5	3.02	277	75		8.220	21	0	277	D-5
30	W80	73.2	20.1	19.8	3.22	278	81		8.206	20.8	0	278	D-5
31	W81	73.2	20.2	19.5	3.09	280	76		8.254	22.5	0	280	D-5
AUG 1	W82	75.7	20.3	20.8	3.30	294	82		8.042	21.5	0	294	D-5
2	W83	75.7	20.8	21.4	3.44	285	86		8.179	23	0	285	D-5
3	W84	75.5	21.0	21.7	3.44	297	87		8.140	22	0	297	D-5
4	W85	76.6	21.6	22.3	3.46	292	89		8.143	22	0	292	D-5
5	W86	76.9	21.4	22.8	3.56	294	94		8.212	22	0	294	D-5
6	W87	78.2	21.8	22.6	3.60	298	87		8.181	22	0	298	D-5
7	W88	76.9	21.6	22.3	3.55	298	84		8.205	22.5	0	298	D-5
8	W89	80.4	21.8	23.2	3.74	302	89		8.120	25	0	302	D-5
10	W91	78.1	21.4	23.3	3.86	298	98		7.977	15.1	0	298	D-5
11	W92	78.1	21.7	23.3	3.90	294	98		8.131	15.5	0	294	D-5
12	W93	78.5	21.7	23.3	4.02	300	103		8.297	16.0	2	302	D-5
13	W94	70.9	19.9	23.3	3.85	280	99		8.179	17.6	0	280	D-5
14	W95	71.5	22.1	23.1	3.80	280	85		8.293	17.5	2	282	D-5
15	W96	72.0	25.9	23.1	3.86	298	87		8.340	19.0	4	302	D-5
16	W97	73.8	22.3	23.4	3.48	296	82		8.351	17.5	4	300	D-5
17	W98	72.0	21.6	22.4	3.70	290	93		8.351	17.5	4	294	D-5
18	W99	78.5	21.7	23.2	3.82	294	92		8.388	18.3	4	298	D-5
19	W100	80.0	21.6	23.2	3.82	298	95		8.210	22.0	0	298	D-5
20	W101	79.4	22.1	23.2	3.86	282	97		8.364	20.	6	294	D-5

DATE	SAMPLE NO.	Ca^{++}	Mg^{++}	Na^{+}	K^{+}	HCO_3^-	$SO_4^=$	Cl^-	pH	TEMP. °C	$CO_3^=$	$HCO_3^- + CO_3^=$	LOCATION OF SAMPLE
AUG													
21	W102	80.4	21.8	23.5	3.98	298	99		8.368	19.	1	306	D-5
22	W103	81.0	21.6	23.7	4.41	288	101		8.412	14.5	8	296	D 5
23	W104	82.4	21.75	23.2	4.10	295	99		8.365	19	6	301	D-5
24	W105	83.0	21.5	23.5	4.00	302	105		8.198	27.0	0	302	D-5
25	W106	83.5	21.7	23.1	3.99	296	100		8.383	18.0	6	302	D-5
26	W107	83.5	21.7	23.3	4.02	302	98		8.071	15.2	0	302	D-5
27	W108	45.5	12.7	16.0	3.18	171	76		7.715	15.7	0	171	D-5
28	W109	76.4	21.4	21.2	3.48	286	97		8.373	15	4	290	D-5
29	W110	79.1	21.8	23.2	3.91	296	97		8.300	21	2	298	D-5
30	W111	81.0	21.8	23.2	4.82	306	99		8.201	19	0	306	D-5
31	W112	83.7	22.5	23.9	3.79	295	99		8.270	14.8	2	297	D-5
SEPT													
1	W113	82.5	21.9	23.3	3.86	306	103		8.039	19.5	0	306	D-5
2	W114	82.5	21.7	23.6	3.88	300	96		8.344	17	2	302	D-5
E:	32	1.06	.68	2.46	1.69								
	33	1.47	.72	1.37	1.03								
	34	.64	.55	.76	.46								
													Packhorse Cr
MAY													
14	P3	55.4	19.7	18.0	9.05	246	80	2.5	8.346	18	7.84	254	D-4
15	P4	53.4	25.4	18.8	2.71	248	81	2.5	8.189	10	0	248	D-4
16	P5	53.4	20.2	19.5	2.80	234	89	3.0	8.396	14.2	6	240	D-4
17	P6	55.6	20.4	21.2	2.80	238	95	2.5	8.450	11.5	8	246	D-4
18	P7	52.2	21.4	20.8	2.89	238	100	3.0	8.391	12.6	8	246	D-4
19	P8	48.8	21.4	24.3	2.71	246	99	3.0	8.298	12.8	4	250	D-4
20	P9	54.8	19.8	21.6	2.89	246	99	2.5	8.320	10.5	4	250	D-4
21	P10	48.8	20.2	20.1	3.24	254	86	2.5	8.067	8.3	0	254	D-4
22	P11	51.9	23.8	20.7	3.06	248	109	2.5	8.505	11.5	12	260	D-4
23	P12	52.0	20.5	22.8	3.07	274	110	2.6	8.610	16.0	4	278	D-4
24	P13	53.6	20.6	23.1	3.02	254	105	3.0	8.242	10.5	0	254	D-4
25	P14	54.3	20.8	24.0	3.20	247	100	2	8.495	20.0	8	255	D-4
26	P15	52.4	20.8	24.3	3.47	240	98	3	8.494	25.0	8	248	D-4
27	P16	67.4	20.7	21.3	3.07	238	84	3	8.662	11.5	12	250	D-4
28	P17	47.8	21.1	20.1	3.07	232	88		8.444	12	8	240	D-4
29	P18	52.6	20.3	23.3	3.24	252	87		8.352	23	2	254	D-4
30	P19	54.9	21.3	23.7	3.40	244	118		8.340	12.9	4	248	D-4
31	P20	54.6	20.9	21.0	3.16	250	102		8.285	9	2	252	D-4

ATE	SAMPLE NO.	Ca^{++}	Mg^{++}	Na^{+}	K^{+}	HCO_3^{-}	$SO_4^{=}$	Cl^{-}	pH	TEMP. °C.	$CO_3^{=}$	$HCO_3^{-} + CO_3^{=}$	LOCATION OF SAMPLES
JNE													
1	P21	40.5	16.3	6.4	1.71	200	35		8.005	19.5	0	200	D-4
2	P22	38.4	15.5	6.9	1.42	190	35		8.150	19.5	0	190	D-4
3	P23	41.0	17.7	10.2	1.89	209	49		8.229	19.8	0	209	D-4
4	P24	46.9	18.7	12.1	2.12	220	60		8.343	20.0	4	224	D-4
5	P25	47.2	18.5	14.6	2.36	239	70		8.282	20.4	1	240	D-4
6	P26	50.6	19.9	16.7	2.82	242	74		8.381	20.4	4	246	D-4
7	P27	61.8	21.4	18.1	2.56	248	71		7.980	20.5	0	248	D-4
8	P28	66.0	23.1	19.7	2.82	254	76		8.246	20.5	0	254	D-4
9	P29	71.2	21.9	21.3	2.95	248	87		8.397	20.5	4	252	D-4
10	P30	70.4	22.0	22.4	3.46	252	106		8.379	21.0	8	260	D-4
11	P31	70.5	22.3	22.0	2.96	264	93		8.324	21.0	4	268	D-4
12	P32	72.6	22.4	23.0	2.46	254	98		8.362	22.3	4	259	D-4
13	P33	71.9	22.6	24.2	3.10	256	105		8.390	22.2	4	260	D-4
14	P34	72.6	22.6	25.2	3.22	258	101		8.321	24.0	2	260	D-4
15	P35	74.5	22.6	25.8	3.32	252	102		8.471	22.0	8	260	D-4
16	P36	72.2	22.9	26.6	3.42	253	104		8.421	16.5	3	256	D-4
17	P37	74.6	23.0	26.8	3.37	260	117		8.364	22.3	2	262	D-4
18	P38	74.5	22.9	27.4	3.48	262	115		8.421	16.5	4	266	D-4
19	P39	74.5	23.2	27.7	3.38	260	103		8.354	12.5	5	265	D-4
20	P40	73.5	23.4	27.7	3.48	267	108		8.325	15	4	271	D-4
26	P41	70.6	23.1	28.1	3.54	256	98		8.470	19	8	264	D-4
22	P42	72.4	23.6	28.7	3.60	266	103		8.443	24.0	4	270	D-4
23	P43	71.6	23.4	29.2	3.81	262	101		8.432	23.3	4	266	D-4
24	P44	72.1	23.2	30.0	3.77	262	103		8.345	23.5	2	264	D-4
25	P45	70.9	23.0	31.5	3.74	260	114		8.432	16.0	8	268	D-4
26	P46	39.8	13.2	4.8	1.49	172	13		7.785	20	0	172	D-4
28	P48	42.5	12.7	5.9	2.13	158	38		8.040	18.8	0	158	D-4
29	P49	42.5	11.6	4.7	22.1	172	29		7.960	20.1	0	172	D-4
30	P50	39.5	12.1	5.7	1.63	152	32		8.090	20.5	0	152	D-4
LY													
1	P51	53.6	16.9	9.7	2.02	196	51		8.192	21.2	0	196	D-4
2	P52	57.2	17.1	10.9	2.12	206	60		8.235	21.2	0	206	D-4
3	P53	61.0	18.9	13.7	2.53	221	77		8.201	21.3	0	221	D-4
4	P54	61.5	17.8	14.0	2.40		66		8.222	25			D-4
5	P55	54.2	16.6	11.7	2.01	210	54		8.200	21	0	210	D-4
6	P56	58.6	17.9	14.5	2.36	225	75		8.280	24.5	1	226	D-4
7	P57	51.5	15.7	10.4	1.88	208	55		8.118	24.5	0	208	D-4
	P58	42.7	12.8	5.7	2.04	213	39		8.170	21.2	0	213	D-4
9	P59	53.0	15.8	10.6	1.92	208	55		7.912	17.0	0	208	D-4

ATE	SAMPLE NO.	Ca^{++}	Mg^{++}	Na^{+}	K^{+}	HCO_3^{-}	$SO_4^{=}$	Cl^{-}	pH	TEMP. °C	$CO_3^{=}$	$HCO_3^{-} + CO_3^{=}$	LOCATION OF SAMPLE
ULY													
10	P60	59.6	18.1	13.8	2.39	258	75		8.042	20.5	0	258	D-4
11	P61	64.0	18.7	17.3	2.68	238	90		8.261	21.8	2	240	D-4
12	P62	66.0	19.5	19.0	2.95	244	100		8.243	21.2	2	246	D-4
13	P63	66.8	19.8	21.4	3.10	240	93		8.431	21.2	8	248	D-4
14	P64	66.2	20.0	21.4	3.24	250	108		8.303	20.3	4	254	D-4
15	P65	66.5	28.7	23.3	3.28	248	113		8.355	20.2	6	254	D-4
16	P66	66.6	20.1	24.2	3.32	250	108		8.375	19.0	4	254	D-4
17	P67	65.4	20.4	24.7	3.37	254	113		8.345	19	4	258	D-4
18	P68	66.5	20.4	24.5	3.39	248	118		8.277	20.2	2	250	D-4
19	P69	68.0	20.9	24.4	3.37	264	107		8.295	21.0	4	268	D-4
20	P70	68.6	21.0	24.8	3.49	259	116		8.340	21.8	4	263	D-4
21	P71	69.0	21.2	24.3	3.46	260	101		8.372	22.2	6	266	D-4
22	P72	69.2	21.3	25.4	3.54	259	106		8.318	22.2	3	262	D-4
23	P73	69.2	21.4	26.0	3.60	256	111		8.428	20.5	6	262	D-4
24	P74	72.0	20.6	28.0 → 3.68	260	119 →			8.080	21.2	0	260	D-4
25	P75	72.0	20.4	28.9	3.26	262	121		8.135	21.2	0	262	D-4
26	P76	73.2	20.7	27.3	3.67	254	120		8.285	21.2	2	261	D-4
27	P77	65.0	19.1	16.5	2.39	254	76		8.403	21.0	6	260	D-4
28	P78	69.7	19.8	21.4	3.00	260	86		8.341	22.0	4	264	D-4
29	P79	70.9	20.1	22.3	3.22	266	86		8.399	22	6	272	D-4
30	P80	90.5	20.3	25.1	3.44	262	99		8.380	22	4	266	D-4
31	P81	72.6	21.0	26.3	3.43	267	102		8.403	22	4	271	D-4
UG													
1	P82	73.9	20.1	27.4	3.30	278	112		8.245	22	0	278	D-4
2	P83	73.9	21.0	28.6	3.72	269	109		8.301	24	2	271	D-4
3	P84	73.9	20.8	29.5	3.65	274	113		8.179	24	0	274	D-4
4	P85	74.1	21.1	29.9	3.80	269	111		8.291	23	4	273	D-4
5	P86	75.1	21.0	30.5	3.51	266	120		8.337	24.5	4	270	D-4
6	P87	75.1	21.2	29.3	3.89	269	113		8.295	23.5	2	271	D-4
7	P88	80.4	21.0	28.9	3.71	268	98		8.338	23.5	4	272	D-4
8	P89	73.9	20.9	31.2	4.05	266	116		8.356	25.5	10	276	D-4
9	P90	75.4	20.9	30.6	3.92	278	112		8.331	25.0	4	282	D-4
10	P91	75.0	21.6	31.3	4.12	264	133		8.035	14.6	0	264	D-4
11	P92	73.9	21.1	32.3	4.24	266	130		8.362	15.8	6	272	D-4
12	P93	74.8	22.2	32.8	4.36	278	145		8.212	17.6	0	278	D-4
13	P94	70.9	20.7	31.2	4.21	256	125		8.417	17.8	4	260	D-4
14	P95	75.5	22.0	32.0	4.25	268	117		8.420	18.0	6	274	D-4
5	P96	74.4	21.8	32.9	4.40	264	117		8.345	15.7	6	270	D-4
6	P97	74.9	21.8	33.6	4.26	264	113		8.364	17.0	4	268	D-4

ATE	SAMPLE NO.	Ca^{++}	Mg^{++}	Na^{+}	K^{+}	HCO_3^{-}	$SO_4^{=}$	Cl^{-}	pH	TEMP. °C	$CO_3^{=}$	$HCO_3^{-}+CO_3^{=}$	LOCATION OF SAMPLE
AUG.													
17	P98	74.9	21.8	30.0	4.03	276	130		8.327	18.0	4	280	D-4
18	P99	72.5	21.3	32.4	4.12	266	140		8.418	19.0	4	270	D-4
19	P100	74.8	21.9	32.8	4.24	268	140		8.360	21.0	6	274	D-4
20	P101	73.5	22.3	32.9	4.25	262	140		8.384	20.0	6	268	D-4
21	P102	73.0	21.3	33.6	4.30	264	140		8.220	15.5	0	264	D-4
22	P103	72.5	21.1	34.6	4.61	248	145		8.437	15.0	6	254	D-4
23	P104	73.0	21.5	34.3	4.54	265	145		8.240	17.0	1	266	D-4
24	P105	73.5	21.3	34.9	4.56	263	150		8.245	23.0	1	264	D-4
25	P106	73.5	21.1	34.9	4.44	256	158		8.435	20.0	6	272	D-4
26	P107	73.1	21.2	35.2	4.59	254	162		8.406	19.0	4	258	D-4
27	P108	52.2	14.2	22.6	4.21	194	110		7.793	13.8	0	194	D-4
28	P109	76.4	22.2	30.9	4.10	288	125		8.289	15.5	2	290	D-4
29	P110	77.1	22.4	32.9	4.32	271	145		8.408	22.0	8	279	D-4
30	P111	77.1	22.6	33.7	4.30	276	145		8.279	20.5	2	278	D-4
31	P112	76.1	22.6	34.6	4.28	295	140		8.315	18.0	2	297	D-4
SEPT													
1	P113	75.5	22.4	34.6	4.31	266	140		8.453	14.8	6	272	D-4
2	P114	74.8	22.5	35.0	4.30	272	145		8.363	19.0	2	274	D-4
16	McKinnon	85.5	27.9	31.9	2.50	358	47	4	8.285	25.5	8		D-7
7	Deadox	76.7	22.4	12.35	2.77	326	34	4	7.959	26.0	0		D-6

TIME	SAMPLE NO.	Ca^{++}	Mg^{++}	Na^{+}	K^{+}	HCO_3^-	$SO_4^=$	Cl^-	pH	TEMP. °C	$CO_3^=$	$HCO_3^- + CO_3^=$	LOCATION OF SAMPLE
25													
4:10 PM	T5-1	69.5	24.5	22.6	3.31	284	83		8.102	20.6	0		D-5 Wilson C. Weir.
10:05PM	2	69.1	20.4	21.6	3.26	264	85		8.143	21.0	0		D-5
1:15 PM	3	64.0	19.4	20.2	3.20	252	79		8.159	21.5	0		D-5
26													
12:10AM	4	64.0	19.3	19.9	3.18	246	83		8.125	21.5	0		D-5
4:15 AM	5	63.0	19.0	18.9	3.11	236	77		8.159	17.5	0		D-5
7:10 AM	6	58.5	18.5	19.7	2.96	234	75		8.031	19.0	0		D-5
1:15 PM	7	69.5	19.2	15.3	2.82	236	83		7.955	19.3	0		D-5
4:15 AM	8	61.0	18.9	13.3	2.68	228	86		7.834	21.0	0		D-5
5:15 AM	9	52.9	16.6	11.2	2.45	228	64		8.129	20.7	0		D-5
7:15 AM	10	53.0	15.5	9.3	2.22	196	49		7.924	20.1	0		D-5
9:10 AM	11	52.8	14.9	8.0	2.22	185	39		7.913	19.5	0		D-5
1:15 AM	12	46.0	13.2	7.95	1.95	182	29		7.825	19.5	0		D-5
3:15AM	13	42.4	12.45	7.4	1.82	170	27		7.895	20.0	0		D-5
5:20AM	14	44.2	12.5	7.45	1.76	160	27		7.922	21.0	0		D-5
7:15 PM	15	44.1	12.3	8.20	1.60	165	25		7.915	20.2	0		D-5
9:15 PM	16	36.9	11.5	8.0	1.65	171	29		7.979	20.5	0		D-5
11:00PM	17	38.6	12.0	7.75	1.69	189	26		8.040	21.0	0		D-5
27													
1:30 PM	18	40.6	11.8	6.76	2.30	176	27		8.000	19.0	0		D-5
3:05 PM	19	38.2	11.5	6.40	2.12	156	30		7.950	20.5	0		D-5
5:50PM	20	38.2	11.5	6.15	2.89	160	32		7.901	20.5	0		D-5
27													
7:10AM	21	40.0	10.45	8.5	4.70	148	32		7.796	19.5	0		D-5
9:15 AM	22	38.7	9.85	8.1	5.54	142	30		7.902	19.5	0		D-5
11:15 AM	23	38.9	9.55	6.85	5.98	130	37		7.845	21.5	0		D-5
1:15 AM	24	45.0	12.3	6.60	6.45	122	30		7.875	22.0	0		D-5
3:50 AM	25	43.2	12.7	4.45	5.48	122	27		7.927	23.0	0		D-5
5:30 AM	26	47.8	12.7	4.35	3.14	117	26		7.899	23.5	0		D-5
7:15 AM	27	42.4	12.8	4.39	3.2	132	25		7.850	22.2	0		D-5
9:15PM	28	42.2	12.9	4.61	2.92	132	28		7.831	21.0	0		D-5
11:45 PM	29	42.5	13.1	4.54	2.65	132	27		7.890	21.5	0		D-5
2:00PM	30	49.5	14.8	4.75	2.42	142	33		7.841	20.0	0		D-5
28													
7:45AM	31	54.5	15.8	5.87	2.22	156	33		7.895	21.0	0		D-5
11:20AM	32	53.0	16.1	6.25	2.33	166	35		7.979	21.0	0		D-5
2:00PM	33	67.3	19.9	6.50	2.42	166	38		7.989	22.0	0		D-5
5:55PM	34	63.5	17.8	6.70	2.42	166	39		8.101	23.0	0		D-5
8:07PM	35	59.6	16.6	7.14	2.37	175	38		8.092	20.0	0		D-5
29													
3:25AM	36	59.6	17.1	7.14	2.27	173	34		7.871	20.0	0		D-5
7:50AM	37	53.1	16.3	6.45	2.16	168	43		7.921	19.5	0		D-5
11:15AM	38	58.4	16.1	5.87	2.14	172	40		8.010	19.0	0		D-5
1:15 PM	39	49.0	15.5	5.05	2.22	165	36		8.044	19.2	0		D-5

TIME	SAMPLE NO.	Ca^{++}	Mg^{++}	Na^{+}	K^{+}	HCO_3^{-}	$SO_4^{=}$	Cl^{-}	pH	TEMP. °C	$CO_3^{=}$	HCO_3^{-} + $CO_3^{=}$	LOCATION OF SAMPLE
29 :55 PM	T5-40	44.8	13.9	4.0	2.07	141	32		7.930	22.0	0		D-5
2:20 PM	41	44.4	13.9	4.09	1.79	139	25		8.009	22.2	0		D-5
30 8:10 AM	42	45.4	14.8	4.84	1.76	156	26		8.015	21.0	0		D-5
8:20 PM	43	45.5	15.3	5.50	1.85	166	30		8.130	20.5	0		D-5
7:00 PM	44	66.5	15.7	5.76	1.93	170	33		8.089	20.5	0		D-5
1:30 PM	45	39.0	17.0	6.17	1.89	176	34		7.819	19.1	0		D-5
1 7:55 AM	46	53.3	14.65	6.4	1.90	186	36		8.101	19.5	0		D-5
10:25 PM	47	51.5	14.4	7.7	2.0	203	39		8.209	19	0		D-5

* SAMPLE NO. IS ALSO LOCATION

SAMPLE NO*	Ca^{++}	Mg^{++}	Na^{+}	K^{+}	HCO_3^{-}	$SO_4^{=}$	Cl^{-}	pH	TEMP. °C	$CO_3^{=}$	$HCO_3^{-} + CO_3^{=}$
F1-1	93.9	22.9	19.1	4.95	334	85	9	7.205	22	0	
F1-2	93.9	21.4	22.4	4.36	345	124	6	7.200	22.5	0	
F1-3	83.1	29.2	46.9	17.6	562	67	790	7.549	21	0	
F2-1	104	18.4	52.2	10.9	313	124	26	7.501	22	0	
F2-2	98.6	22.6	24.9	4.90	336	95	4.5	7.252	22.5	0	
F2-4	42.9	3.9	226	13.4	50	32	710	10.070	25	0	
F3-1	96.7	23.5	44.8	7.82	452	75	17	7.870	22.5	0	
F3-2	100	24.4	26.4	550	332	129	8	7.150	21.5	0	
F3-3	69.6	21.1	347	16.0	450	34	570	7.520	21.5	0	
F4-2	75.0	22.6	25.9	1.78	400	39	10.5	7.354	17.5	0	
F5-3	95.0	24.7	34.5	5.30	336	131	13.5	7.445	20.	0	
F5-4	82.5	22.9	35.2	5.25	332	99	15	7.462	17.5	0	
F6-1	91.6	25.2	44.6	8.14	368	108	18	7.660	18.5	0	
F6-2	85.6	23.8	27.2	5.28	358	125	9.5	7.450	18	0	
F6-3	202	81.0	1628	37.9	402	50	3270	7.288	21.5	0	
F7-1	44.5	16.7	5.04	2.99	141	16	4	6.908	22.5	0	
F7-3	78.0	23.4	18.5	4.02	300	69	4	7.552	16.1	0	
F8-3	71.6	18.8	52.6	8.88	250	80	8.0	8.900	16.5	0	
F9-1	85.6	29.8	43.7	9.31	429	92	37.5	7.825	18	0	
F9-2	109	23.4	28.8	5.50	420	95	9	7.287	22	0	
F9-3	114	19.2	39.3	7.96	340	83	14	7.500	20.5	0	
F10-1	73.5	17.6	70.0	8.95	342	68	39	7.721	21.5	0	
F10-2	104	22.6	27.2	4.21	403	82	7.0	7.151	22.2	0	
F10-3	49.8	13.2	223	14.1	480	78	208	7.812	23	0	
F11-1	108	23.8	28.5	5.05	414	76	7.0	7.163	22.2	0	
F11-2	88.6	22.4	38.2	5.65	396	83	6.0	7.362	23.5	0	
F12-1	102	22.3	43.8	7.55	350	90	21.5	7.484	23	0	
F12-2	110	23.2	28.4	4.19	386	101	7.5	7.024	21	0	
F13-1	43	9.95	201	11.2	430	131	41.5	9.105	23	28.0	
F13-2	123	24.2	23.8	4.94	461	112	6.0	7.223	20.	0	
F14-1	116	24.0	25.2	5.95	386	108	4	7.252	21	0	
F14-2	167	32.5	21.4	4.10	592	12.2	5	6.938	20.5	0	
F17-1	107	30.7	4.16	4.52	394	11	6	7.483	23	0	
F18-1	82.7	28.0	2.98	2.56	239	13	3	7.739	23.5	0	
F19-1	118	41.3	7.15	3.46	554	39	10	7.135	23	0	

SAMPLE NO. + LOCATION	Ca^{++}	Mg^{++}	Na^{+}	K^{+}	HCO_3^{-}	$SO_4^{=}$	Cl^{-}	pH	TEMP °C	$CO_3^{=}$
F20-1	84.1	23.2	6.10	3.18	354	10	4	7.303	22.2	0
F21-1	90.7	37.3	1.67	1.77	4.30	6	2	7.144	19.5	0
F22-1	88.4	27.9	4.76	3.33	392	2	3	7.193	20.5	0
F23-1	133	36.3	3.57	4.59	542	3	3	7.118	17.5	0
F24-1	55.6	14.5	9.50	3.79	306	11	3	7.632	18.2	0
F25-1	67.2	27.4	1.67	.64	360	5	2	7.197	22.2	0
F26-1	110	39.4	1.10	.81	577	1	2	7.032	20.2	0
F27-1	93.4	21.7	2.68	1.57	320	6	2	7.445	21.0	0
F27-2	39.6	.60	15.1	8.55	32	3.8	5	11.448	82	144
F27-3	58.4	15.1	2.23	2.86	212	21	5	7.612	17	0
F28-1	111	36.2	5.05	2.82	509	25	6.5	7.537	23.5	0
F28-2	113	34.6	1.71	3.14	556	15	4	7.042	19	0
F28-3	82	22.0	5.36	4.59	358	33	3	7.395	18	0
F29-1	103	17.5	14.7	5.80	230	108	9	8.500	20.5	0
F29-2	6.07	3.0	116	11.03	94	104	5	11.248	19.5	236
F29-3	70.7	24.1	59.9	8.96	3	40	4	7.505	23	0
F30-1	107	32.0	7.45	6.56	428	33	4	7.295	20	1
F33-1	46.0	13.3	8.92	2.79	194	25	3	6.270	25	0
F34-1	100	25.9	24.0	5.89	350	74	5	7.350	21	0
F35-1	99.8	24.1	35.3	5.47	402	88	4	7.020	21.5	0
F36-1	85.6	20.2	37.3	8.40	276	92	9	7.320	25	0
F37-1	103	25.0	19.3	3.84	414	63	6	7.180	22	0
F38-2	98.9	25.2	27.8	6.84	340	116	5	7.645	22	0
F38-3	77.9	21.2	36.0	5.95	390	47	16	7.639	20	0
F39-3	94.4	20.8	28.6	3.92	300	113	4	7.450	21.5	0
F39-2	74.6	19.6	27.8	4.62	285	111	10	7.670	19.5	0
F41-1	101	21.7	20.2	4.30	330	72	6	7.630	20.4	0
F41-2	102	25.3	26.9	4.85	342	115	4	7.420	17.0	0
F42-1	74.6	20.8	182	15.1	530	70	154	7.660	25	0
F43-1	28.5	10.8	820	17.0	662	11	1075	7.947	20.5	0
F43-2	60.6	.121	23.1	5.46	89	94	5	10.80	23.5	33
F44-1	40	16.6	40.0	7.26	110	209	11	9.29	21.5	14
F44-2	125	29.2	213	12.5	410	397	144	7.58	17.5	0
F44-3	136	43.1	715	21.8	444	590	830	8.90	18.0	0
F45-1	172	35.2	36.0	5.26	296	321	26	7.150	25.0	0

SAMPLE NO. LOCATION	Ca^{++}	Mg^{++}	Na^{+}	K^{+}	HCO_3^{-}	$SO_4^{=}$	Cl^{-}	pH	TEMP. °C	$CO_3^{=}$
GS 1	27.2	17.2	3.50	1.97	168	5	2		21.5	0
GS 5	8.49	3.23	6.14	2.57	56.0	7	2		20.8	0
GS 6	43.5	96.0	3280.	68.2	107	19	5980.	8.991	19.5	22
GS 7	21.2	10.3	697.	42.4	482	23	955	9.170	20.0	26
GS 8	8.6	.06	173	5.77		91	161	10.880		
GS 9	146	30.7	1725.	40.7	116	44	5450	6.68	24.0	0
GS 10	11.8	10.8	48.0	9.74	200	24	9	7.705	20.0	0
GS 12	12.7	1.01	244	11.0	443	101	14	8.204	19.0	0
GS 16	8.6	1.91	82.4	8.69	210	1	6	9.822	19.0	36

SAMPLE LOCATION	PERCENT SATURATION									CATION ANION RATIO
	CALCITE	DOLOMITE	ARAGONITE	GYPSUM	MAGNESITE	NESQUEHONITE	LANSFORDITE	HYDRO-MAGNESITE	HUNTITE	
1-1	112.0	76.3	72.5	2.7	0.0	0.1	0.1	0.0	0.0	100.4
1-2	113.9	74.2	73.4	3.8	0.0	0.1	0.1	0.0	0.0	89.5
1-3	268.0	637.5	175.1	1.2	0.1	0.3	0.2	0.0	0.0	83.2
2-1	221.6	215.9	143.5	4.1	0.0	0.1	0.1	0.0	0.0	109.5
2-2	133.3	102.6	86.0	3.1	0.0	0.1	0.1	0.0	0.0	104.9
2-4	4374	40626	2759	.3	0.3	0.9	0.7	0.0	0.0	71.6
3-1	706	3044	455	2.3	0.1	0.5	0.3	0.0	0.0	94.2
3-2	99.4	59.5	64.7	4.1	0.0	0.1	0.0	0.0	0.0	99.2
3-3	191.3	281.1	124.4	.6	0.1	0.2	0.1	0.0	0.0	85.6
4-2	132.7	120.9	89.6	1.1	0.0	0.1	0.1	0.0	0.0	88.3
5-3	179.9	201.6	118.5	4.0	0.0	0.1	0.1	0.0	0.0	97.6
5-4	149.2	139.8	100.8	2.8	0.0	0.1	0.1	0.0	00	96.7
6-1	292.3	543.3	195.5	3.2	0.1	0.2	0.2	0.0	0.0	100.0
6-2	161.7	165.9	108.7	3.6	0.0	0.1	0.1	0.0	0.0	86.4
6-3	183.4	358.6	119.3	1.0	0.1	0.2	0.2	0.0	0.0	88.5
7-1	14.5	2.0	9.4	0.3	0.0	0.0	0.0	0.0	0.0	141.0
7-3	156.2	161.1	106.9	2.0	0.0	0.1	0.1	0.0	0.0	103.9
8-3	2507	34504	1709	2.1	0.6	1.8	1.4	0.0	0.0	120.8
9-1	456.1	1655	3065	2.5	0.1	0.5	0.3	0.0	0.0	88.6
9-2	187.2	188.4	121.3	3.2	0.0	0.1	0.1	0.0	0.0	96.0
9-3	256.0	267.9	168.0	3.1	0.0	0.1	0.1	0.0	0.0	119.0
10-1	293.5	507.9	190.9	1.8	0.1	0.2	0.1	0.0	0.0	103.3
10-2	130.8	93.5	84.6	2.7	0.0	0.1	0.1	0.0	0.0	98.0
10-3	321.9	703.3	206.7	1.2	0.1	0.2	0.2	0.0	0.0	88.7
11-1	142.2	112.2	92.0	2.6	0.0	0.1	0.1	0.0	0.0	101.7
11-2	187.4	229.0	119.8	2.4	0.0	0.1	0.1	0.0	0.0	96.2
12-1	244.7	333.4	157.1	2.9	0.0	0.1	0.1	0.0	0.0	109.8
12-2	92.7	44.5	60.6	3.5	0.0	0.1	0.0	0.0	0.0	101.1
13-1	3945	83043	2534	1.5	0.7	2.2	1.6	0.0	0.0	100.9
13-2	182.6	157.6	119.9	4.1	0.0	0.1	0.1	0.0	0.0	92.4
14-1	164.3	136.9	107.3	3.9	0.0	0.1	0.1	0.0	0.0	103.6
14-2	156.1	116.8	102.4	5.2	0.0	0.1	0.1	0.0	0.0	97.3
17-1	3240	6504	1953	0.4	0.1	0.2	0.2	0.0	0.0	119.0
9-1	192.5	335.7	123.6	1.3	0.1	0.2	0.1	0.0	0.0	95.2
20-1	145.7	147.7	94.2	0.3	0.0	0.1	0.1	0.0	0.0	105.3
21-1	113.9	128.1	75.5	0.2	0.0	0.1	0.1	0.0	0.0	106.7
22-1	121.5	114.1	79.7	0.1	0.0	0.1	0.1	0.0	0.0	106.9
23-1	174.0	190.7	117.5	0.1	0.0	0.1	0.1	0.0	0.0	129.6
24-1	134.3	162.9	110.2	0.3	0.0	0.1	0.1	0.0	0.0	84.0
25-1	95.9	94.9	62.0	0.1	0.0	0.1	0.1	0.0	0.0	94.0
26-1	139.2	170.7	91.6	0.0	0.0	0.1	0.1	0.0	0.0	93.6
27-1	149.7	228.1	130.5	0.2	0.0	0.1	0.1	0.0	0.0	121.7

SAMPLE LOCATION	PERCENT SATURATION									
	CALCITE	DOLOMITE	ARAGONITE	GYPSUM	MAGNESITE	HEXAHYDRITE	ANHYDRITE	HYDRO-MAGNESITE	HALITE	CATION-ANION RATIO
27-2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	46.3
31-3	111.6	72.5	25.7	0.6	0.0	0.1	0.1	0.0	0.0	106.8
38-1	4500	1771	287.	0.8	0.1	0.4	0.3	0.0	0.0	97.4
28-2	134.5	132.7	89.7	0.5	0.0	0.1	0.1	0.0	0.0	90.6
18-3	152.2	143.0	102.3	1.0	0.0	0.1	0.1	0.0	0.0	94.2
29-1	1573	4408	1032	3.8	0.2	0.7	0.5	0.0	0.0	117.4
29-3	1.9	0.0	1.2	1.2	0.0	0.0	0.0	0.0	0.0	8.34
26-1	190.8	264.1	125.7	1.1	0.1	0.2	0.1	0.0	0.0	108.4
33-1	5.0	0.2	3.2	0.5	0.0	0.0	0.0	0.0	0.0	101.7
34-1	169.3	182.0	110.6	2.4	0.0	0.1	0.1	0.0	0.0	112.1
35-1	90.1	48.7	58.6	2.8	0.0	0.1	0.0	0.0	0.0	101.2
36-1	125.1	98.4	78.9	2.7	0.0	0.1	0.1	0.0	0.0	98.4
37-1	143.3	125.1	92.9	2.1	0.0	0.1	0.1	0.0	0.0	98.4
38-2	325.2	669.0	210.7	3.7	0.1	0.2	0.2	0.0	0.0	103.2
38-3	283.5	526.3	186.8	1.3	0.1	0.2	0.1	0.0	0.0	93.9
39-3	174.1	164.1	113.3	3.6	0.0	0.1	0.1	0.0	0.0	105.2
39-2	206.0	262.5	136.4	3.0	0.0	0.2	0.1	0.0	0.0	91.7
41-1	303.8	479.1	199.5	2.5	0.1	0.2	0.1	0.0	0.0	110.4
41-2	165.4	152.0	112.2	3.9	0.0	0.1	0.1	0.0	0.0	104.1
42-1	400.9	1310	2528	1.5	0.1	0.3	0.2	0.0	0.0	94.8
43-1	251.7	607.5	165.2	0.1	0.1	0.3	0.2	0.0	0.0	92.7
43-2	9434	39918	6031	1.8	0.3	1.0	0.7	0.0	0.0	89.7
44-1	1988	22888	1648	2.9	0.6	1.8	1.3	0.0	0.0	76.3
44-2	266.6	375	180.0	11.0	0.1	0.2	0.2	0.0	0.0	95.7
44-3	4350	164000	3259	11.0	1.4	4.3	3.2	0.0	0.0	97.7
45-1	143.0	1115	96.2	12.8	0.0	0.1	0.1	0.0	0.0	107.4
51	20.1	6.6	13.4	0.1	0.0	0.0	0.0	0.0	0.0	102.1
56	439.5	20665	284	0.1	1.0	2.9	2.2	0.0	0.0	89.9
57	23600	162000	11800	0.3	0.0	0.0	0.0	0.0	0.0	92.0
59	10.2	0.6	6.5	0.6	0.0	0.0	0.0	0.0	0.0	54.8
510	31.3	21.6	20.6	0.1	0.0	0.1	0.0	0.0	0.0	94.6
512	168.3	51.3	112.0	0.5	0.0	0.0	0.0	0.0	0.0	118.9
516	—	—	—	—	—	—	—	—	—	—
104	236.2	434.1	163.3	1.5	0.1	0.3	0.2	0.0	0.0	47.8
1	574	2459	379	1.7	0.2	0.6	0.5	0.0	0.0	89.2
6	560.6	2380	345	2.2	0.2	0.7	0.5	0.0	0.0	89.5
10	30.3	6.94	21.2	1.9	0.1	0.3	0.3	0.0	0.0	90.4
14	877	6747	578	1.8	0.3	0.9	0.7	0.0	0.0	84.7
15	169.6	363.6	103.2	1.7	0.5	1.6	1.2	0.0	0.0	92.0
16	939	6505	662	1.7	0.4	1.1	0.8	0.0	0.0	90.1
17	657.5	3312	456	1.9	0.2	0.8	0.6	0.0	0.0	92.7
22	261	631	170	0.7	0.1	0.3	0.2	0.0	0.0	91.1
26	730	4463	468	1.4	0.2	0.7	0.5	0.0	0.0	85.8
30	635	3201	419	2.2	0.2	0.6	0.4	0.0	0.0	96.2

SAMPLE LOCATION	PERCENT SATURATION									CATION-ANION RATIO	
	CALCITE	DOLOMITE	ARAGONITE	GYPSUM	MAGNESITE	NESQUEHONITE	LANSFORDITE	HYDRO-MAGNESITE	HUNTITE		
34	955	7485	616.5	2.2	0.3	0.8	0.6	0.0	0.0	95.9	
37	775	6458	505.8	2.4	0.2	0.7	0.5	0.0	0.0	101.2	
38	750	4181	504	2.4	0.2	0.7	0.5	0.0	0.0	98.4	
39	528	1815	373	2.3	0.2	0.5	0.4	0.0	0.0	96.5	
40	444	1554	308	2.1	0.2	0.5	0.4	0.0	0.0	89.5	
41	867	6538	562	2.3	0.3	0.8	0.6	0.0	0.0	90.9	
42	800	5262	520	1.6	0.2	0.7	0.5	0.0	0.0	99.6	
43	902	6598	574	2.1	0.2	0.7	0.6	0.0	0.0	101.0	
44	760	4142	450	2.0	0.2	0.6	0.5	0.0	0.0	97.9	
45	775	4355	516	2.2	0.2	0.7	0.5	0.0	0.0	100.4	
46	156	168	102	0.6	0.0	0.1	0.1	0.0	0.0	110.6	
47	111	94	72	0.5	0.0	0.1	0.1	0.0	0.0	124.2	
48	216	345	141.3	0.8	0.1	0.2	0.0	0.0	0.0	121.7	
49	242	377	161.2	1.0	0.1	0.2	0.1	0.0	0.0	121.8	
50	196	305	128.0	0.6	0.1	0.2	0.1	0.0	0.0	117.6	
51	300	589	199.1	0.9	0.1	0.2	0.2	0.0	0.0	108.0	
52	343	879	224	1.0	0.1	0.3	0.2	0.0	0.0	100.4	
53	387	1187	248	1.2	0.1	0.3	0.2	0.0	0.0	102.2	
54	449	1533	291	1.2	0.1	0.4	0.3	0.0	0.0	99.3	
55	344	911	229	1.0	0.1	0.3	0.2	0.0	0.0	100.0	
80	734	3550	480	2.2	0.2	0.6	0.4	0.0	0.0	98.8	
81	862	5077	556	2.0	0.2	0.6	0.5	0.0	0.0	99.8	
82	554	2011	360	2.3	0.1	0.4	0.3	0.0	0.0	97.4	
83	776	4146	498	2.3	0.2	0.6	0.4	0.0	0.0	99.4	
84	707	3420	458	2.4	0.2	0.5	0.4	0.0	0.0	96.5	
85	704	3434	456	2.4	0.2	0.5	0.4	0.0	0.0	99.0	
86	828	4650	536	2.6	0.2	0.6	0.5	0.0	0.0	97.4	
88	864	5162	555	2.3	0.2	0.6	0.5	0.0	0.0	99.9	
89	803	4610	506	2.5	0.2	0.6	0.4	0.0	0.0	99.4	
87	801	4387	519	2.4	0.2	0.6	0.4	0.0	0.0	100.3	
S-19	139.5	141	91.5	0.6	0.0	0.1	0.1	0.0	0.0	98.4	
S-20	127	117.4	83.3	0.6	0.0	0.1	0.0	0.0	0.0	95.6	
S-21	94.6	55.2	62.7	0.6	0.0	0.1	0.1	0.0	0.0	106.1	
S-22	111.5	74.5	73.8	0.6	0.0	0.1	0.1	0.0	0.0	107.4	
S-23	98.0	58.3	63.7	0.7	0.0	0.1	0.0	0.0	0.0	102.7	
Kinta	1474	18564	929	1.3	0.4	1.2	0.9	0.0	0.0	110.9	D6
Red Oak	593	2732	374	1.0	0.1	0.5	0.3	0.0	0.0	101.9	D-7
P14	904	7310	596	2.1	0.3	0.9	0.7	0.0	0.0	85.9	
P15	991	10115	625	1.9	0.3	0.1	0.7	0.0	0.0	86.5	
P16	1139	7910	801	2.2	0.3	1.1	0.8	0.0	0.0	99.0	
P17	560	2794	393	1.8	0.2	0.7	0.6	0.0	0.0	84.8	
P37	995	7474	643	3.0	0.3	0.8	0.6	0.0	0.0	100.3	
P38	927	5727	632	3.1	0.3	0.8	0.6	0.0	0.0	99.4	
P39	687	2999	481	2.9	0.2	0.7	0.5	0.0	0.0	103.2	
P40	725	3547	501	2.9	0.3	1.0	0.7	0.0	0.0	95.2	

Appendix F

Hydraulic head data for piezometers

Piezometer No.	Depth to water, feet, from top of casing Date: Aug 21-23	Date: Sept 8	Date: Oct 7&8	Date: Oct 21
F1-1	8.70	8.80	8.80	8.85
F1-2	9.45	9.55	9.80	9.70
F1-3	8.40	8.55	9.05	9.10
F2-1	15.65	17.40	7.55	7.60
F2-2	15.60	17.30	7.60	7.65
F2-3	15.65	17.45	7.60	7.70
F2-4	16.40	18.0	8.20	8.30
F3-1	18.95	19.10	9.30	9.45
F3-2	21.5	21.60	12.45	11.95
F3-3	18.8	18.45	8.40	8.40
F4-2	27.7	27.7	18.40	19.20
F4-1	27.0	.60	2.50	4.10
F5-1	7.30	7.40	7.85	7.95
F5-2	DRY	DRY	DRY	DRY
F5-3	10.0	11.90	12.35	12.4
F5-4	8.40	8.60	9.10	9.15
F6-1	6.60	6.85	7.20	7.30
F6-2	8.45	10.15	10.60	10.60
F6-3	16.55	15.25	13.60	13.00
F7-1	29.65	30.15	21.05	21.50
F7-2	DRY	26.55	13.05	17.05
F7-3	40.55	40.65	31.25	29.85
F8-1	DRY	31.70	21.95	21.95
F8-2	DRY	DRY	11.35	21.45
F8-3	45.35	44.95	34.50	34.70
F9-1	13.45	15.05	6.80	6.80
F9-2	15.95	15.85	5.95	6.10
F9-3	15.25	16.75	5.20	5.15
F10-1	13.10	8.70	8.90	8.90
F10-2	10.85	10.90	11.20	11.20
F10-3	12.90	14.00	14.40	15.0
F11-1	3.05	2.95	3.20	3.10
F11-2	3.30	3.20	3.40	3.30
F12-1	2.50	2.40	2.50	2.55
F12-2	4.30	4.20	4.50	4.30
F13-1	7.45	6.60	6.90	7.85
F13-2	5.65	5.55	5.90	5.80

Piezometer No.	Depth to water, feet Date: Aug 21-23	Date: Sept 8	Date: Oct 7-8	Date: Oct. 21
F14-1	13.45	15.55	5.75	5.65
F14-2	12.50	14.05	3.95	3.70
F17-1	7.45	8.45	8.05	7.25
F18-1	4.25	4.80	2.35	3.10
F19-1	4.25	4.90	2.15	2.40
F20-1	3.35	3.90	1.95	2.35
F21-1	8.75		1.00	1.20
F22-1	—	—	1.70	1.90
F23-1	2.80	3.00	2.75	2.90
F24-1	7.40	8.50	6.75	6.90
F25-1	4.25	4.95	3.80	4.0
F26-1	5.95	6.45	4.80	4.6
F27-1	5.40	5.65	6.65	7.20
F27-2	21.80	23.60	14.90	14.90
F27-3	33.1	33.0	24.00	24.30
F27-4	DRY	DRY	21.15	DRY
F28-1	8.65	9.60	10.30	10.40
F28-2	5.60	7.35	8.20	8.90
F28-3	8.45	9.60	10.95	11.60
F29-1	7.75	8.90	8.35	8.45
F29-2	9.15	10.10	9.90	10.10
F29-3	10.65	11.50	11.45	11.60
F30-1	DRY	DRY	28.40	DRY
F30-2	7.85	8.50	8.50	8.65
F33-1	8.75	10.45	10.55	10.85
F34-1	2.25	2.50	2.75	2.65
F35-1	2.75	3.00	3.15	3.20
F36-1	6.55	6.60	7.15	7.25
F37-1	11.15	11.10	11.14	11.55
F38-1	DRY	18.3	8.70	DRY
F38-2	—	18.0	8.55	12.2
F38-3	—	16.55	4.05	9.45
F39-1	7.45	8.00	8.35	9.00
F39-2	9.80	10.45	11.75	8.80
F39-3	8.45	8.40	9.15	7.35

Piezometer No.	Depth to water, feet Date: Aug 21-23	Date: Sept 8	Date: Oct 7 & 8	Date: Oct 21
F40-1	MUD	1.80	2.50	MUD
F41-1	10.50	10.40	9.80	10.00
F41-2	9.15	9.25	10.75	10.90
F42-1	18.25	20.20	10.60	10.80
F42-2	18.35	19.85	10.80	11.00
F43-1	10.00	12.20	2.80	2.80
F43-2	18.05	18.05	9.10	9.60
F44-1	9.30	11.60	11.20	11.0
F44-2	9.55	11.65	11.45	11.15
F44-3	10.15	11.80	12.30	12.25
F45-1	9.50	9.65	10.4	10.4

APPENDIX G

Detailed description of the hydrograph separation technique.

Discharge at any time t during the storm runoff period for a given component is as follows:

$$Qc = \frac{Cst \cdot Qst}{C_c}$$

where Qc is the discharge contribution from the source under consideration.

Cst is the total concentration of the characteristic ion in the streamflow

Qst is the total stream discharge

Cc concentration of the characteristic ion in the groundwater

Expressing the above relationship in another manner, the discharge contribution to the streamflow is equal to the product of the dilution ratio and stream discharge. For each data point, the above calculation is made. It is necessary to assume a linear variation in concentration of the characteristic ion during the storm runoff period from a value before to a value after the storm runoff period.