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[illegible]DELING REGIONAL GROUNDWATER FLOW WITH ENVIRONMENTAL ISOTOPES: ROSS CREEK BASIN, ALBERTA

by

© James Thomas Freeman

A THESIS
SUBMITTED TO THE FACULTY OF GRADUATE STUDIES AND RESEARCH
IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE
OF MASTER OF SCIENCE

DEPARTMENT OF GEOLOGY

EDMONTON, ALBERTA
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....
Supervisor

Frank W. Schwartz
....

....

Date May 15, 86

DEDICATION

I dedicate this project to Catherine, my wife and friend.

ABSTRACT

Groundwater samples from Ross Creek Basin have been analyzed for the stable isotopes of water ^{18}O and D, and the radioisotopes tritium and ^{14}C. Ross Creek Basin is a 600 km^2 watershed in the southeastern corner of Alberta on the northern flank of the Cypress Hills and is an area that is characterized by worsening water allocation issues. A field mapping and drilling program was carried out by the Alberta Government in 1983-84 in order to delineate aquifers in the region. The results from this work have been compared and contrasted with the isotope data in assembling a conceptual model of regional groundwater flow in Ross Creek Basin.

Stable isotopes were utilized to distinguish types of groundwater flow systems and to point out the mechanisms of recharge in the basin. Because of the large annual variation in the $\delta^{18}O$ and δD content of precipitation (over 20‰ and 160‰ respectively), the delineation of a meteoric water line for the area was straight forward. This line has the equation:

$$\delta D = 7.7\delta^{18}O + 2.00\text{‰}$$

Many of the groundwater samples taken in the area plotted to the right of the meteoric water line. Depression-focused water bodies appear to undergo simultaneous evaporation and recharge, resulting in isotopic enrichment of the groundwater.

Several groundwater systems appear may have been recharged under climatic conditions that are 3 to 4°C colder than present day recharge temperatures. A single ^{14}C datum indicated that this water was recharged at approximately 9000 years before present. No altitude effect on modern groundwaters was found.

Radioisotope analyses were compared to transit time predictions from numerical modeling of the basin. In this manner, the effects of different levels of groundwater flow could be accounted for in the age dating of this largely unconfined hydrological system. It was demonstrated that the poorly sorted material capping the Cypress Hills is several orders of magnitude less permeable than was previously thought. The K_x of the Cypress Hills Formation was found to be 10^{-}[illegible]m/s. In addition, the effects of regional and intermediate flow systems on recharge to a series of large springs at the geologic contact between the Eastend sandstone and Bearpaw shale were noted to be minimal, even though age dates in the springs indicate water recharged 6000 to 7000 ybp. Local groundwater systems, originating north of the Hills, appear to supply the bulk of recharge to these springs.

Groundwater management models for Ross Creek Basin must account for evaporative losses from ponded recharge as well as the localized nature of groundwater flow.

ACKNOWLEDGEMENTS

In any project of this magnitude, a lot of support is required from people other than those who appear on the title page. This thesis was no exception: financial, logistical and spiritual sustenance was provided by a number of individuals and organizations.

The Alberta Environmental Centre performed the tritium and ^{14}C analyses through the sponsorship of the Alberta Research Council. In particular, I would like to thank J. Garfitt, D. Arnold, D. Dougall and E. Wallick for their contributions to this aspect of the thesis.

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I am grateful to all the members of my thesis committee, not only for their efforts in the review and examination process, bu[illegible]lso because they have made substantial contribut[illegible]o all stages of the work. J. Gray graciously allowed me [illegible]use of his hydrogen extraction facilities in the Department of Physics for deuterium analysis. J. Toth, through a series of one on one discussions in Geology 686, resulted in both my sense of excitement about hydrogeology as a scientific discipline and the choice of this thesis topic. F. Schwartz has helped me to shape my enthusiasm into a sense of professionalism; this I hope to retain throughout my working life.

I would particularly like to thank my supervisor, K. Muehlenbachs, for fostering the research aspects of my thesis. Few graduate students finish their training with the sense that they had an ideal supervisor, and I feel fortunate to be able to count myself in the ranks of the minority. Karlis has lent support to me in my work, having encouraged me to participate in professional meetings; to meet other workers in the field; to actively seek out new literature and new ideas; and to contact him at any time with questions. His financial support, through grants from the National Scientific and Engineering Research Council, has been very generous. I am grateful for the opportunity of being able to work with such a fine man and scholar.

I want to thank my many friends and colleagues in Edmonton who have lent support in ways too numerous to mention. Principal among these is D. Ophori, a true and generous friend, who has served both as a tutor and as a sounding board for the ideas expressed in this thesis. I am likewise grateful to K. Rakhit, L. Ringham, the Ojamaa family and the Campbells.

Lastly, I would like to thank C. Main Freeman. Not only does she run a mean mass spec, but she has been a continual source of support and encouragement in every way.

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1. INTRODUCTION

Water is the staff of life. Man, as part of the biological chain, has always depended on a reliable supply of potable water to sustain himself and his activities; the rise and fall of many past civilizations can be directly linked to the availability of abundant and clean water resources. Modern man and modern technology have increased their need for water and this has resulted in the degradation of existing supplies at an alarming rate. This trend has led to widespread pessimism and speculation in the popular literature. (e.g. Hunt and Garrels 1972; Powledge 1982).

While increasing our search for good quality water sources however, modern technology has also lent mankind the tools to delineate, develop and manage these supplies more efficiently. In the past several years strides have been made in the science of groundwater hydrology which allow society to more effectively describe, exploit, remediate and protect the world's subsurface water resources. Advances in the theoretical understanding of regional groundwater flow (e.g. Tóth 1962) have provided a conceptual framework for the interpretation of features on a large scale, such as those encountered in a typical prairie basin. In the absence of detailed data, accurate decisions about the nature and patterns of groundwater flow systems may still be made without having to turn to more (and expensive) test drilling for answers.

Part of a complete understanding of groundwater systems is a thorough gathering and analysis of the data that are available. Groundwater field mapping techniques, groundwater chemistries and existing well data are easily collected and compiled into useful information. With the advent of isotopic technology in hydrology over the past several decades and the relatively inexpensive nature of these methods, isotopic analyses provide a further application of regional groundwater flow theory to groundwater exploration techniques.

The use of multi-faceted approaches in groundwater flow system delineation is not new: Harpaz et al. proposed the use of isotopes along with more conventional techniques in a detailed matrix of needs and common methods in groundwater exploration in 1963. It was Hendry et al. (1983) however, who described this type of approach as an "integrated" one, that through the use of as many techniques as the researcher has at his disposal, a multiple input system of checks and balances can be developed which will provide a clearer picture of the real world than would otherwise be possible.

The current study was undertaken with the primary objective of gathering, analyzing and interpreting isotopic data on groundwater in the Ross Creek Basin of southern Alberta. These data were to be interpreted utilizing an integrated approach; developed in a context of the theories of regional groundwater flow and analyzed in light of known information about the Canadian prairie environment. These results were to be compared and contrasted with those realized by the other workers in the area. (e.g. Ophori 1986; Ophori and Toth 1983, 1985). By fulfilling this objective a further understanding of the unique hydrological setting of the prairies would be achieved.

A secondary purpose of the study was to refine the conceptual framework by which isotope analyses may be interpreted. Past approaches to modeling real groundwater systems have been based on vast oversimplifications, many of which have been borrowed from accepted tracer methods of chemical engineering. It is thought that these techniques are best left in the laboratory where systems of pipes and well-mixed reservoirs are easily described by mathematics; under field conditions mixing, heterogeneity and anistropy within the rock framework are the norm, and this study has tried to model isotopic age dates utilizing numerical methods. These models provide graphical insight into the transport of conservative and semi-conservative groundwater tracers in groundwater systems.

The structure of the present study is as follows. First, the background information for an integrated approach will be given, and an outline of the methods of quantitative and field hydrogeology and use of groundwater isotopes developed. Second, the design of the study will be set out. The conceptual and experimental basis of the project will be discussed. Third, the results of the study will be given and will be followed by a discussion and summary of the principal findings of the study. Finally, an integrated model of the dynamics of groundwater flow in Ross Creek Basin will be compiled and presented.

It is hoped that this study will provide a basis for the wise use of water resources in Ross Creek Basin and that the current project will provide a blueprint for the future study of groundwater flow in prairie basins. Perhaps someday planners will have the insight to utilize all of the hydrogeological tools at their disposal in order to make enlightened choices about the exploitation of a valuable and often scanty commodity, the world's water.

2. BACKGROUND INFORMATION

2.1 Quantitative Methods in Hydrogeology

2.1.1 Aquifer Evaluation Methods

Quantitative methods form the basis of predictive hydrogeological work today. A proper and integrated approach to hydrogeology must therefore be firmly based on quantitative hydrogeological methods.

Quantitative techniques grew out of early work in groundwater resource exploitation and development, as it became clear that the prediction of water depletion must be made with respect to proposed pumping schemes. A number of solutions to problems of subsurface water movement that were based on flow to pumping wells were brought forth. While full of over-simplifying and partially unrealistic assumptions, the postulated well hydraulics methods allowed for a mathematical examination of aquifer response and thus represented a distinctive area of research in groundwater hydrology.

Theis (1935) was the first to develop an analytical solution for transient flow to a well in a confined aquifer system which accounted for the properties of homogeneity, isotropy and hydraulic isolation from surrounding geological units. Hantush and Jacob (1955) developed an analytical solution for pumping wells in leaky aquifer situations. Later workers have developed methods of mathematical analysis of wells under other, more general scenarios.

Along with determinations of permeability, effective porosity and compressibility, aquifer tests are useful methods of quantifying the characteristics of groundwater systems. These tests are summarized by Freeze and Cherry (1979) and Krusemann and de Ridder (1979).

2.1.2 Groundwater Flow Modeling

The use of quantitative groundwater flow modeling techniques began with a 19th Century French engineer, Henry Darcy. In a 1856 report submitted to the City of Dijon describing the public water supply, Darcy published the procedures and results of experiments performed with lengths of sand filled pipe, and an equation that was later to bear his name. In these experiments, water was introduced into one end of a pipe and allowed to flow out the other, while manometers at each end recorded the hydraulic head at the inflow and outflow points.

Darcy found that the specific discharge, q, defined as the volumetric flow rate divided by the cross sectional area of the pipe, was inversely proportional to the length of the pipe and directly proportional to the difference in water levels in the manometers. If the proportionality is represented by a constant K, the hydraulic conductivity, which is a function of the sand packing in the pipe, then Darcy's law may be written as:

$$q = Q/A = -K\, dh/dl \tag{2.1}$$

Where Q is the discharge rate, A is the unit area of a cross section of the pipe, h is the head in a manometer, l is the length of the pipe and dh/dl is the hydraulic gradient. The minus sign is introduced as a convention.

Darcy's law is an important empirical law. It has never been successfully derived from basic physical principles, but it nevertheless allows for quantification of flow through a porous medium in a single dimension (Freeze and Cherry 1979). Darcy's law has provided the basis for numerical and analytical solutions in hydrogeology.

Several extensions of Darcy's law allow for more realistic uses of the principle. Charles Slichter (1899) linked Darcy's law to the Laplace equation of potential theory where partial differential equations are applied in three dimensions. Assuming steady state flow through an isotropic, homogeneous medium, Darcy's law becomes:

$$\delta^2 h/\delta x^2 + \delta^2 h/\delta y^2 + \delta^2 h/\delta z^2 = 0 \tag{2.2}$$

Hubbert (1940) linked Darcy's law to physical principles by defining the concept of fluid potential and expressing hydraulic head in terms of energy. Hubbert also broke K down into terms of permeability, fluid density and viscosity. In Hubbert's application, only permeability remains to be ascertained for a particular aquifer under examination and, as discussed above, many permeability evaluation methods are now in constant use.

Hubbert (1940) also sketched a flow net for a typical cross sectional configuration of hills and valleys. In doing so, he graphically demonstrated the effects of topography on groundwater flow patterns. Figure 2.1 is a reproduction of Hubbert's original (1940) flow net. Water enters a groundwater flow system on the valley flanks and leaves via the stream bed. The upland region is considered to be a recharge area; the creeks are a discharge line. The arrows on the diagram are streamlines which trace the path of water through the system.

Tóth introduced an analytical solution for heads in a basinal cross section (Tóth 1962, 1963). He was able to distinguish between different types of groundwater flow systems, as shown in Figure 2.2. Local flow systems were defined to exist between adjacent topographic highs and lows; intermediate systems might include one or more local flow regimes. Regional groundwater flow systems are recharged at the highest point and are discharged at the lowest point in a basin (Tóth 1963).

The analytical method of head calculations, while useful, might have fallen into disuse had it not been for the advent of numerical methods and digital computer techniques in the 1960's. Computers drastically improved the cumbersome procedure of applying long analytical solutions to large basins, although for a time, electric analogue

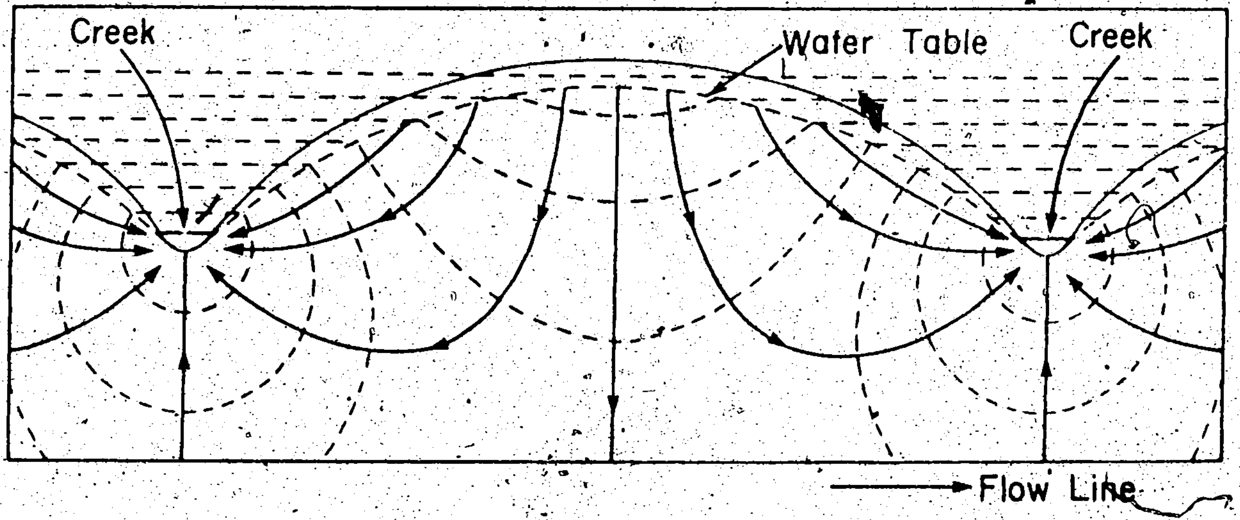
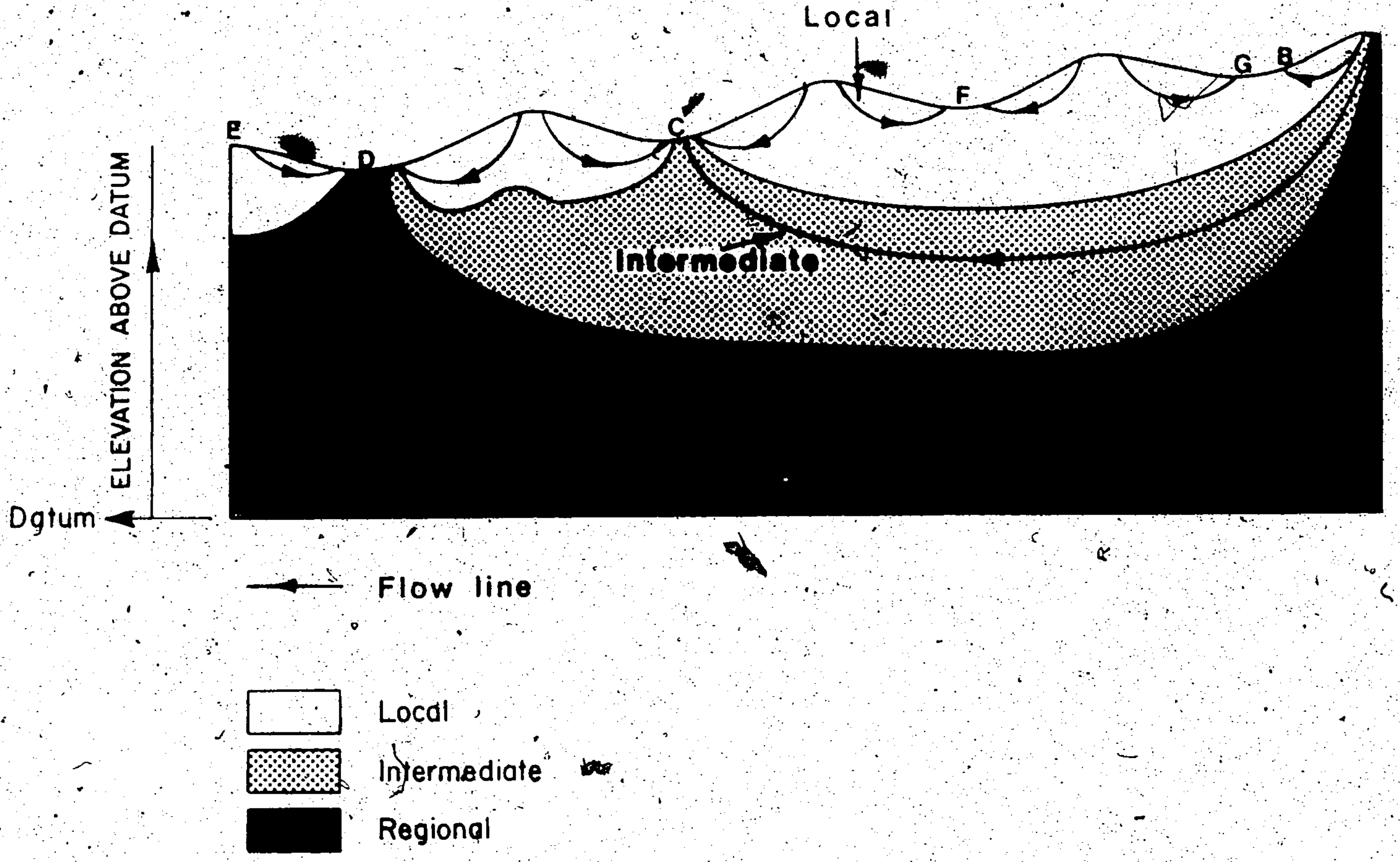


Figure 2.1. The effects of topography on groundwater flow patterns. The lines with arrows are streamlines or flow lines; the dashed lines represent equipotentials (after Hubbert 1940).

Figure 2.2. Regional groundwater flow in prairie basins. Shown for isotropic, homogeneous case (after Tóth 1963).



models (e.g. Toth 1970) provided a substitute method for simulating head distribution in a two dimensional system. Freeze (1969b) and Freeze and Witherspoon (1967) presented a finite difference approximation of the two dimensional groundwater flow equation and because of the use of computers, were able to alter model parameters such as geology, regional slope and topography. The result was a useful demonstration of how real groundwater flow systems operated.

Following the work of Freeze and others, the use of computer modeling as a predictive tool became a widespread practice. In the 20 years since the initial work of Freeze and others, a variety of groundwater models have emerged. Van der Heijde et al. (1985) list over 550 computer models that describe various aspects of groundwater flow. Many are able to take into account such functions as hydrochemical reactions, heat transport and management practices, but most are based on Darcy's law and some form of the continuity equation.

Despite their sophisticated nature however, groundwater models are seldom useful in more than a semi-quantitative sense if used alone. Freeze (1969a, 1969b) provides an excellent case history of the melding of computer models and other groundwater delineation techniques. Hendry et al. (1983) calibrate a computer model utilizing geochemistry and well data. To work, computer modeling must be combined with other hydrogeological methods.

2.2 Field Mapping Techniques

2.2.1 Physical Phenomena

In addition to the quantitative predictions of groundwater conditions that are afforded by aquifer evaluation techniques and computer modeling, the occurrence of groundwater may be discovered by reconnaissance field mapping. By utilizing a systematic mapping technique in much the same way that any geological exploration is performed, groundwater features such as recharge and discharge areas may be located in a quick and cost effective manner.

The scientific application of surficial groundwater mapping on the Great Plains began with Meyboom's description of the "Prairie Profile" (1962). He noted that recharge on the till covered plains occurs in topographically high areas, while system outflow is manifest as rivers and/or evapotranspiration in topographically low areas. He states that mapping of groundwater flow systems may be accomplished "in a classical geological fashion; that is by means of a large number of outcrops" (1962:10). Later workers, notably Toth (1966), extended Meyboom's original definition of groundwater outcrops to include surficial features that indicate flow conditions and human inputs on the prairies.

The systematic delineation of groundwater outcrops in this fashion provides a tool for hydrogeologists to describe large scale groundwater flow systems in the natural environment. Such features as springs, seepages, flowing wells and salt precipitates denote discharge regions, while good quality water, dry depressions and topographic highs indicate recharge zones. Work by Freeman and Toth (1984); Freeze (1969a); Lissey (1968); Meyboom (1962, 1966); Mollard (1970) and Tóth (1966, 1972) have done much to establish solid links between field features and groundwater flow conditions. Freeze (1969a, 1969b), Ophori and Tóth (1983) and Tóth (1966) provide comprehensive studies demonstrating the application of mapping physical groundwater phenomena for prairie surveys.

2.2.2 Chemical Phenomena

In addition to the noting of physical field features for use in groundwater mapping, several chemical phenomena may also assist in the qualitative delineation of flow systems. The methods are based on the simple principle that, as water moves in the subsurface, it acquires an increasing quantity of dissolved constituents and undergoes an overall chemical evolution process. As stated by Freeze and Cherry: "It has been observed in groundwater investigations in many parts of the world that shallow groundwater in recharge areas is lower in dissolved solids than water in shallow zones in the discharge areas" (1979:241).

The Chebotarev sequence is often cited in describing the chemical evolution of the major ions found in groundwater. This empirical observation was based on the interpretation of thousands of water chemistry samples from the Great Artesian Basin of Australia. From these analyses, Chebotarev (1955) noted that groundwater changed from a bicarbonate water through a dominantly sulphate water into a chloride water as it travelled along its flow path.

Back (1960) found a typical chemical evolution pattern in groundwater of the Coastal Plain aquifer of the middle Atlantic region of the U.S.. He carried the Chebotarev sequence one step further by applying the principles of stratigraphic facies to the major ion areas of the aquifer. Back (1960) defined both cationic and anionic facies and postulated that water in the Coastal Plain aquifer could be traced from recharge to discharge zones by following these hydrochemical units.

Similar patterns have been observed in other groundwater settings (e.g. Back and Handshaw 1970; Issar and Rosenthal 1968, as reported in Tóth 1980). Freeze (1969a) and Ophori and Tóth (1983) have provided field project histories where hydrochemical facies evolution have been utilized to map groundwater flow systems on the Canadian prairies.

2.3 Isotopes in Hydrological Studies

2.3.1 The stable isotopes

The stable isotopes of oxygen - 18 (^{18}O) and Deuterium (D) are useful tools in hydrogeology, for they function as environmental tracers. Unlike most other groundwater tracers however, ^{18}O and D are both a component of the water molecule and are conservative in that the isotopic content of groundwater is generally not altered by physical or chemical processes in the subsurface. The isotopic content is generally fixed at the time of recharge and is carried unaltered to the point of discharge.

Variations in the isotopic signature of recharge waters may be caused by:

1. Seasonal differences in meteoric precipitation values of $\delta^{18}O$ and δD;
2. Differences in the altitude of recharge;
3. Temporal and climatic effects;
4. Isotopic fractionation processes, including evaporation.

In theory, stable isotopes may be utilized within the context of integrated regional flow investigations to delineate sources and conditions of groundwater recharge. Using this recharge information, it may be possible to formulate a model of regional groundwater flow in a region

In addition, the unique stable isotope content of a particular water may allow for that water to be used as a tracer in a study area.

2.3.1.1 Background

Potential applications of the stable isotopes of oxygen and hydrogen in hydrological work have been well understood for over three decades. Following the Second World War, work at the University of Chicago by a group led by H.C. Urey resulted in the perfection of a double collecting mass spectrometer for analysis of the light stable isotopes (McKinney et al. 1950). Throughout the 1950's, worldwide surveys of isotope ratios in various substances were published, with much attention focused on the pairs: $^{13}C/^{12}C$; $^{18}O/^{16}O$ and D/H (e.g. Craig 1952, 1957; Epstein and Mayeda 1953; Friedman 1953)

In natural waters, it soon became clear that the D/H and $^{18}O/^{16}O$ ratios were highly variable (Epstein and Mayeda 1953; Friedman 1953). It was not until 10 years later however, that Harmon Craig demonstrated the systematic worldwide relationship between δD and $\delta^{18}O$, a function that became known as the meteoric water line:

$$\delta D = 8 \cdot \delta^{18}O + 10 \qquad (2.3)$$

(Craig 1961). Subsequent work by Dansgaard (1964) demonstrated the extreme linearity of the $\delta D/\delta^{18}O$ covariance found in precipitation samples taken during a worldwide survey conducted under the auspices of the International Atomic Energy Agency and the World Meterological Organization. The values of δD and $\delta^{18}O$ at a specific location are dependent on the temperature at which the condensation of the precipitation occurs and the isotopic content of the vapor reservoir from which the condensation derives. Thus, stations of increasing latitude and altitude have decreasing D/H and $^{18}O/^{16}O$ ratios. Figure (2.3) shows the meteoric water line as first given by Craig (1961) and later modified by Dansgaard (1964) to account for seasonal fluctuations in the quantity of precipitation collected at each station. As is apparent from Figure (2.3), the worldwide weighted monthly means of δD and $\delta^{18}O$ in precipitation exhibit high positive correlation. Gat and Gonfiantini (1981) give a correlation coefficient of $r = 0.997$ for 74 stations.

The slope of the meteoric water line appears to be very close to that derived during column distillation under equilibrium conditions (Gat and Gonfiantini 1981). Air masses which derive from surface water bodies such as the oceans (δD, $\delta^{18}O = 0.0$‰ vs. SMOW) move across the continents and progressively "rain-out" the heavier isotopes, resulting in a residual moisture that becomes increasingly enriched in the lighter isotopes. This is known as the "continental effect". Hage et al. (1975) reviewed the rain-out and continental effects on inland

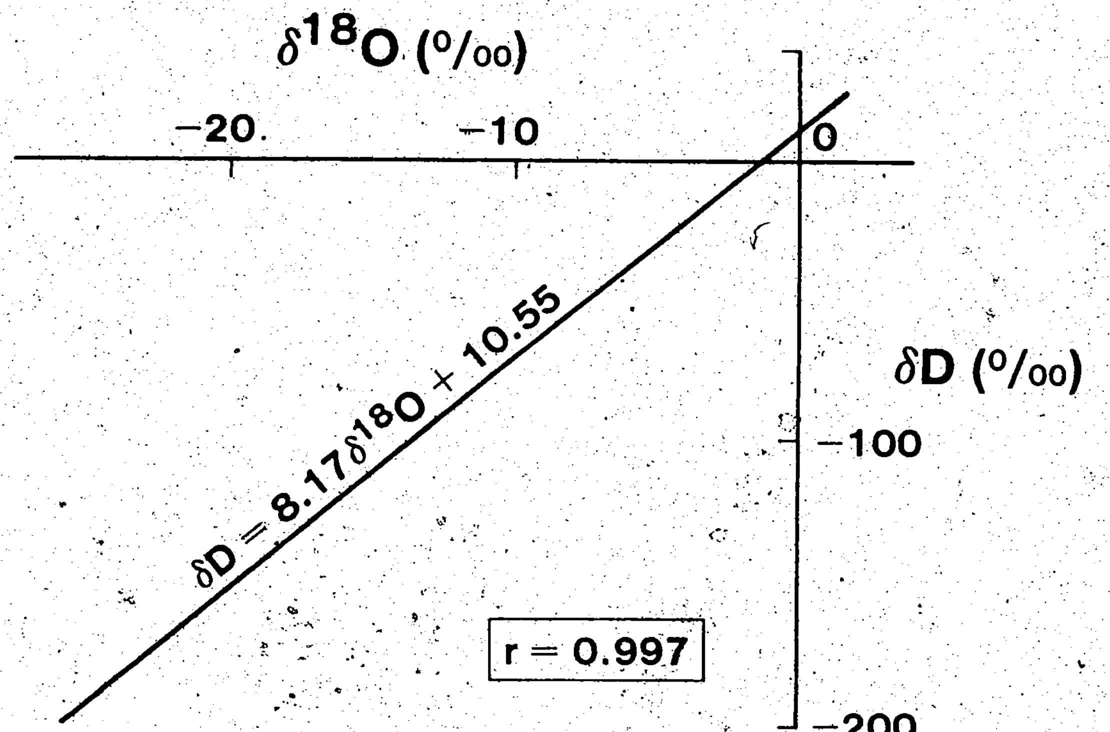


Figure 2.3. Worldwide meteoric water line for all network stations. Compiled using monthly averages weighted for quantity of precipitation (after Gat and Gonfiantini 1981).

precipitation. Effects of extreme variability of δD and $\delta^{18}O$ may be expected for individual storms occurring in the middle of continents.

However, the distillation of ocean water bodies does not occur under conditions of complete equilibrium, and rain along the coastlines of continents does not usually have an isotopic value of 0°/oo. For this reason the intercept of the meteoric water line is not at δD = 0.0°/oo. In addition, the movement of air masses over areas of high altitude will cause isotopic enrichment in excess of the rain-out effect. Figure (2.4) is a schematic depiction of a typical change in isotopic values that might be expected in precipitation from moving air masses as a function of altitude and continental effects. Rain-out effects will cause proportional shifts in $\delta^{18}O$ and δD and result in movement of isotopic levels in a given water that are parallel to the meteoric water line. Other processes, some of which will be discussed later, cause the isotopic values of a water to plot off the meteoric water line.

The markedly linear relationship between D and ^{18}O in meteoric waters has rendered these isotopes very useful in hydrological studies. In regions like Alberta, the annual contrast in the isotopic content of heavy summer rainfall versus light winter snow makes the delineation of a local meteoric water line a straight

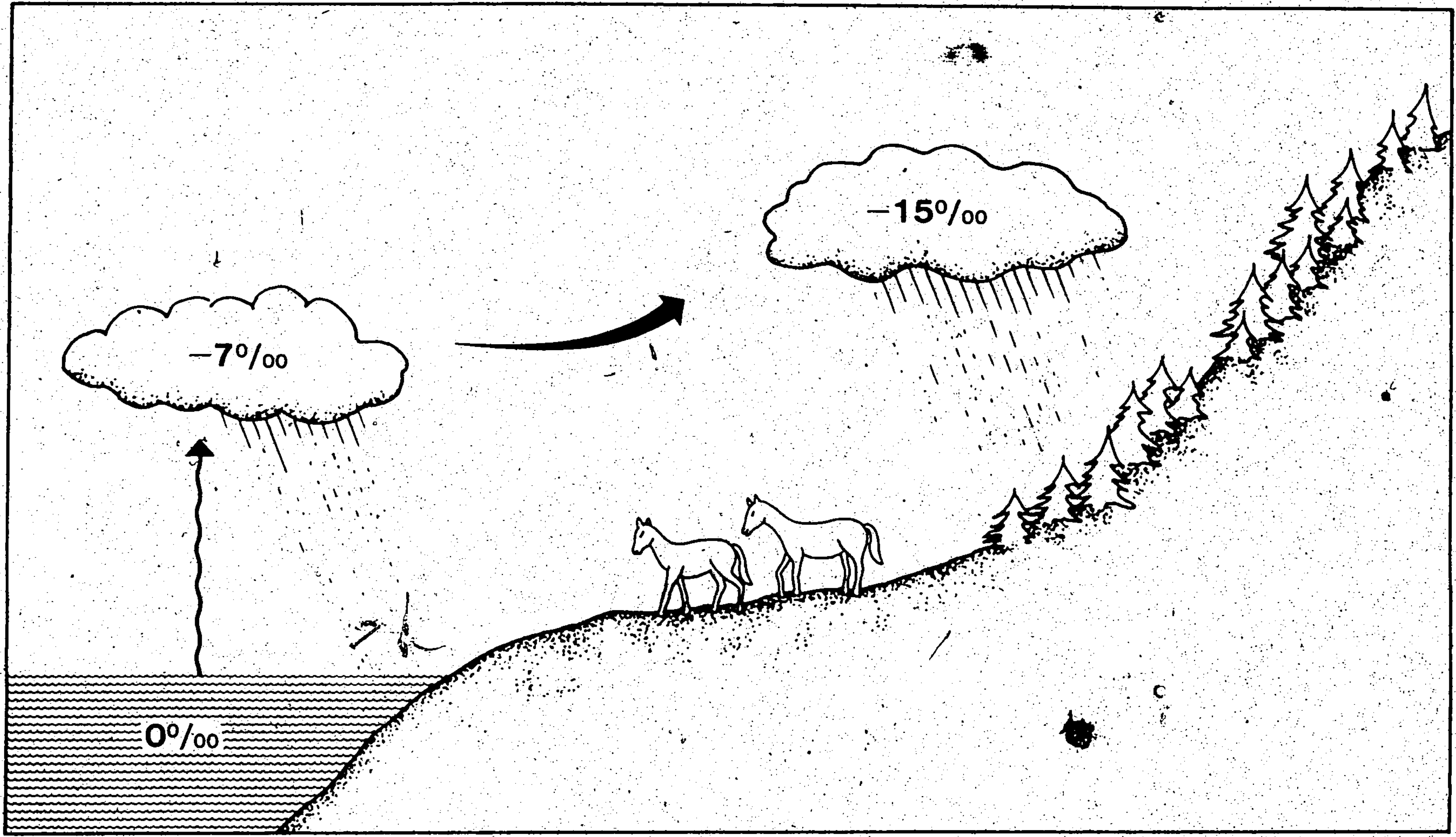


Figure 2.4. Rayleigh-type fractionation of isotopes during movement of continental air masses. Clouds, which form under non-equilibrium conditions over the ocean, move inland and progressively "rain-out" the heavier isotopes. The result is isotopically depleted weather systems over mid-continental areas such as Alberta.

forward process. Samples which plot on the line may be evaluated as to their relative position: changes in isotopic content of groundwater that are parallel to the meteoric water line may be attributed to effects of temperature, while changes that result in a sample plotting off of the line have to be explained by non-Rayleigh fractionation processes.

2.3.1.2 Stable isotopes as hydrological tracers

In many hydrological studies, stable isotopes are useful delineators of mixing between water sources with distinctive D and ^{18}O values. This is perhaps the least sophisticated use of the stable isotopes, but may give an elegant tracer result. Examples of this type of experiment are presented in groundwater studies by Fritz et al. (1976) and Payne and Schroeter (1978). Sklash et al. (1976) performed base flow analyses during a runoff event from a rain storm having a unique isotopic signature. Comparison of the δD values of rivers given by Brown (1970) and those in precipitation by Dansgaard (1964) and Hage et al. (1975) show that the potential exists across much of North America for the separation of isotopically light river waters and heavier local groundwaters if the groundwaters are assumed to reflect the average isotopic content of area precipitation. In the Edmonton area, this difference may be as much as 10‰ for δD and 2‰ for $\delta^{18}O$, however to the author's knowledge, no studies of this kind have been undertaken.

2.3.1.3 The altitude effect

Stations at increasing elevations will show decreasing values of δD and $\delta^{18}O$ in precipitation due to temperature controls. In areas of high topographic relief, the "altitude effect" may be used to imply recharge areas of a specific elevation. This technique has been employed most successfully in southern Europe, where extreme elevation changes are highly conducive to this type of approach.

In almost all cases, a regression line is calculated from the $\delta^{18}O$ or δD of precipitation and/or local groundwater. The isotopic content of study waters are then tied to a specific altitude of recharge utilizing this relationship. A summary of published altitude effects is given in Table 2.1, and is seen to vary between 0.1 ‰ and 0.5 ‰ $\delta^{18}O$ per 100 meters of elevation. In one study the altitude line was plotted as a negative value when derived from snow samples, however this was attributed to the isotopic aging of snow (Moser and Stichler 1970). The altitude effect is seen as a useful tool for groundwater recharge identification in areas with substantial topographic relief.

TYPE OF WATER	STUDY LOCATION	ALTITUDE EFFECT (0/00 PER M)	INVESTIGATORS
PPT AND GROUNDWATER	NICARAGUA	.0020-.0031	PAYNE AND YURTSEVER(1974)
GROUNDWATER	GREECE	.0016	STAHL ET AL (1974)
PPT	ITALY	.0011-.0054	FONTES AND ZUPPI(1976)
GROUNDWATER	CANARY ISLANDS	.0013-.0025	GONFIANTINI ET AL (1976)
GROUNDWATER	GREECE	.0021	KALLERGIS AND LEONTIADIS(1983)
PPT	ITALY	.0031	BORTOLAMI ET AL (1978)
PPT AND GROUNDWATER	JURA ALPS	.0040-.0020	SIEGENTHALER ET AL (1970)

Table 2.1. Values of altitude effects from the literature.

2.3.1.4 Stable isotopes as paleoclimatic indicators

Isotopic fractionation processes affecting the $\delta^{18}O$ and δD of precipitation have so far only been assumed to alter the isotopic content of water in space. However, as groundwater studies often deal with water of considerable age and $\delta^{18}O$ in precipitation is well known to be directly related to temperature (Dansgaard 1964), in many cases information about paleoclimates may be yielded by analyzing the stable isotope content of groundwater.

Groundwater samples containing levels that are less than present day values are usually found to be coincident with ages of several thousand years. This has been noted in Africa (Dincer et al. 1974); South America (Salati et al. 1974) and the Middle East (Bath et al. 1978). In Manitoba, Fritz et al. (1974) found depleted levels of $\delta^{18}O$ and δD in water samples dated at over 10,000 years old. Attempts to quantify the changes in annual temperatures represented by stable isotope shifts are given by Clayton (1981) and Gat and Gonfiantini (1981).

Complex patterns of isotope values also may be manifest in groundwater due to paleoclimatic changes. These have been analyzed by Back et al. (1978); Airey et al. (1978) and Sonntag et al. (1978). Cerling (1984) utilized $\delta^{18}O$ values in soil waters and carbonates to infer periglacial, coastal and monsoonal weather patterns during the Quaternary period in the continental North America. It is not clear why evidence of the "Altithermal", a period of warmer than present climates in North America, are not noted in waters 3000 to 11000 years old (e.g. Hendry 1986).

2.3.1.5 Evaporation effects

Not all isotopic fractionation processes acting on water result in proportional shifts in oxygen and deuterium. Several mechanisms exist that cause natural waters to be shifted off of the meteoric water line.

Non-equilibrium evaporation is an important example of a process that results in a shift with a $\delta D/\delta^{18}O$ slope that is less than eight. If water is allowed to evaporate into an atmosphere where equilibrium between the gaseous and liquid phases is not achieved, then the residual fluid become increasingly rich in the stable isotopes, and this process will affect oxygen to a greater extent than hydrogen. A slope of less than eight on a δD vs $\delta^{18}O$ diagram will result. Craig et al. (1963) found that worldwide evaporative lines had slopes of between 4 and 6. Thus an isotopic survey of water in an area where a high evaporative potential exists must examine the isotopic values in order to detect evaporation. Misinterpretations might result if one were to analyse water samples for one stable isotope and draw conclusions about the differences in isotope levels without analyzing for the second isotope.

Efforts to quantify evaporation effects utilizing δD and $\delta^{18}O$ have met with only limited success, despite early enthusiasm for the potential use of these tools. The limitations of the common methods by which evapotranspiration is calculated are well known (e.g. Freeze and Cherry 1979; Wartena 1974). Craig et al. (1963) and Craig and Gordon (1965) attempted to describe empirical relationships as well as derive the basic parameters of isotopic fractionation during evaporation. These equations have been summarized and simplified by Gat (1971, 1980); Gat and Gonfiantini (1981) and Whelan and Fritz (1977), but the modern researcher is left with only a very crude tool for calculating evaporation using isotopic means. Constant values of important and non-constant parameters such as humidity, wind speed and influx to the evaporating water body have to be assumed (Gat 1971). Salting effects begin to be important at later stages of desiccation (Friedman et al. 1976; Gat 1980), as does the slope of the δD vs $\delta^{18}O$ function. Recent research by Knauth and others (1986) at Arizona State University has suggested that near the end of evaporation, the evaporative line takes on a parabolic shape which is in sharp contrast to the linear trends assumed by most researchers. This may explain the greater than 50% error that is expected in evaporation estimates even when good data on system parameters are available (Zimmermann and Ehhalt 1970).

Undaunted by the limited theoretical and laboratory success in predicting evaporation by the isotopic method however, numerous studies have appeared in which the water balance of lakes have been estimated utilizing δD and $\delta^{18}O$ (Dincer 1968; Barry and Merritt 1970; Dincer et al. 1979; Payne 1970). Soil scientists have also attempted to estimate the amount of infiltrated water that is lost from the soil due to evaporation; likewise with limited results (Allison 1982; Allison et al. 1983; Allison and Hughes 1983; Barnes and Allison 1983, 1984; Dincer et al. 1974a). Zimmermann et al. (1967) showed that plant transpiration resulted in a negligible isotopic enrichment. Evaporation has been observed in rainfall in regions of unusually low humidity (Ehhalt et al. 1963; Gat and Tzur 1967; Leguy et al. 1983).

Despite the fact that evaporation acting on soil water, rainfall and/or surface water bodies results in isotopic fractionation, very little evidence of isotope enrichment due to evaporation has been noted in groundwater samples. Exceptions to this are two shallow wells in Quatar which are reported by Yurtsever and Payne (1978), a few samples from the eastern Sahara (Conrad and Fontes 1970) and groundwater samples collected near the Chimbo River (Payne and Schroeter 1978). Ponded recharge to the Quatar wells is believed to account for the evaporative signature there. Dune evaporation causes the eastern Sahara wells to be fractionated, while the influent characteristics of the Chimbo River provides a source of evaporated groundwater in the Payne and Schroeter (1978) study.

2.3.1.6 Deep basin isotope effects

Non-equilibrium evaporation is not the only process by which waters can become enriched in the heavier isotopes. Deep basin waters are often found to plot to the right of the meteoric water line (e.g. Fig. 2.3). This is due to at least two reasons:

1. High temperature rock-water interactions can result in exchange between oxygen-depleted waters and oxygen-enriched rocks. Since little hydrogen exists in most rocks, this will cause the residual fluid to be enriched in ^{18}O as opposed to D. These effects are discussed extensively by Savin (1980).

2. Formation fluids have been noted to contain more ^{18}O than D when compared to meteoric waters. This has been noted for several structural basins in North America by Clayton et al. (1966) and verified in the Alberta Basin by Hitchon and Friedman (1969). The reason for this shift has been much debated, but recent work by Knauth and others at Arizona State University has found that these effects may be due to evaporation contemporaneous with deposition of the sediments (P. Knauth, unpublished data, 1986).

Meteoric trends are expected to occur in shallow groundwater systems unless a means of mixing with deeper waters is maintained. This was demonstrated by Airey et al. (1978) who showed that water from the Great Artesian Basin of Australia, despite ranging in ages up to 3.5 x 10^5 years, plotted as meteoric on a δD versus $\delta^{18}O$ diagram. No evidence of exchange with the host rock or mixing with formation fluids over that time was noted.

2.3.2 Radioactive tritium

The buildup of nuclear arsenals has had few beneficial effects for the world, but the infusion of large amounts of tritium into the atmosphere during the period of open air testing has, at least, been of some help in hydrogeology. The identification of post-1952 water in the subsurface has been simplified because of the high levels of tritium that it contains. It is estimated that "pre-bomb" tritium values were less than 2-4 tritium units (TU), but levels in Ottawa, Canada rainfall reached a maximum monthly mean concentration of approximately 7000 TU in the summer of 1963 after the last major open air nuclear tests by the superpowers (Freeze and Cherry 1979). At the same time, the monthly mean of Alberta peaked at over 8000 TU as the middle of continents had much higher values of tritium than did coastal areas during the periods of maximum fallout (Eriksson 1967). However, because the half-life of tritium is only 12.35 years; the ocean contains almost exclusively "dead" levels of tritium which only slowly mix with atmospheric vapor; and political agreements have halted fresh inputs to the atmosphere, tritium levels have plummeted since the early 1960's (Ferronsky and Polyakov 1982). In 1984-85, tritium values in Alberta precipitation averaged 28 TU but fluctuated between 10 and 70 TU (D. Arnold, unpublished data).

Until recently, tritium has been largely the tool of soil scientists in hydrological studies. Many investigations using models of infiltration flux through the unsaturated zone have calibrated the bomb tritium infiltration profile as a tracer (e.g. Allison and Hughes 1974; Desaulniers et al. 1981; Thoma et al. 1978). Groundwater studies have historically done little more than to distinguish between pre and post 1952 recharge (e.g. Hendry 1986; Mazor et al. 1974). Recent, more sophisticated uses of tritium provide encouragement for the utilization of tritium analyses in studies of regional groundwater flow. The work of Egboka et al. (1983) and Herweijer et al. (1985) will be discussed at more length below.

2.3.3 Carbon-14

The use of carbon-14 (^{14}C) as a tool in age determination of water was first proposed by Munnich (1957) after W.F. Libby pioneered techniques for the dating of carboneous materials. In theory, groundwater age dating is uncomplicated. Although ^{14}C inputs to groundwater recharge have not technically been stable over the past several thousand years, for groundwater dating it is usually assumed that levels of ^{14}C in precipitation have remained constant until the last 40 years (Mook 1980). Since the advent of thermonuclear testing ^{14}C levels have approximately doubled. In the atmosphere, ^{14}C oxidizes to form CO_2 which is incorporated as dissolved carbon in infiltration water, becoming isolated from the atmosphere and thus supplying a means for dating the carbon in groundwater. ^{14}C atoms break down into a nitrogen atom and a β particle; a process which obeys the law of radioactive decay. By measuring the activity of the dissolved carbon in a groundwater sample, one may ascertain the amount of remaining ^{14}C and thus an estimation of the absolute age of the groundwater may be made. The radioactive half life of ^{14}C is 5730 years and this allows for the valid dating of carbon containing materials up to approximately 50,000 years old.

In practice, ^{14}C dating in groundwaters is not very straight forward, however. The number of sources of dissolved carbonate in groundwater systems is large, and because each carbon source may have a unique ^{14}C signature, following carbon inputs along flow paths is an extremely complex geochemical problem (Mook 1980). Despite systemmatic complexities, many groundwater studies have utilized ^{14}C as an age indicator. Vogel and Ehhalt (1963) demonstrated the existence of two distinct groundwater layers in a Netherlands aquifer. Back and Hanshaw (1970) and Pearson and

Hanshaw (1970) successfully mapped the southward flow of water in the Floridan aquifer using equilibrium geochemical principles.

Other workers have found that the uses of age dating with ^{14}C are extremely limited. Winograd and Farlokas (1974) found that the generation of CO_2 downgradient from the recharge area of a New Jersey aquifer invalidated traditional adjustments of input factors for ^{14}C age conversions. In addition, leakage from units confining the aquifer were seen to significantly affect the hydrological properties of the system and, presumably, the age as determined by ^{14}C dating. Loosli and Oeschger (1978) compared the ages of 12 well samples determined from both ^{39}Ar and ^{14}C activity. While the general age trends were similar, the absolute dates were in disagreement.

Groundwater age dating by the use of ^{14}C methods is a useful procedure, but bounded by many uncertainties. Foremost among these is the fact that most of the arguments posed have dealt with the geochemistry of groundwater but few have attempted to pose realistic conceptual arguments for the flow of the water. Only with an understanding of the concepts of regional groundwater flow is an interpretation of the isotopic measurements rendered meaningful.

2.3.4 Other isotopes

In recent years, the use of isotopes other than ^{18}O, D, ^{14}C and tritium has come into common practice. These isotopes are generally radioactive and used to date groundwater in aquifers. As the current study only made use of ^{18}O, D, tritium and ^{14}C, the discussion here is limited to a topic related directly to these four isotopes. The reader is directed to Ferronsky and Polyakav (1982), Fabryka-Martin et al. (1985) and Fritz and Fontes (1980) for examples of work utilizing groundwater isotopes such as ^{36}Cl, ^{39}Ar, ^{129}I and others.

2.4 Integrated Approaches in Hydrogeology

Hydrogeological investigators have a number of tools at their disposal for the delineation of groundwater flow systems. Groundwater manifestation features may be [illegible] chemical facies can be delineated and are seen to evolve in the direction of groundwater flow. Aquifer tests and computer modeling provide bases for predictive evaluation of flow systems. Isotopes may be utilized both as tracers and for groundwater age dating.

Unfortunately, past groundwater studies using environmental isotopes have not had a sound hydrogeological underpinning. As well, traditional groundwater based projects have under-utilized the full spectrum of isotopic technology. For a full and thorough scientific evaluation of groundwater resources, it is important that the researcher employ isotope measurements within a context of regional groundwater flow theory, using every available means to interpret his results.

Theis (1963) and Harpaz et al. (1963) were among the first hydrologists to instruct the isotope science community about the basic principles of hydrology, and began what Hendry et al. (1983) labelled an "integrated approach" to hydrogeology. Thus the modern hydrologic researcher can employ a multi-disciplined approach as part of his science, and increasingly one sees groundwater investigations that take advantage of simultaneous engineering, biological, geological, chemical and physical arguments to solve complex problems.

Certain authors have outlined the theories of an integrated approach (e.g. Dincer and Davis 1984; Harpaz et al. 1963; Wallick and Toth 1976); other groups, notably the reseach group from the University of Waterloo in Ontario have employed these principles in their work. Examples of the integrated approach in practice are provided by Fritz et al. (1978); Hendry et al. (1983, 1986) and Cherry (1983).

By developing an integrated approach, the hydrogeologist is able to make full use of the many tools that are at his disposal. As will be demonstrated in the present work, Ross Creek Basin, Alberta has provided an excellent site for the application of these principles in a large region, for no single, simplified model is adequately able to explain the various factors influencing the groundwater regime.

3. EXPERIMENTAL DESIGN

3.1 Conceptualization and Site Selection

In order to utilize isotopic techniques as part of an integrated groundwater investigation, a choice had to be made for the location of a study area. Alberta Environment had contracted D.U. Ophori, then a Ph.D. student at the University of Alberta, to examine groundwater resources in the Ross Creek Basin of southeastern Alberta. In the spring of 1984 it was decided that this would provide an excellent location for applying isotopes as a reconnaissance tool.

In the summer of 1983, Mr. Ophori mapped groundwater outcrops and took water levels and chemistry samples throughout the area. In the summer of 1984, he returned to carry out a drilling program in order to define groundwater resources in the area. Ultimately, he was to formulate a groundwater management program for the basin (Ophori 1986).

The choice of Ross Creek Basin seemed ideal for the application of isotopes. The basin is in the southeastern corner of Alberta, between 49° 36' and 50° 20'N latitude and 110° 11' and 110° 36'W longitude (Fig. 3.1). It includes all or parts of Townships 8 to 13; Ranges 2 to 5, west of the 4th Meridian. The area has high topographical relief with the Cypress Hills ~~loom~~ing more than 700m out of the plains. Therefore an altitude effect of 0.8 to $3.9^{\circ}/_{\circ\circ}$ on $\delta^{18}O$ was expected from the highest to the lowest points of the basin (Table 2.1). Few attempts to document altitude effects in

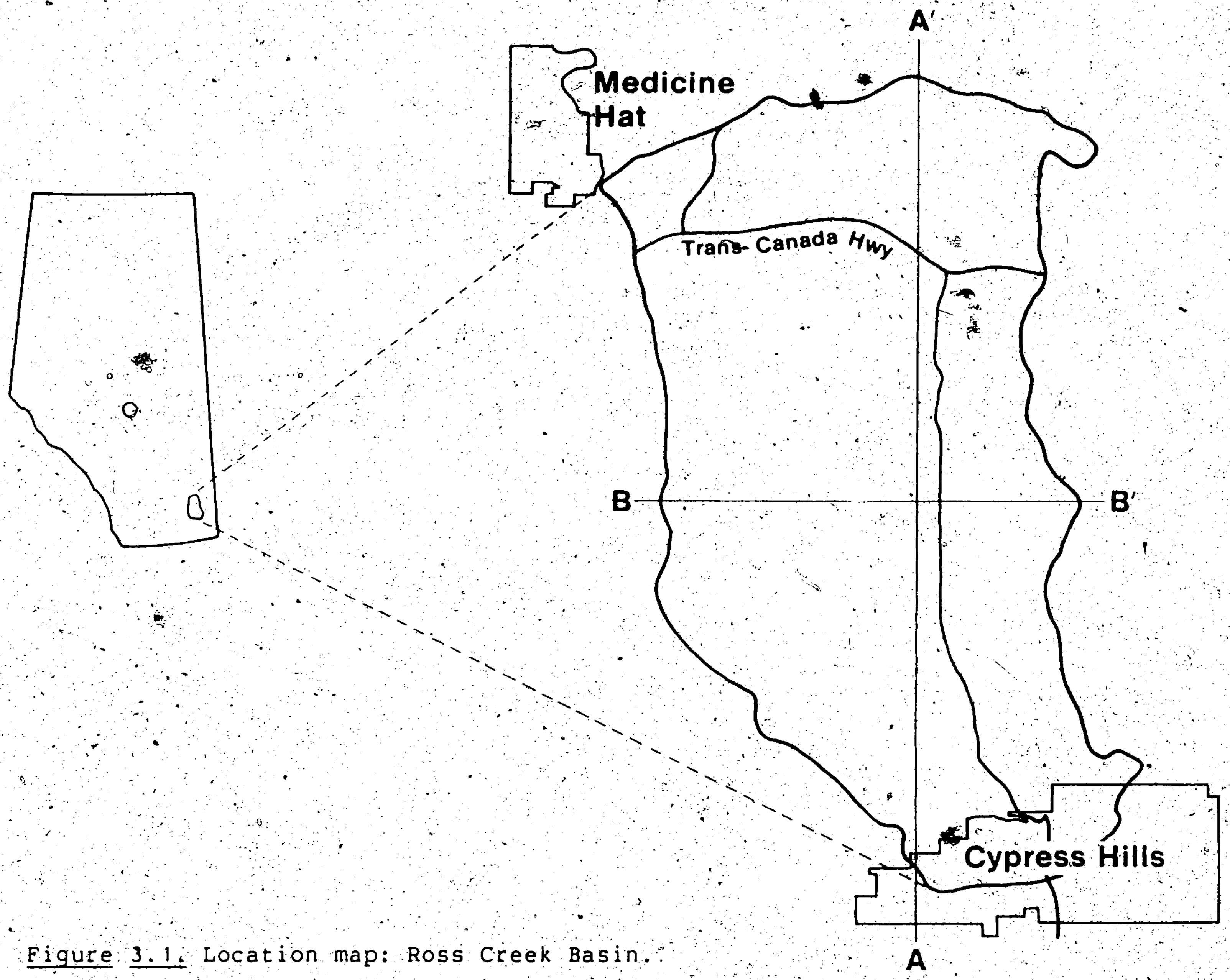


Figure 3.1. Location map: Ross Creek Basin.

North American groundwaters have ever been made and this study was seen as a chance to evaluate this phenomena. In addition to the altitude effect, the potential use of stable isotopes in separating groundwater flow systems also appeared promising. Within a few months of the program initiation, the help of the Alberta Research Council in securing radioisotope analyses at the Alberta Environmental Centre in Vegreville was received. For the first time in Alberta, extensive use of isotopes was to be made in a groundwater exploration program.

Despite its high topographic relief, Ross Creek Basin is a typical prairie basin. It is approximately 600 sq km and is defined by an irregularly-shaped surface water drainage area, as shown in Figure 3.1. The basin channels drainage into Gros Ventre Creek and Ross Creek. Both streams flow northward, with Gros Ventre channeling eastward several kilometers south of the Trans-Canada Highway to a point where it meets Ross Creek and the two proceed northward. Ross Creek then flows onto a large flat area, turns westward, and flows into its confluence with the South Saskatchewan River just east and downstream of the City of Medicine Hat.

Early indications were that regional groundwater flow systems, originating in the Cypress Hills, flowed out to discharge along Ross Creek at the Trans-Canada Highway. If the concepts put forth by Ophori and others on the basis of field mapping in the region could be verified or rejected through the use of isotopes, the overall Ross Creek Basin groundwater study would then be integrated into a composite, state-of-the-art analysis which utilized an integrated interpretation of chemistry, well, test drilling, isotopic and computer-generated groundwater data.

Unfortunately, current isotopic age dating models proved inadequate for application in Ross Creek Basin. Because of the lack of discrete, continuous aquifers in the area, it became necessary to account for isotopic contributions from a variety of recharge sources. A methodology for calculating groundwater transit time using a steady-state numerical stream function model was assembled.

3.2 Background to Ross Creek

3.2.1 Isotopes in prairie groundwater investigations

As mentioned, isotopes had not previously been used in Western Canada either to delineate an altitude effect or as a groundwater reconnaissance tool. However, several important investigations had measured levels of stable isotopes on the Canadian prairies.

Fritz and Krouse (1973) examined the $\delta^{18}O$ values in carbonate shells, groundwater and lakewater from Wabamum Lake in central Alberta to determine groundwater flow directions and to infer paleoclimates. Fritz et al. (1978) found isotopically depleted waters in a Manitoba aquifer, changes which were linked by radioisotopic dating to climatic changes since the Pleistocene era.

Large systematic shifts in the $\delta^{18}O$, δD and several major ionic constituents of groundwater from the Milk River aquifer of southern Alberta have been observed by several different groups. These shifts were noted first by Schwartz and Muehlenbachs (1979) and were utilized to imply the presence of a large scale dispersion process acting on the aquifer. Schwartz et.al. (1981) found evidence of past mixing with underlying permeable units. Recent modeling studies have indicated that present day transient flow dynamics characterize the Milk River Aquifer system (Toth and Corbet 1986). Recent attempts to date the water in the unit isotopically have either proved unsuccessful (e.g. Swanick 1982) or have not been completed (M.J. Hendry and P. Fritz, pers. comm.; C. Robertson, pers. comm.).[1]

Hendry et al. (1986) utilized isotopes to demonstrate the origin of sulphate in the weathered tills of southern Alberta by contrasting present-day values of $\delta^{18}O$ in water with those of sulphates, which are believed to have been in equilibrium with prior groundwater conditions. Hendry (1986) cites isotopic evidence in claiming that groundwater movement in layers of weathered till in the province is considerably more dynamic than flow in the homogeneous and unfractured layers of the unweathered till below it. His

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[1] The Milk River Formation underlies Ross Creek Basin, but nearly a hundred meters of aquitard separate it from the shallow groundwater flow systems in the basin. It is thought that the Milk River aquifer does not participate in the near surface flow dynamics of Ross Creek Basin.

data also indicate that groundwater in Saskatchewan Sands and Gravels are younger than waters in overlying unweathered till.

3.2.2 Regional geology and hydrogeology

The geology of the Cypress Hills has been well investigated, as the Plateau represents a major feature on the Alberta landscape. Much information exists on the glacial features of the area (e.g. Stalker 1960); buried channels (e.g. Farvolden 1963; Stalker 1961); geomorphological features (e.g. Beaty and Young 1975); Quaternary stratigraphy (e.g. Stalker 1963; Veseth and Montagne 1980) and regional hydrology (e.g. Stevenson and Borneuf 1977; Tokarsky 1974).

The Cypress Hills are the highest of five levels of terraces left over from Miocene sedimentation and subsequent erosional events. Because the Plateau protrudes 700m above the surrounding dissected plains, the Hills receive more precipitation, are cooler and thus support a more verdant foothills-type biota than other parts of Ross Creek Basin.

The highest parts of the Cypress Hills were not glaciated during the Pleistocene epoch. The Elkwater Drift, the oldest and most extensive of the till units found in the Ross Creek Basin, can be found at elevations in excess of 1370m ASL on the north slope of the Hills, but this is more than 120m below the surface of the Plateau. Several other drift sheets cover the remainder of the basin, in many places burying the bedrock to depths of more than 30m. The surficial drift units present in Ross Creek Basin are all believed to have been laid down during the Wisconsin stage of glacial advances (Westgate 1968). These drift sheets are mapped in Westgate (1965).

The bedrock stratigraphy of the region is shown in a diagrammatic cross section (Fig. 3.2) and a map of bedrock geology is included as Figure 3.3. Because the geological units are virtually flat-lying and faulting in the area is minimal, the gradual decrease in elevation from south to north results in the exposure of progressively older strata[2]. Tertiary materials occur only at the top of the Cypress Hills plateau in the extreme southern portion of the basin (Fig 3.3). The Cypress Hills gravels and loess cap the hills and are underlain by the Ravenscrag Formation; a sandy claystone. Beneath the Ravenscrag lies the first formation of Cretaceous age; the Frenchman Butte, a loosely consolidated silty sandstone. A massive, spectacularly cross-bedded section of Frenchman Butte occurs just upslope from the western edge of the town of Elkwater. The Frenchman Butte Formation is underlain by the Battle and Whitemud Formations. While the afore-mentioned units are confined to the near vicinity of the Hil[illegible], the Eastend Formation extends several kilometer[illegible]e north and west of the town of Elkwater (Fig 3.3).

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[2] Westgate (1968) states that several small high angle normal faults exist in the extreme southeastern side of Ross Creek Basin. No evidence for these features was noted in the current work however.

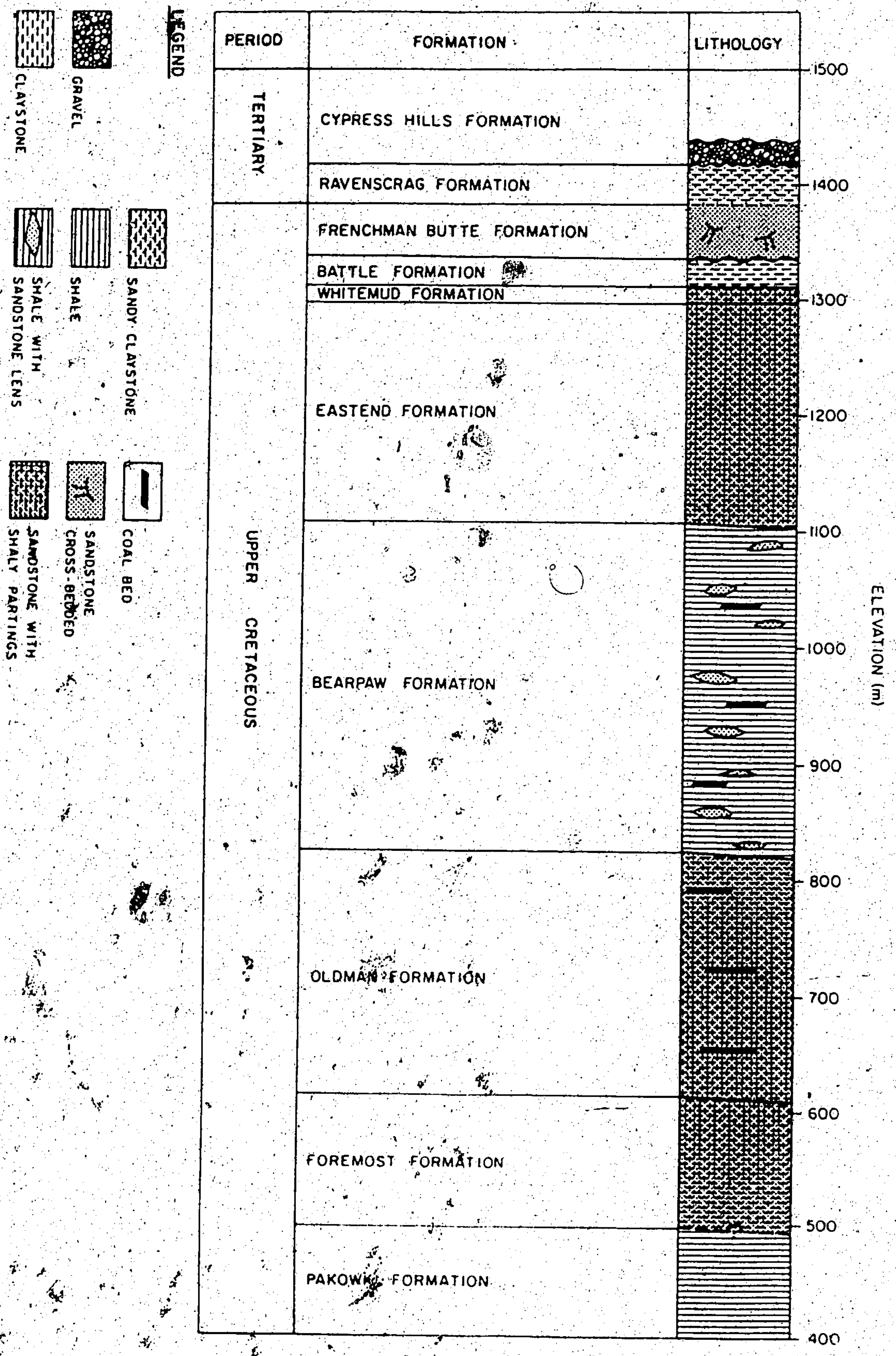
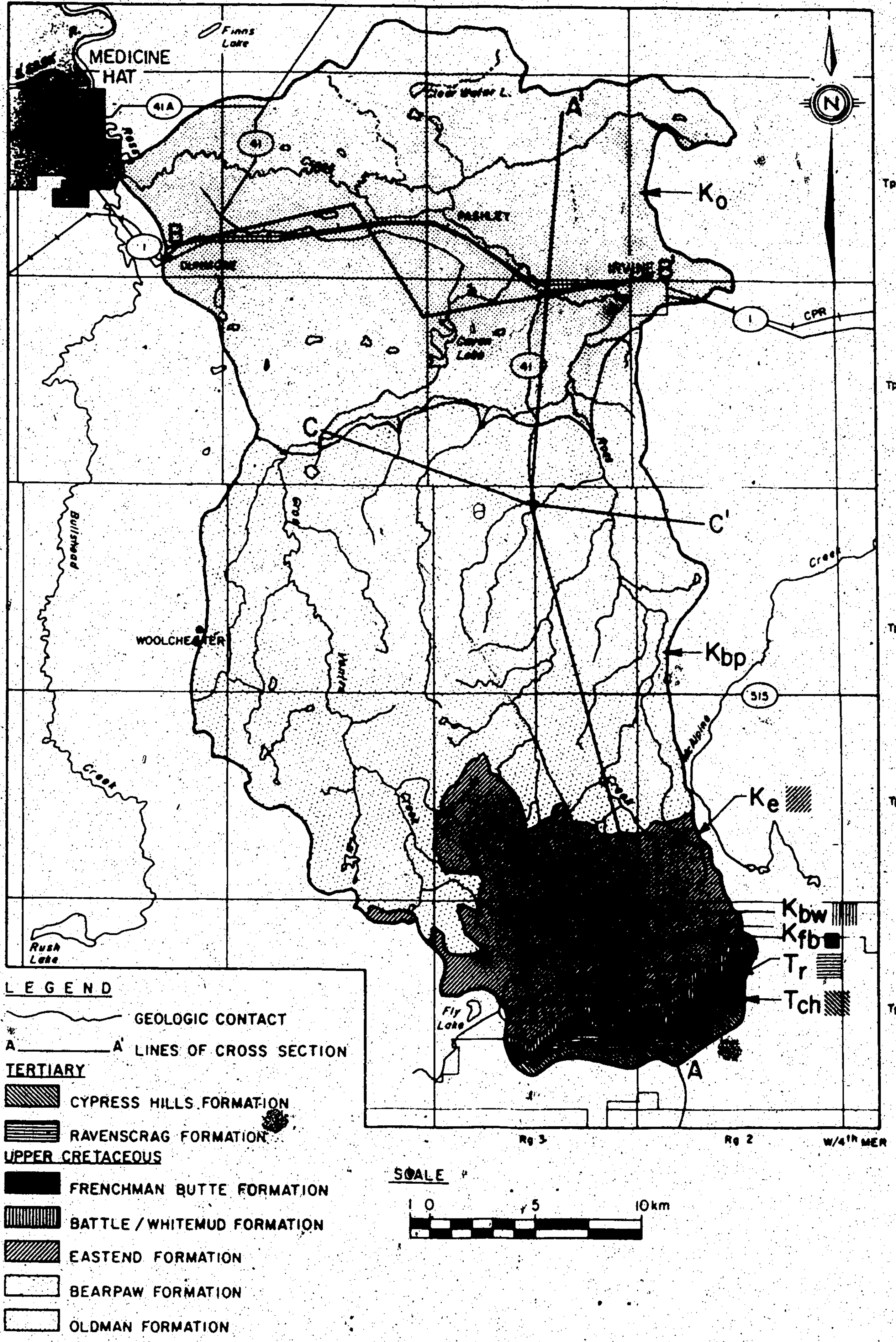


Figure 3.2. Composite stratigraphic column for Ross Creek Basin.

Figure 3.3. Bedrock geology map of Ross Creek Basin. Lines of section refer to Figures 3.4 to 3.6.



The Bearpaw Formation underlies the Eastend Formation and directly subcrops the drift throughout most of Ross Creek Basin. It is a thick shale unit with only occasional sand lenses and seams of lignite (Fig 3.2) The Oldman Formation is found beneath the Bearpaw Formation. This unit is described as a sandstone by Westgate (1968), but was found to occur almost exclusively as a shaly siltstone in the Ross Creek region. The Foremost and Pakowki Formations probably do not occur as the top unit of bedrock anywhere in Ross Creek, and are a silty shale and a shale, respectively.

Three structural cross sections have been assembled for Ross Creek Basin from information obtained from the Groundwater Information Centre (GIC) files (Alberta Environment, Edmonton), stratigraphic decriptions contained in Westgate (1968), and from the test drilling results of Ophori and Toth (1985). The lines of section are shown in Figure 3.3; the cross sections are given as Figures 3.4, 3.5 and 3.6. Strip charts of lithological logs are shown on the figures, if availible, as are geophysical logs.

The Cypress Hills and Eastend Formations provide the only productive bedrock aquifers besides discontinuous sand and coal lenses that may occasionally be found in other units. Lines of springs are found at both the Cypress Hills/Ravenscrag and Eastend/Bearpaw formational contacts, suggesting that a substantial amount of groundwater recharge that enters flow systems in the Hills is deflected laterally to discharge at these points. The lack of residents in this

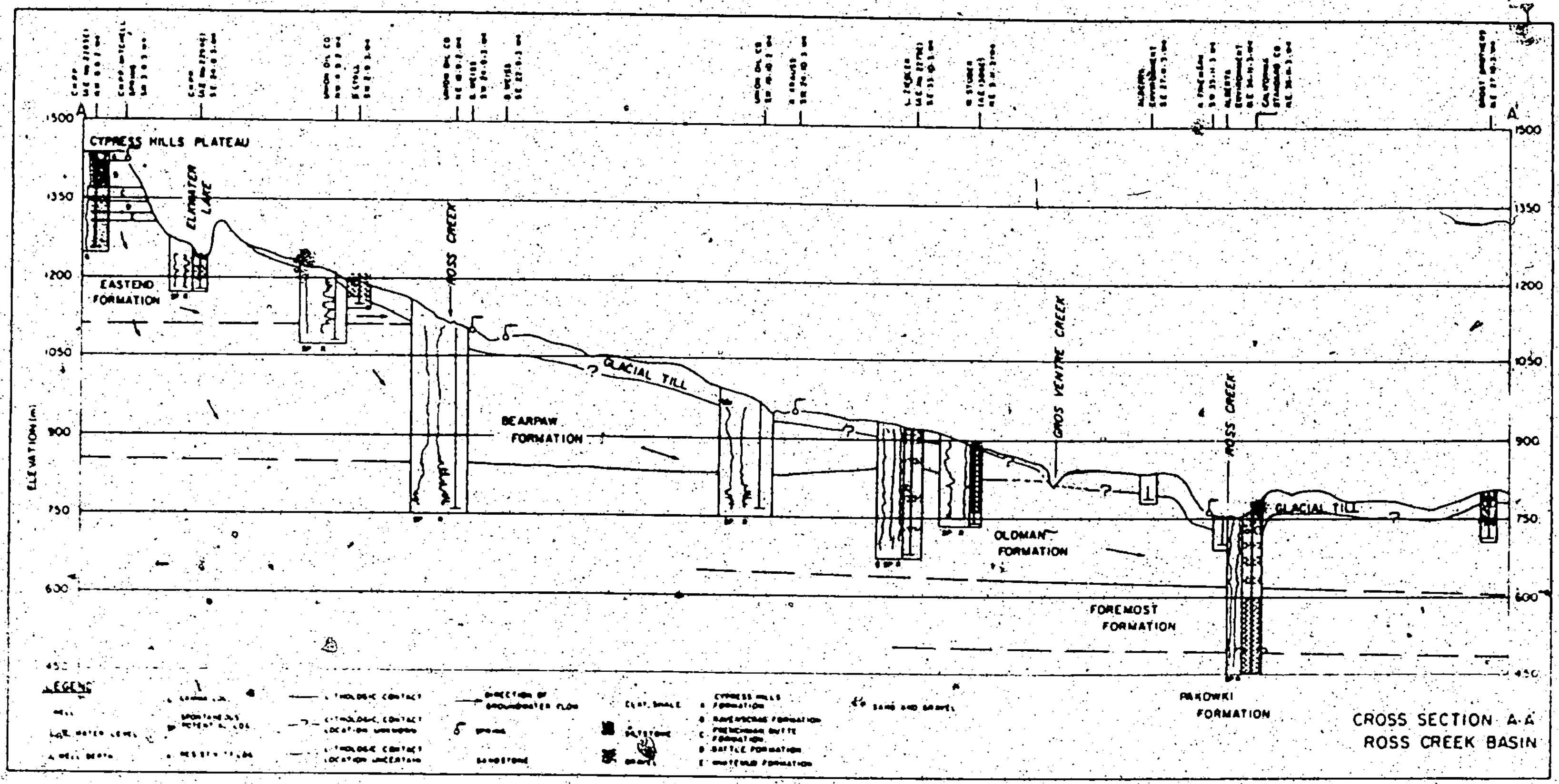


Figure 3.4. Structural cross section A-A'.

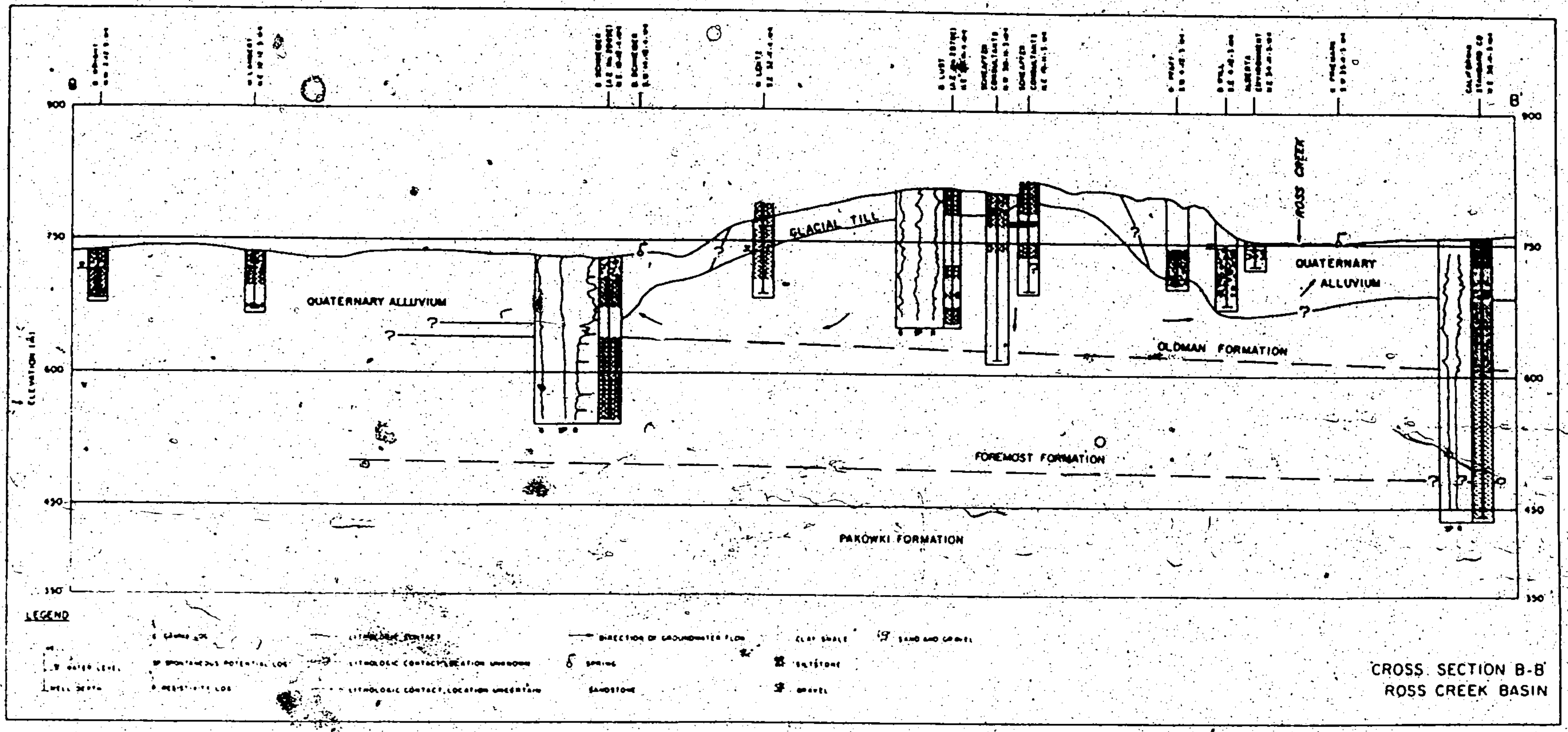


Figure 3.5. Structural cross section B-B'.

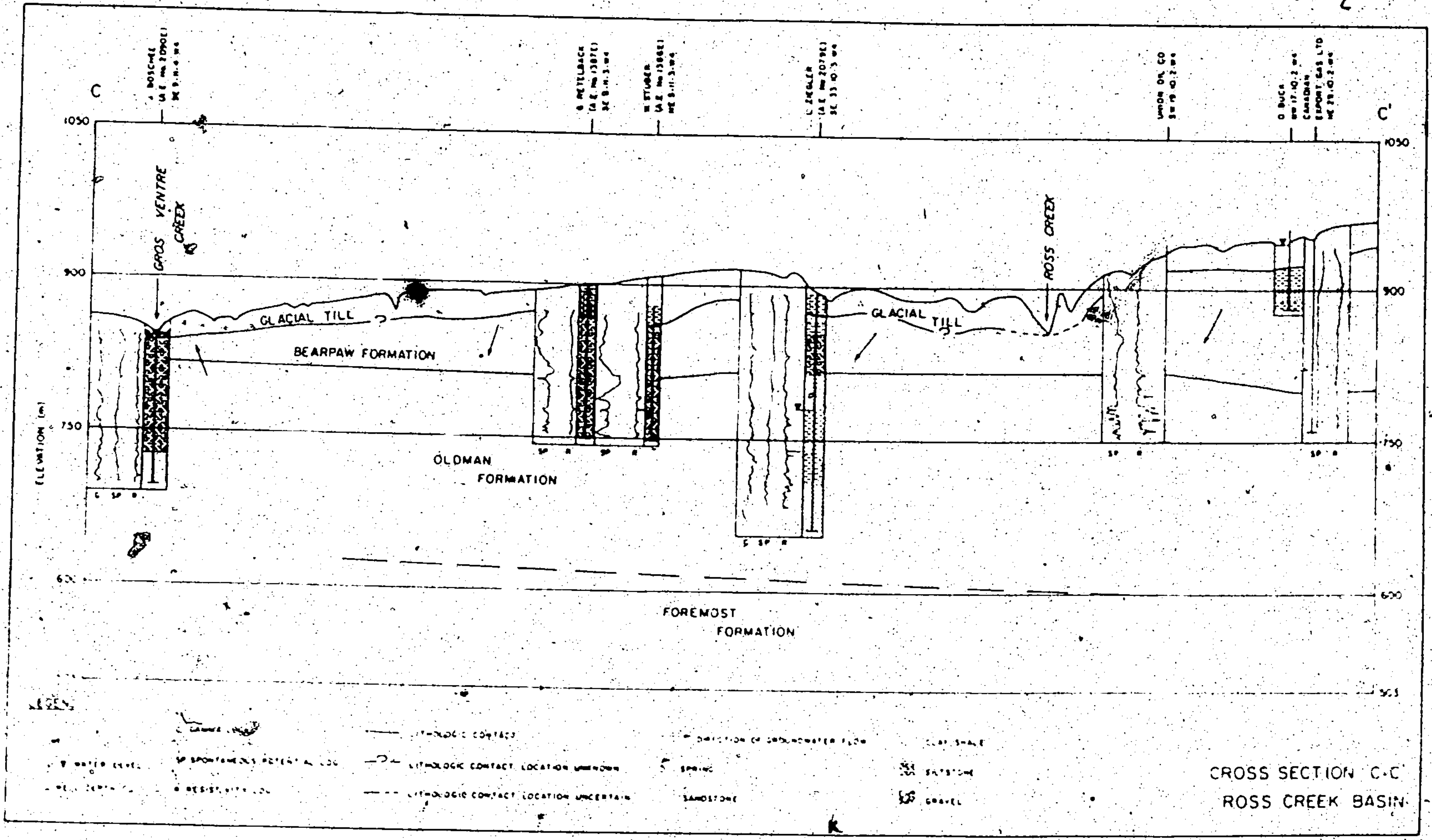


Figure 3.6. Structural cross section C-C'.

part of the basin means that little exploration of either unit has occurred. Table A.2.2 (Appendix I) lists the sampling points that are discussed in the current work and that had information available in either GIC files or the Ophori test drilling results (Ophori and Tóth 1985).

As becomes apparent from Table A.2.2, most of the residents of Ross Creek are scattered through the region north of Township 8, and most rely on shallow wells completed into permeable zones within the glacial drift. These units are not laterally extensive and are not reliably found. One buried channel deposit was located by the test drilling program in section 10-12-4W4 (B. Schneider well, Fig. 3.5; RCE-17, Table A.2.2), but attempts to locate one of two other buried glacio-fluvial deposits believed to exist beneath the area and to run along the northward trending courses of Gros Ventre and Ross Creeks were unsuccessful (Ophori 1986).

Limited information on the hydrogeology of the Cypress Hills and area is also given in Freeze (1969a), although the investigations were limited to the Saskatchewan side of the Cypress Hills. Freeze (1969a) determined permeabilities for the formations discussed in this section.

3.2.3 The Ophori/Alberta Environment work

The structural cross sections given in Figures 3.4 through 3.6 portray the geology of the Ross Creek Basin. The correlation of geological contacts with groundwater features such as the lines of springs at the Cypress Hills/Ravenscrag and Eastend/Bearpaw becomes clear once the geology of the area is fairly well known. Some good information is available from the GIC files, but the sparse population in the region, combined with the fact that many of the wells have been in use since the area was settled in the 1920's, made reliable predictions about groundwater flow patterns extremely difficult.

Using the field reconnaissance methods outlined by Toth (1966), hydrogeological field mapping was carried out by Ophori in the summer of 1983. These results are summarized in Ophori and Tóth (1983) and Ophori (1986). The location of the discharge and recharge areas in Ross Creek Basin mapped by Ophori is shown in Figure 3.7. According to this work, Recharge that occurs in the Cypress Hills is discharged along Gros Ventre and Ross Creeks. Large regions of discharge also occur along the Trans-Canada Highway in the northern part of the basin. However, the large "uncertain" area in the centre of the basin had neither discharge or recharge properties assigned to it (Fig. 3.7).

In addition to the field mapping effort, groundwater quality samples were taken throughout the Ross Creek Basin. These data were combined with valid existing water chemistry records from the GIC files. Using hydrochemical facies principles (Back 1960), groundwater facies types were plotted on an aerial map of Ross Creek Basin. These are shown in Figure 3.8. In addition, contours of total

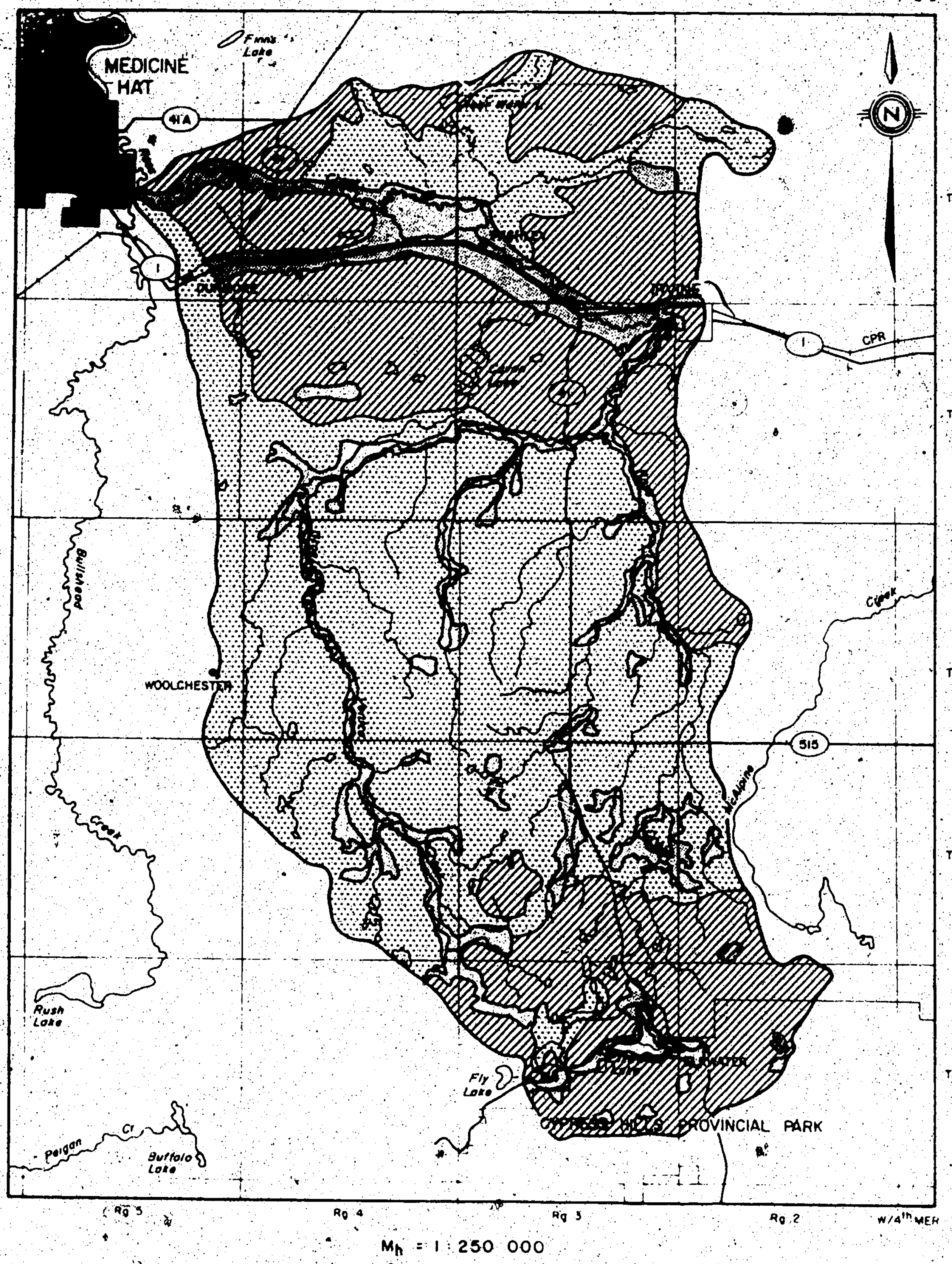
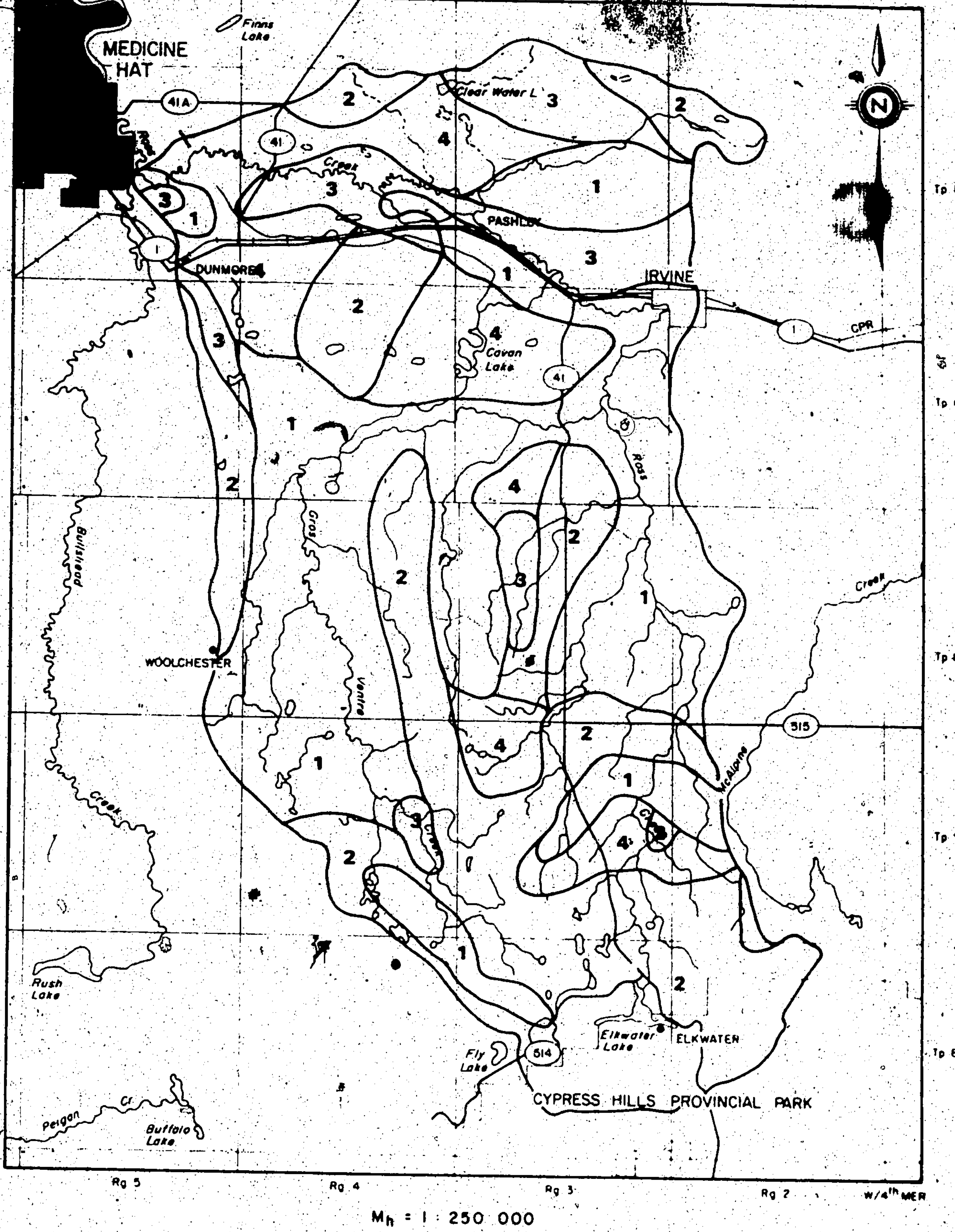


Figure 3.7. Results of groundwater outcrop mapping. Source: Ophori (1986).

LEGEND

▨ Recharge area
☐ Discharge area
░ Uncertain area



L E G E N D

- ~ Facies Boundaries
- 1 Calcium, magnesium, sulphate, biocarbonate
- 2 — Calcium, magnesium, biocarbonate
- 3 — Sodium, sulphate, biocarbonate
- 4 — Sodium, biocarbonate

Figure 3.8. Distribution of hydrochemical facies in Ross Creek Basin. Source: Ophori (1986).

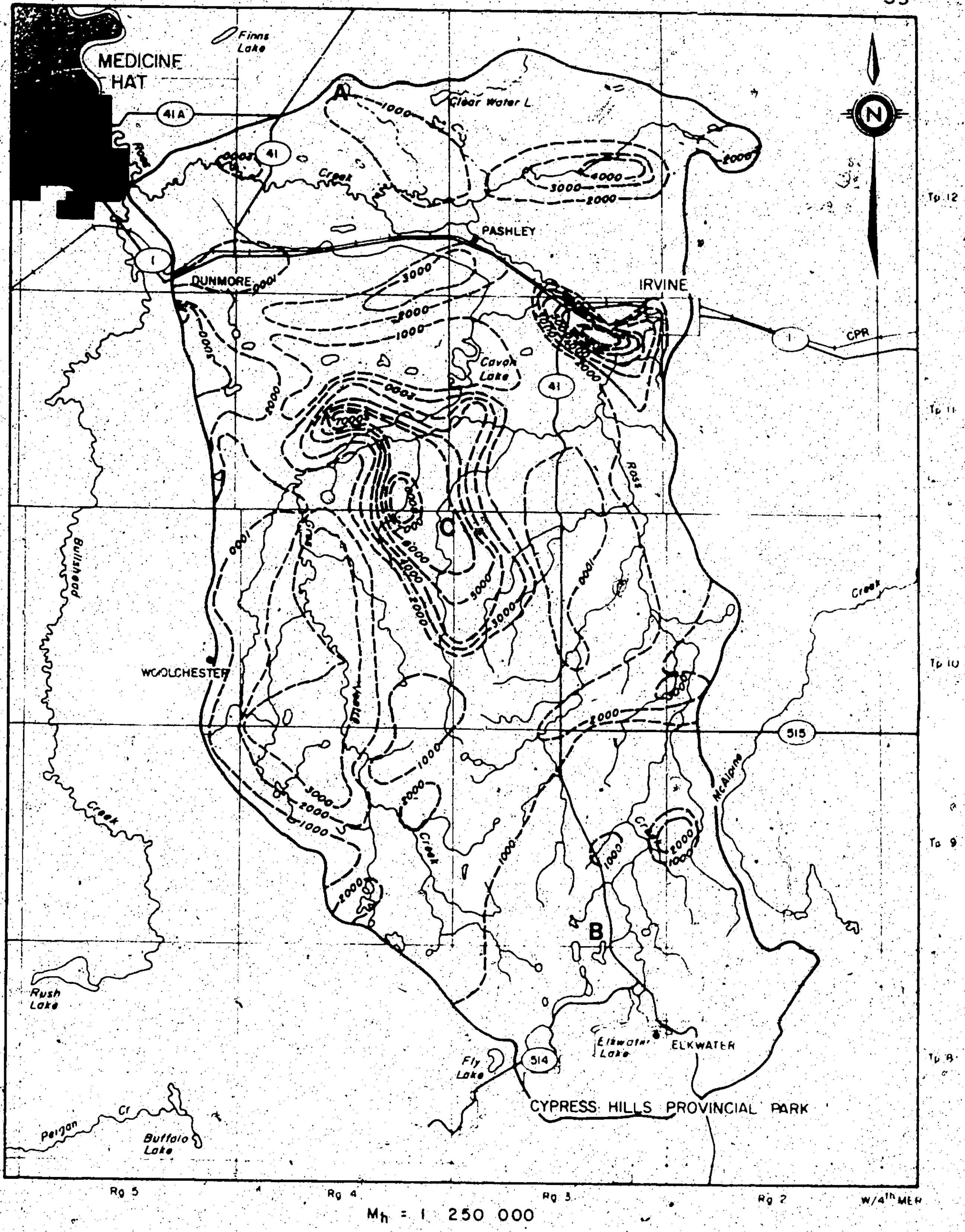
dissolved solids (TDS) were drawn on a map of the area. (Fig. 3.9).

After completing a drilling program, a computer simulation of flow conditions for Ross Creek Basin was calibrated. This would appear to confirm the results found by mapping and the plotting of hydrochemistry parameters, as this work showed that much of the recharge from the Cypress Hills is discharged in the northern part of the basin (Ophori and Tóth 1985).

Later work by Ophori has focused on the calibration and refinement of a groundwater management model for Ross Creek Basin (Ophori 1986). This is a conceptually sound idea, but the lack of good aquifers in the region make a management model difficult to apply.

3.2.4 Potential applications of isotopic techniques in Ross Creek Basin

As one can see in Figures 3.2 - 3.9, much remained to be determined about the hydrogeology, the directions and patterns of groundwater flow and the hydrochemical relationships in Ross Creek Basin at the onset of this program. The investigations of Ophori and others proposed and verified the existence of large scale components of regional groundwater flow in Ross Creek Basin. However, these results could not be quantified by any of the data gathered for the Ophori/Alberta Environment work. Because of the lack of precise detail, it was decided that the stable



L E G E N D

—1000— Total Dissolved Solids Contour

Figure 3.9. Distribution of Total Dissolved Solids in Ross Creek Basin. Source: Ophori (1986).

isotope sampling program would be expanded to include the radioisotopes of tritium and ^{14}C. The delineation of an altitude effect for the basin would help to isolate specific recharge areas and that groundwater age dating would help to delineate individual components of flow systems in the basin.

Specific areas, such as the high total dissolved solids region in the center of Ross Creek Basin (Fig. 3.9) would be examined carefully to determine the age relationships of groundwaters in the area. More of the "uncertain area" in the groundwater discharge and recharge map (Fig. 3.7) could be separated into specific components of groundwater flow utilizing isotopic interpretations. The correlation of springs and geological contacts (Fig. 3.5) would be examined to determine their age and whether or not the source of water was in the Cypress Hills.

3.3 Interpretation of Isotopic Age Dates

3.3.1 Problem definition

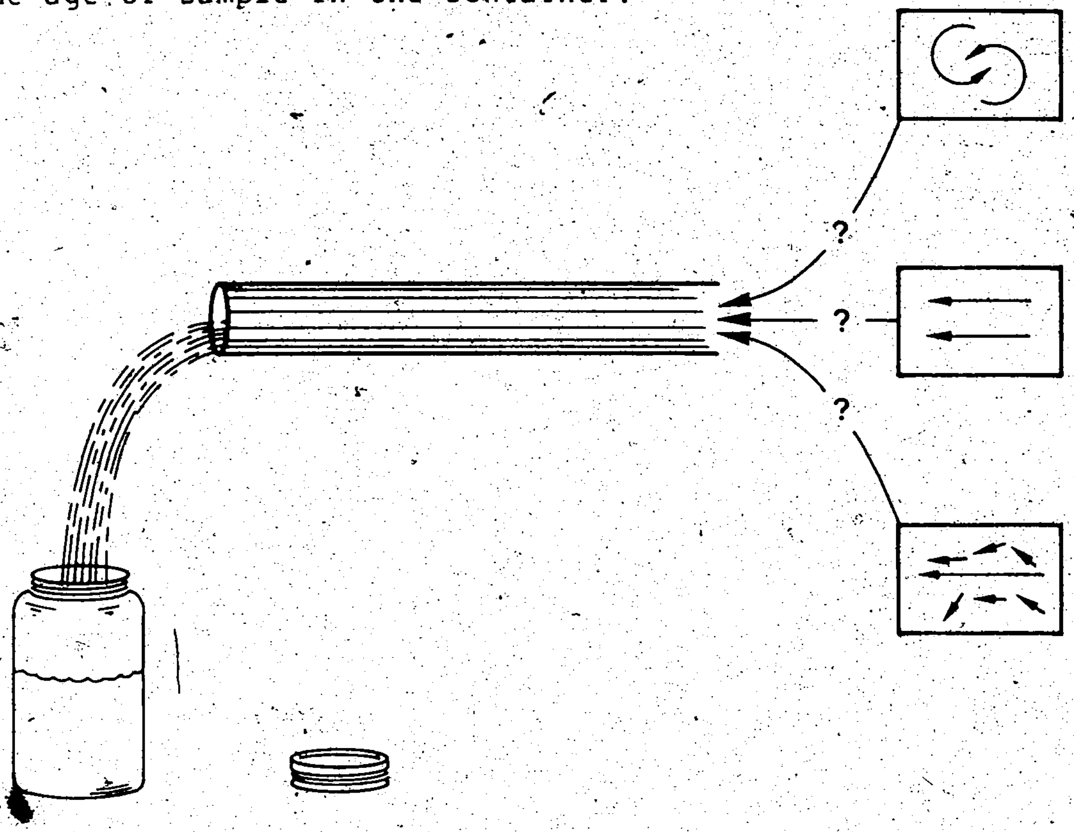
Groundwater tracing with environmental isotopes lends much to an integrated groundwater study. An age value for groundwater holds the promise of being an important bit of evidence because from it groundwater velocity may be calculated. This may be used as an empirical clue in a determination of values of dispersion and permeability. In the past, most applications of isotopic dating have used vastly oversimplified groundwater flow systems.

In the real world, simplified examples do not exist. Perfectly confined aquifers cannot be found; even the original "classic" aquifer, the Dakota Sandstone, has been reconsidered in a recent series of papers from the USGS (Jorgenson and Signor 1984). Therefore, the isotopic age interpretor is usually faced with a challenging situation: how did the bottle of water that was sampled end up having the isotopic "age" or composition that it does? Did the water originate from a single, line source? Does it represent mixing? Is the isotopic age the same as that of the water? This dilemma is shown diagrammatically in Figure 3.10. Consider the case of sampling in a regional or intermediate flow system, as shown in Figure 2.2. It would make quite a difference to the groundwater age, depending on where the sample was taken in this profile.

The use of isotopic age dating will not, unfortunately, yield unequivocal quantitative results. Barring errors in sampling and laboratory methodology, the use of environmental tracers, in many cases, may leave unsolved more questions than the researcher had originally hoped to answer. However, the proper application and interpretation of age dates has "considerable potential to extend our range of useful hydrologic data" (Nir 1973:80).

To some studies even a semi-quantitative answer is more than enough, in others, estimates of groundwater velocity and age are useful in the calibration or elimination of

Figure 3.10. Groundwater age dating dilemma. When one collects a sample from a well or spring, it is not known the extent to which (from top to bottom) mixing, flow and retardation of the tracer will affect the age of sample in the container.



previously assumed models. It is this approach that will be pursued for Ross Creek Basin.

3.3.2 Current models

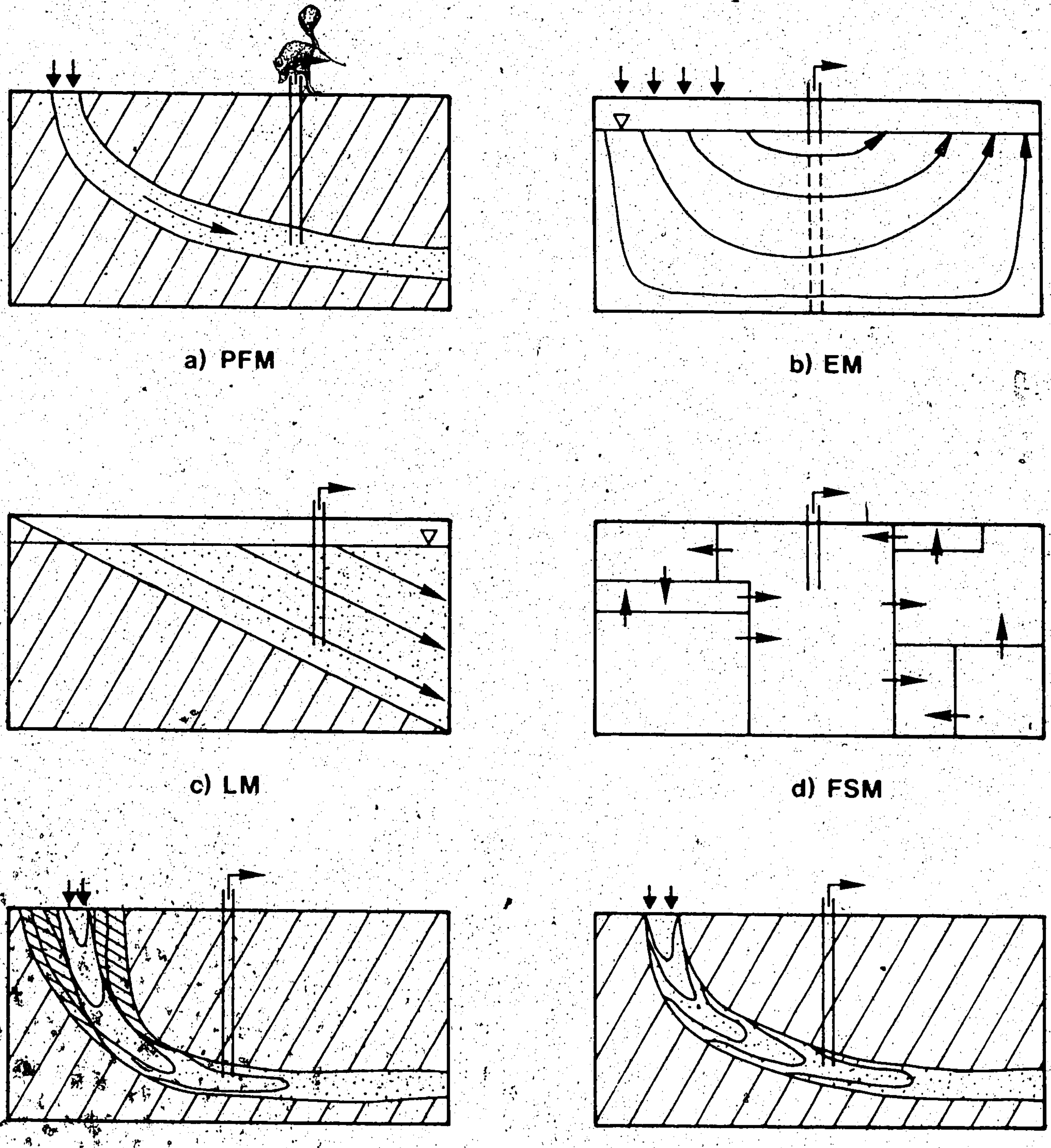
Where isotopic age dates are applied, one has to have a model against which the data may be evaluated. The model may be based on any combination of conceptual or field data, and if the isotopic dates appear to agree, then one assumes that the model has been verified. If, on the other hand, the isotopic ages do not fit with those predicted by the model, then some of the parameters that have been used in acquiring the isotopic data or in formulating the model would appear to have been incorrectly conceptualized and implemented.

A major problem in groundwater age ~~dating~~ is that while much effort has gone into modeling the geochemical processes that influence the ^{14}C content of dissolved carbon species in the water, little effort has been spent in trying to decide how water at a sampling point ended up with the isotopic signature that it has. Most of the flow models that isotope reseachers apply to hydrogeological systems have been developed in chemical engineering (e.g. Levenspiel 1972) and only recently adapted for use in "natural" groundwater situations by hydrologists (Nir 1973).

These models suffer from two major problems. Firstly, they are too rigid. The isotopic age is calculated directly from the application of whatever equation has been derived to fit that system. In this sense, most of the models utilize a set of lumped parameters and few have the ability to be calibrated to fit a more sophisticated or different situation. Secondly, they just are not formulated to include valid assumptions of realistic groundwater conditions, as shown in Figure 3.11. Mathematically, these models break down into ~~combinations~~ combinations of pipes (PFM, Fig 3.11a), well-mixed boxes (EM, Fig.3.11b); cells that transfer lumps of groundwater and isotopes back and forth (FSM, Fig 3.11d); and one dimensional solutions of the dispersion equation, with (DM, Fig 3.11e) and without diffusion taken into account (DM, Fig 3.11f). The linear model has not been applied in groundwater studies (LM, Fig. 3.11c). These models are discussed by Nir (1964); Vogel (1970); Przewlocki and Yurtsever (1974); Maloszewski and Zuber (1985); and Kreft and Zuber (1978). Maloszewski and Zuber (1982); Ferronsky and Polyakov (1982); and Martinec et al. (1974) review the various models from a mathematical standpoint, but ignore the hydrological validity of the conceptualization process that went into their formulation. If a true integrated approach is to be applied, one must utilize valid groundwater modeling.

Several valid applications of the dispersion model have been carried out. Egboka et al. (1983) used the chloride plume from the Borden landfill to delineate the center of the groundwater flow path. In this example, an analytical solution of the dispersion equation was applied along the flow path and utilized to calibrate tritium values with

Figure 3.11. Different models used in groundwater age dating. a) Piston flow model; b) Exponential model; c) Linear model; d) Finite state mixing-cell model; e) Dispersion model with diffusion taken into account; f) Dispersion model without a diffusion coefficient. a), b) and c) after Maloszewski and Zuber (1982); d) after Frind and Sudicky (1981).


a) PFM

b) EM

c) LM

d) FSM

e) DM with diffusion

f) DM without diffusion

known system parameters such as dispersivity, groundwater flow velocity and permeability. A numerical approximation of the dispersion equation was applied by Herweijer et al. (1985) in a two-dimensional interpretation of age dates in a Netherlands aquifer. Calibration of the model included adjustment of geological configuration, permeability, precipitation, porosity and both transverse and longitudinal dispersivity factors.

However, Maloszewski and Zuber (1982) provide evidence that dispersion is not a major factor in large scale groundwater flow systems. Because the age of a tracer such as an isotope is assumed to be dependent on travel length and average linear velocity, v:

$$v = X/T \tag{3.1}$$

where X is the distance from the recharge point and T is the travel time, while dispersivity, D_d/v is approximately a system constant (Anderson 1979; Wang and Anderson 1982), then time is a direct function of travel distance. This means that the "dispersion parameter" of chemical engineering (D/vx) becomes very small on the scale of regional groundwater flow systems. This is demonstrated ~~in~~ Figure 3.12. Small values of the dispersion parameter, implying either low dispersivity or a long transit distance, begin to approximate tube flow, or the PFM. As an example, in a system with a dispersivity of 50m (Egboka et al. 1983),

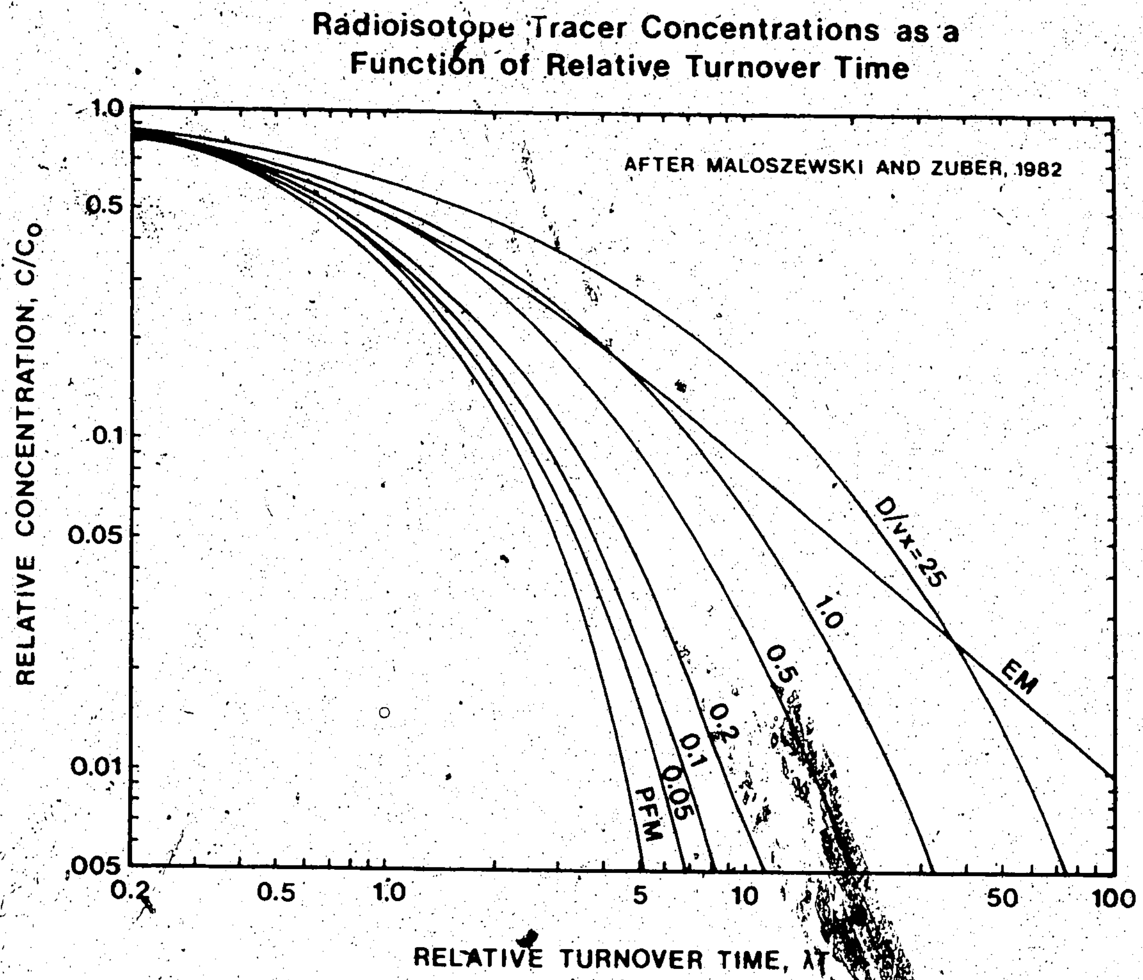


Figure 3.12. Radioisotope tracer concentrations as a function of relative turnover time. Note how the dispersion parameter D/vx approaches the piston flow model at large travel distances.

a sample taken at 500m will result in a dispersion parameter value of 0.1. The value is close to the line of the piston flow model in Figure 3.12. Therefore, the application of the piston flow model becomes a reasonable approximation of a dispersion model in a large scale system, a fact that is stated by Nir (1964) and shown by Maloszewski and Zuber (1982).

3.3.3 Formulation of solution

3.3.3.1 Conceptualization

It was decided to model isotope dates in the basin utilizing steady state flow, radioactive decay and the adjustment factor, Q. Modeling would be performed along calculated groundwater flow paths, by applying the piston-type flow model (PFM) along one or a number of streamtubes using a simple method for the conversion of steady state groundwater flow models to calculate stream functions (Frind and Matanga 1985).

The advantages of applying such a model are as follows:

1. A unique model representing the special groundwater and geological conditions at each site may be applied.

2. The model is formulated according to the theories of regional groundwater flow and thus is more

representative of realistic hydrological conditions than current methods.

3. The numerical model is not constrained by assumptions of homogeneity, isotropy or point recharge; conditions that are inherent in other isotopic dating models.

4. Current methods of stream function calculation allow for a direct, graphical determination of travel time, thus providing a direct means for comparison with actual groundwater age dates yielded for isotopic analyses.

The disadvantages to this approach are limiting, but not critical for this study. Firstly, by not accounting for dispersion the model risks undervaluing groundwater velocity. However, as shown in Figure 3.12, the outer bounds of the system velocity; namely those that are calculated by pipe flow (PFM) and a well-mixed box (EM), are known. These may be utilized to show the maximum and minimum time needed to transport a tracer of the analyzed apparent isotopic age. In addition, the effects of dispersion in a large scale system are minimal.

Secondly, the application of a steady state model for simulation of a system which has both transient qualities and a large component of unsaturated flow is a deficiency. Evidence that supports this line of thinking include:

1. The southeastern portion of the Alberta Basin has been demonstrated to represent naturally changing piezometric conditions (Tóth and Corbet 1986);
2. Groundwater levels in Ross Creek Basin have been noted to fluctuate by Ophori (1986);
3. Maloszewski and Zuber (1982) express fears that isotopic dating is usually performed in areas of highly developed groundwater resources, thus invalidating steady state concepts of groundwater movement.

While Ross Creek Basin may represent a transient system, the transient nature of the basin is important only in terms of long term conditions; i.e. on the order of 10^5 years or more, rather than the 10^2 to 10^4 year time frame that has been considered by the use of radiocarbon and tritium. Water level fluctuations and groundwater exploitation are not important on the scale of the basin that will be modeled here. Clearly, the application of a numerical model that would take into account unsaturated, as well as saturated flow, such as that of Davis and Neuman (1972) would have merit, although modeling of large scale systems obviates somewhat considerations of unsaturated flow.

Overall, it was felt that the formulation of a numerical stream function model in conjunction with the calculation of age dates along stream tubes was justified for use in a variably confined system such as Ross Creek Basin. The complexities introduced to isotopic age dating by regional groundwater flow could be expediently modeled and represent a considerable improvement over past interpretations of isotopic age dates. In the following section, the theoretical formulation of the stream function method of isotopic age dating will be developed.

3.3.3.2 Stream functions and the finite element method

In recent years, finite element methods have become a useful technique for the approximation of partial differential equations. The derivation and formulation of finite element methods for use with the equation of steady state groundwater flow are well known and discussed in detail by Wang and Anderson (1982). Typical groundwater applications utilize a stated set of no flow and constant head boundary conditions to calculate potential functions (heads) throughout the region.

Recent work by Frind and Matanga (1985); Frind et al. (1985) and Fogg and Senger (1985) have demonstrated the ease and usefulness of altering commonly utilized steady state computer codes to calculate stream functions or the discharge per unit of medium thickness.

On a flow net, the stream function contours are everywhere perpendicular to the equipotentials provided that the cross section is isotropic. Combined with a contouring software package, the stream function method allows for the generation and representation of either equipotential and/or stream lines and thus the computer aided generation of a flow net. The area bounded by the two stream lines is called a streamtube and, because the stream lines are contoured, the discharge through each streamtube in a cross section is the same and equal to the numerical difference in stream functions between each stream line:

$$\Delta Q = \Psi_2 - \Psi_1 = \Delta\Psi \qquad (3.2)$$

where ΔQ is the Darcy discharge within a streamtube and Ψ_1 and Ψ_2 are the numerical values of the boundary stream lines (Frind and Matanga 1985). This is shown graphically in Figure 3.13.

By knowing the discharge through a streamtube, it is possible to calculate the velocity of water within the streamtube, and since the change in distance, Δs, covered by a particle of water is possible to measure on a cross section; the time of travel of an advected material (such as an environmental tracer) may be calculated:

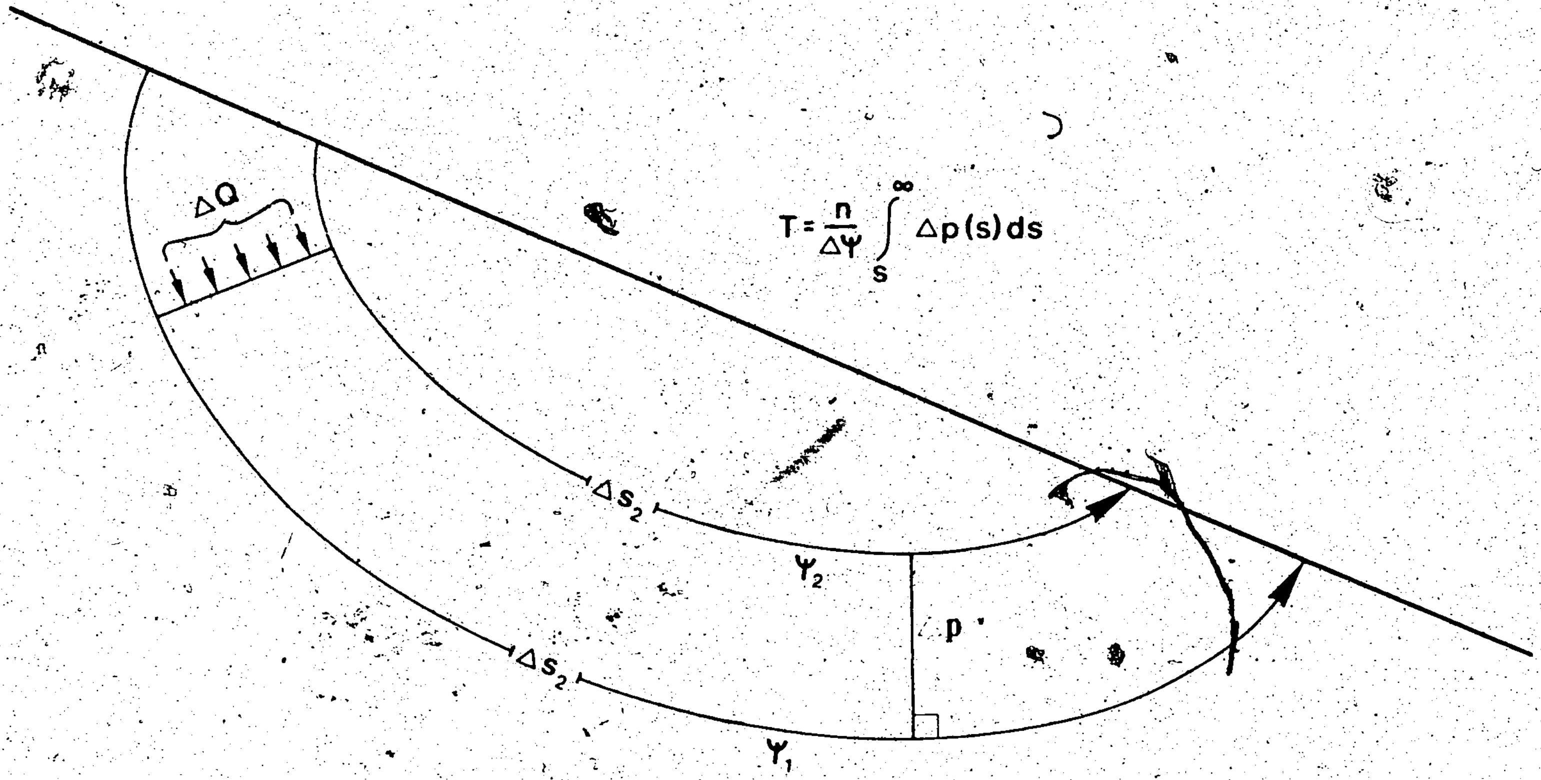


Figure 3.13. Calculation of travel time in a streamtube. The area of the streamtube may be measured from the plot, while the porosity (n) and the $\Delta\Psi$ are constant. $\Delta\Psi$ may be specified when contouring the stream function values.

$$v = q/n = \Delta\Psi/n\Delta p \qquad (3.3)$$

and:

$$T = n/\Delta\Psi \int_{s}^{\infty} \Delta p(s)ds \qquad (3.4)$$

where q is the specific discharge, n is the porosity of the medium, Δp is the distance between two stream lines, T is the travel time and v is the average linear velocity. (Frind and Matanga 1985). It is important to note that Equation (3.4) is expressed simply as the area of the streamtube (obtainable from a plot such as Fig 3.13) multiplied by a constant.

3.3.3.3 Formulation of age determination for constant input cases

To determine the age of a tracer with constant input to a groundwater system at a given time, the following relation may be stated:

$$T = 1/\lambda \ln Q/R \qquad (3.5)$$

where λ is the decay constant of the isotopic species, R is the ratio of sampled to initial tracer concentration and Q is a geochemical adjustment factor. R and Q are discussed in more detail in Section 3.4. For ^{14}C analysis, Equation (3.5) yields:

$$T = -8270 \ln R/Q \tag{3.6}$$

Therefore, the isotopic age due to radioactive decay can be calculated and applied to the flow path and discharge relationships determined by the steady state stream function model. This is mathematically equivalent to applying the PFM along a prescribed number of streamtubes.

3.3.3.4 Formulation for cases of variable input

Implicit in the formulation so far has been an assumption of constant initial tracer concentration: input proportional only to groundwater recharge. The ratio of input mass or activity to recharge has been assumed to be constant over time. While this assumption is more or less true for ^{14}C dating, it cannot be held as valid for tritium input since 1952.

Bomb tritium inputs to the groundwater system must be calculated from a yearly recharge function which has been synthesized for the Alberta setting. Each streamtube in cross section will thus have a unique travel time and must be related to the Alberta recharge function. It must be remembered that this tritium recharge function must account for decay of tritium since infiltration.

The Great Plains region of North America is unique in that tritium levels in precipitation have generally been much higher than anywhere else in the world with the exception of the interior Soviet Union. During the period of maximum atmospheric radioactivity in the summer of 1963, Alberta tritium levels were well over 8000 TU, while values in Ottawa reached a peak of 5000 TU (Egboka et al. 1983, Ferronsky and Polyakov 1982). Values of tritium in these regions have only recently begun to approximate levels found at other stations in the world.

The first three columns in Table 3.1 list the tritium values for Ottawa (Egboka et al 1983), the Netherlands (Herweijer et al. 1985) and Alberta (compiled from Brown 1970; Ferronsky and Polyakov 1982; and Alberta Environmental Centre, unpublished data). Unfortunately, the IAEA station in Edmonton was only in operation during the mid - 1960's, so no data exists for the periods 1952-1962 and 1970 to 1983. The values from Table 3.1, columns 1 through 3 are plotted in Figure 3.14.

On Figure 3.14 the few tritrum values that have been recorded for Alberta are consistently higher than those recorded in Ottawa and much higher than in Holland. At the height of tritium input, Alberta values were 10 times higher than in the Netherlands and 2.5 times higher than at Ottawa. In recent times however, all of the tritium values have begun to approach pre-bomb levels.

YEAR	OTTAWA ANNUAL MEAN	HOLLAND RECHARGE MEAN	ALBERTA ANNUAL (MEAS.)	ALBERTA ANNUAL (ASSUMED)	ALBERTA DECAY TO 1984
1952				50	10
1953				200	35
1954	300			350	65
1955	50			75	15
1956	75			100	20
1957	100	50		150	30
1958	200	120		250	60
1959	450	500		500	120
1960	175	60		300	80
1961	275	50		600	165
1962	825	150		1500	430
1963	2300	400	4020		1230
1964	1075	510	2600		840
1965	600	150	1480		505
1966	375	100	840		300
1967	225	80	460		175
1968	200	60	480		195
1969	175	60	310		135
1970	160	50		225	100
1971	145	60		175	85
1972	100	40		150	75
1973	80	60		140	75
1974	80	30		125	70
1975	75	50		110	65
1976	65	20		100	65
1977	65	30		85	60
1978	65	30		80	60
1979		20		70	55
1980		15		60	50
1981		20		50	40
1982		15		40	35
1983				35	35
1984			28		30

Table 3.1. Tritium input functions in tritium units (TU). Sources: Ottawa from Egboka et al. (1983); Holland from Herweijer et al. (1985); measured Alberta (1963-1969) from Brown (1970) and D. Arnold (unpublished data for 1984). Assumed Alberta annual [illegible] values are rounded to the nearest [illegible]

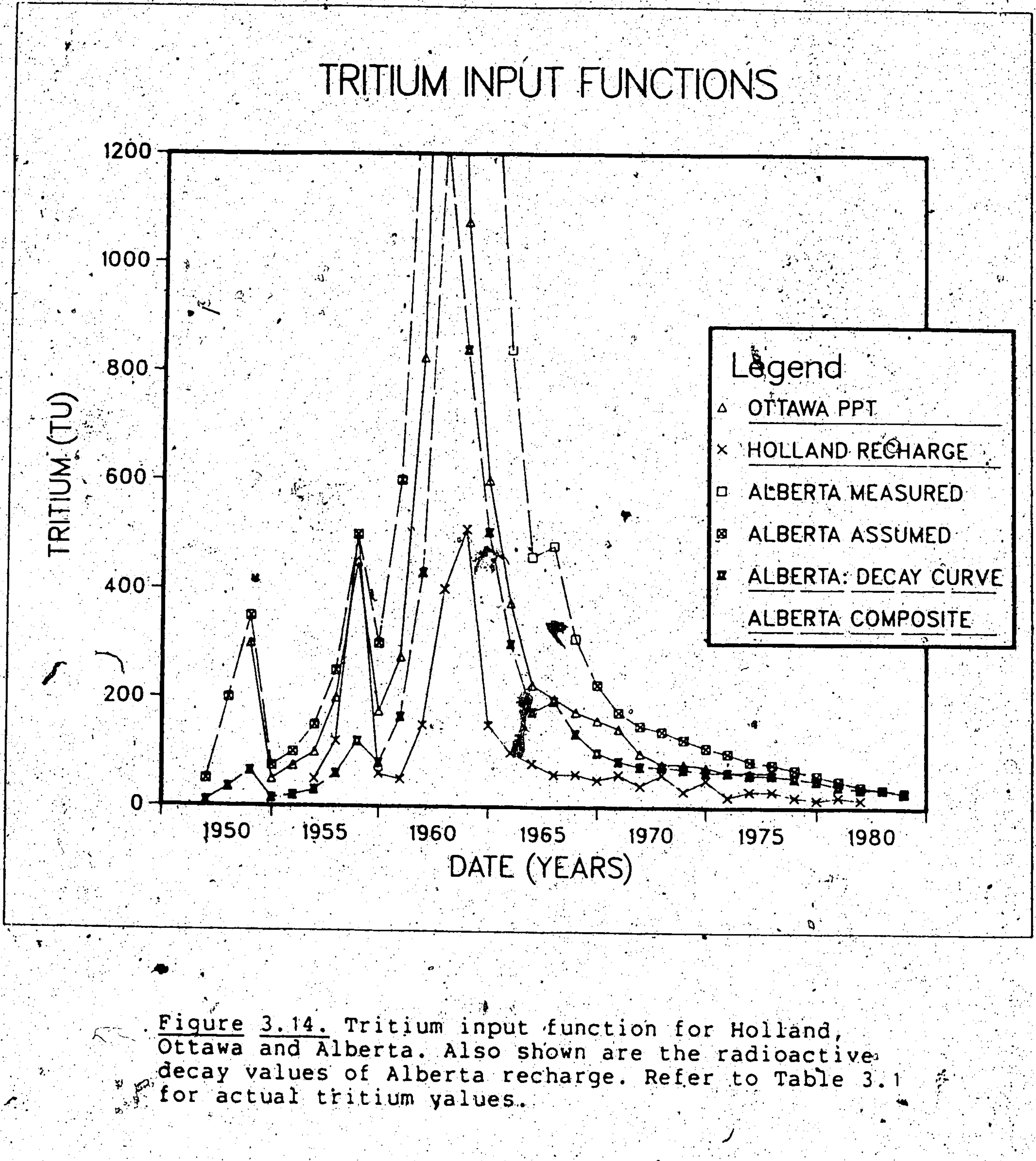


Figure 3.14. Tritium input function for Holland, Ottawa and Alberta. Also shown are the radioactive decay values of Alberta recharge. Refer to Table 3.1 for actual tritium values.

An input function for Alberta may thus be extrapolated from the data shown in Figure 3.14. This function will not be very accurate for the period 1952-1962, as year to year levels in the precipitation at Ottawa and Netherlands did not follow any particular pattern, but since the open-air nuclear weapons testing ban in 1964, levels have slowly declined. Alberta values may be assumed to gradually decline to the measured 1984 value of 28 TU. These estimations are reasonably accurate for the period 1970-1983 and represent a declining error function.

Column 4 of Table 3.1 lists the values of tritium fallout assumed for Alberta for those years for which no recorded data exist. These values are also shown in Figure 3.14. The assumption of constant values for the entire province is not accurate because tritium levels in the southern part of Alberta should be less than in the northern half, however, because of errors connected with an estimation of this type and a postulated difference between the average groundwater recharge levels of tritium and the average annual values, this is probably as accurate an estimate as may be made to this point.

Column 5 of Table 3.1 lists the expected current levels of tritium for each year of input if an Alberta groundwater sample was acquired in 1984. These values were calculated by taking tritium levels listed column 4 and applying the law of radioactive decay. Time, in this situation, is equal to 1984 minus the input year. Thus, 1963 water would contain a tritium level over 1200 TU in 1984 (Table 3.1).

3.4 Sampling and Analysis Procedures

3.4.1 Stable isotopes

A total of 238 groundwater samples were collected for stable isotope analysis. Of these samples, 37 were collected at springs and seepages; 84 were taken from wells, of which 8 were flowing wells; and 26 surface water samples were analyzed. In addition, 28 precipitation samples were collected. Twenty of the 28 precipitation samples were fresh samples taken during three different storm events, the other 8 - 10 were collected from snowbanks and could not be related to a specific meteorological event.

The remaining 53 cases are repeat samples acquired sequentially over the course of a year. These samples were taken to assess the amount of seasonal variability inherent in the groundwater. No quality control samples such as duplicates or replicates were taken: sufficient quantities were collected at one time to ensure enough sample for at least 10 analyses for both $\delta^{18}O$ and δD.

All of the points sampled are listed in Appendix II, in a table that is sorted by township, range, section and lsd (Table A.2.1). In addition, the sampling points for which lithologic data exist are also listed in Appendix II (Table A.2.2). In this study, the numbers given to the stable isotope samples were the central index on which every other numbering scheme was based. Only one water, referred to as RCD - 29 did not have a corresponding stable isotope sample collection made.

Stable isotope samples were collected in wide mouthed, screw cap 150 ml plastic Nalogene bottles (Sybron Corp.; available from Fisher Scientific Corp.). It was felt that 150 ml of sample ensured sufficient quantities for both medium-term storage (as much as 3-5 years) as well as quality control work.

Samples were collected by first rinsing the container with the water to be sampled, then refilling the bottle. The container was filled to overflowing. No rinsing was performed during collection of snow samples; the snow was tamped into the vessels as tightly as possible. In all cases; rinsed or not, the bottles were capped tightly and were later periodically checked during the several phases of storage and handling for analysis to ensure security. The sample vessels were stored at room temperature until the time of analysis. All samples were analysed within 10 months of collection.

Stable isotope analyses were performed at the University of Alberta by the author. For $\delta^{18}O$ analysis, a modified form of the Epstein and Mayeda (1953) CO_2 equilibration method was used. In this procedure, 10 ml of water is pipeted into a sample flask and after evacuation of the atmospheric and dissolved gases, a measured amount of bottled CO_2 from a tank is introduced. The water is allowed to equilibrate in a shaking water bath at 25.3°C overnight. Samples were analyzed against a calcite reference gas (KMCC - 1471) on a Micromass 602D mass spectrometer (manufactured by VG Isotopes, Ltd.). Approximately every fifth water sample was extracted and analysed at least twice for quality control purposes.

The method utilized for D/H analysis is that of Friedman (1953). 17μL of water are injected into a vacuum line and passed across a uranium furnace. The resulting gas is concentrated in a sample container via a Toepler pump. Within several hours, the tubes are attached to a Micromass 602C mass spectrometer (manufactured by VG Isotopes, Ltd.) and analyzed versus a reference gas derived from an international standard water (Greenland Ice Sheet Precipitation; GISP-121). Fresh standard gases are made every day that the samples were analyzed. Care is taken to avoid memory effects by carefully pumping out all lines in contact with the hydrogen gas between the sample runs. Only every 25-30 water samples were run more than once to ensure D/H quality control.

Oxygen analyses were carried out in the Department of Geology. Hydrogen analyses were performed in the Department of Physics.

The zinc method (Coleman et al. 1982) was used for a time in an effort to eliminate both the small memory effects and time consuming aspects of the uranium method. However, reproducability became a concern: one sample that was analyzed 38 separate times over a period of three months had a standard deviation of analysis of $\delta D = 9.6°/_{oo}$. With the uranium method, the standard deviation of three standard waters ranged between .90 and 1.10 $°/_{oo}$. Because of these difficulties, the author elected not to use the zinc method.

Stable isotope analyses are reported in per millage ($°/_{oo}$) values:

$$\delta_1(°/_{oo}) = (R_1 - R_2/R_2) \times 1000 \quad (3.7)$$

Where R is the ratio of heavy to light isotopes; and the subscripts 2 and 1 represent a reference and unknown ratio, respectively.

Data from δD and $\delta^{18}O$ analyses are reported versus Standard Mean Ocean Water (SMOW), proposed by Craig (1961b). Fresh samples of Vienna SMOW (V-SMOW), GISP and SLAP (Standard Light Antarctic Precipitation) were received from the National Bureau of Standards (Gaitherburg, MD.) in October of 1984. The original breakseal containers were opened in January, 1985 for an oxygen standards run and subsequently stored in a refrigerator in glass containers with plastic screw top caps.

The oxygen reference gas (KMCC-1471), derived from a calcite, was observed to be -21.39°/oo versus V-SMOW 135 on January 23, 1985. $\delta^{18}O$ levels were then converted to values versus SMOW with the formula:

$$\delta_{X\text{-}SMOW} = .97880 \pm .00201(\delta^{''} \pm .08°/_{oo}) - 21.36 \pm .13°/_{oo} \qquad (3.8)$$

where $\delta^{''}$ is the value determined from the mass specrometer and converted to the isotopic value of KMCC-1471 on January 23, 1985 and δ_{X-SMOW} is the isotopic value of the sample reported versus SMOW.

The deuterium samples were analyzed daily against a fresh gas derived from GISP-121. GISP is reported to be -189.7 versus V-SMOW (Gonfiantini 1978). Raw deuterium levels were converted to values versus SMOW by the formula:

$$\delta_{X\text{-}SMOW} = .8349 \pm .0028(\delta^{'} \pm 1.0°/_{oo}) - 189.8 \pm .7°/_{oo} \qquad (3.9)$$

Where $\delta^{'}$ is the raw value read off the mass spectrometer, corrected for H_3 production. Further details about the corrections utilized for conversions of raw stable isotope data to SMOW values, as well as the calculation of error values, are given in Freeman (1985). A FORTRAN-77 program called DELSMOW was written by the author to automatically calculate the stated values of stable isotope levels by

Equations (3.8) and (3.9).

3.4.2 Tritium samples

A total of 38 tritium samples were collected at 37 different sites. One sample was acquired from the town of Elkwater well to check seasonal variability and to serve as a quality control sample.

Samples were taken in 250 ml wide-mouthed, screw cap Nalagene plastic containers (Sybron Corp.; available from Fisher Scientific Corp.). The containers were rinsed with the water to be sampled prior to taking a grab aliquot. The bottles were tightly capped after sampling and delivered promptly to the laboratory with no special storage or handling procedure.

No duplicate tritium samples were taken. This is unfortunate, because with the ease of tritium sampling and analysis, duplicates would have provided some valuable data on the laboratory reproducability.

Except for one site, RCA-56, tritium samples were acquired wherever a ^{14}C sample was collected. It was felt that tritium and ^{14}C data could be compared and contrasted to provide information about the groundwater system and also about the reliability of each of the dating techniques.

Tritium samples were analyzed at the Alberta Environmental Centre in Vegreville by the Geochronology Section of the Environmental Technology Wing. The samples were distilled and added to a quantity of Monophase 40 cocktail (Packard Corp.) and counted on a Nokes/Spalding large volume counter or on a Tracore-Mark III; used for sma[illegible]ample sizes. The counters are corrected daily for levels of background activity (L. Arnold, pers. comm.).

Levels of tritium in the water samples are expressed in tritium units (TU). A tritium unit is a direct measurement of the amount of tritium content in a sample: 1 TU is equal to 1 atom per 10^{18} atoms of hydrogen (Freeze and Cherry 1979). Precisional errors were stated for each tritium analysis by the laboratory.

3.4.3 Carbon-14 samples

20 ^{14}C samples were collected at 20 separate sites in Ross Creek Basin. Special attention was given to the sampling of springs and shallow flowing wells, because samples could be collected at these points without having to pump or bail large quantities of water. In addition, these points represent specific hydrologic zones, whereas most wells in the area are generally perforated over their whole depth.

32L of water were collected at each site in two collapsible plastic camping-type containers. The vessels were filled to overflowing and all air pockets worked out through the spout; which was subsequently closed off.

Upon completion of each day's sampling, 20ml of saturated NaOH (filtered to remove $CaCO_3$) and 30g $BaCl_2$ were added to lower the pH of the sample and to precipitate the carbonate, respectively. The sample vessels were agitated several times and allowed to sit overnight. The clear liquid was then poured off leaving the white or yellowish-white carbonate precipitate on the bottom of the container. Once all but the lower 3 or 4L of fluid were decanted, the samples were then agitated, re-suspending the precipitate, and one of the two containers collected at each site was poured into the second. Air was bled out through the spout and the bottle was sealed. In this form the samples were then delivered to the laboratory. Leftover used containers were rinsed with a dilute HCl solution and tap water for reuse.

Because of the involved sampling procedure, no quality control ^{14}C samples were collected during this study. As with the tritium samples, it would have been useful to have sent at least one duplicate to the laboratory, as extreme variability in sampling procedure is suspected to have caused most of the discrepancies in the results. It is believed that fractionation of the ^{14}C occurred in cases where extremely low flow rates resulted in prolonged exposure of the water to the atmosphere. Substantial quantities of CO_2 appear to have been been lost in this way, and there is no way of knowing exactly how much fractionation took place.

^{14}C samples were also analyzed by the Geochronology Section of the Environmental Centre. In standard procedures at the laboratory, the large bottles containing the aqueous slurry are transfered to a glass container which is placed under partial vacuum to drive off excess CO_2. The CO_2 from solution is then liberated by acidifying the sample. The gas is equilibrated with CARBO-SORB® in a graduated cylinder trap at 6 to 7 ° water bath for 1 hour. The CARBO-SORB® solution is then mixed with 12ml of scintillation cocktail for counting. At the end of sample counting, a known weight of spiked standard is added to the mixture; this provides a measure of counting efficiency (D. Dougall, pers. comm.).

Once results in the laboratory have been obtained, the problem then becomes one of correcting the apparent date for carbon sources and sinks in the hydrological system. This adjustment becomes a complex geochemical problem that has been examined by a large number of researchers (e.g. Fontes and Garnier 1979; McKay et al. 1986; Mook 1980; Pearson and Hanshaw 1970; Reardon and Fritz 1978; Wallick 1976; and Wigley 1975). Because ^{14}C analysis is carried out on dissolved carbonate in the groundwater, one must account for all inputs of carbonate along the groundwater flow path.

Traditionally, the ^{14}C geochemistry interpretors have been divided between "lumpers" and "splitters". Lumpers tend to view the entire hydrochemical system, while the splitters build complex arguments based on specific components of the hydrodynamic system (E. Wallick, pers. comm.). The ^{14}C interpretations proposed in the current work will be decidedly on the side of the lumpers. It is felt that any geochemical argument is only as good as the hydrogeological framework from which it is developed. It is felt that in many cases estimations of important hydrochemical parameters may be made without seriously affecting the overall accuracy of the results, as long as the analyses are made in light of an integrated approach.

The values of ^{14}C from Ross Creek Basin are reported by the laboratory as percent modern carbon (pmc) relative to a National Bureau of Standards oxalic acid with a specific activity, A, (defined as 14 disintegrations/minute/gram of carbon) of:

$$A_{ox} = 0.95 \times 13.56 \text{dpm/gC} \qquad (3.10)$$

Because post-1952 ^{14}C levels are greater than 100 pmc, the initial activity is expressed as a pre-bomb activity. The measured activity of a sample may be expressed as a ratio (R) of sample activity to specific activity:

$$R = A(\text{sample})/A_{ox} \times 100 \qquad (3.11)$$

thus rendering the value in pmc (Mook 1980). This ratio expresses the amount of present day carbon remaining in the sample. However, it is useful to calculate how long the sample has been decaying: i.e. how old it is. The law of radioactive decay is stated as:

$$A = 2A_0e^{-t/T} \qquad (3.12)$$

where A is the specific activity after time t, A_0 is the initial level of activity and T is the radioactive half life of the substance. For ^{14}C, T is equal to 5730 years. Using the R convention, Equation (3.12) rearranges to:

$$t = -8270 \ln R \qquad (3.13)$$

where t is the decay age of the carbon (Freeze and Cherry 1979).

If carbon was a conservative isotope of water like tritium, ^{18}O or D, Equation (3.13) could be applied directly to date groundwater. However, carbon may enter or leave groundwater systems via a series of carbon reservoirs. The reservoirs with the most common direct impacts on dissolved carbonate are: 1) dissolved carbonate in soil water which is derived from precipitation and atmospheric CO_2; 2) soil CO_2 derived from decomposition of organic material and plant root respiration; 3) exchange with solid carbonate in the groundwater flow system. These and other processes which affect the carbon content of groundwater are discussed by Mook (1980). Much research has been spent trying to model sources of carbonate to a groundwater flow system. Reardon and Fritz (1978) and Cheng and Long (1984) utilized equilibrum geochemical modeling to estimate inputs. Wigley (1975) and Pearson and Hanshaw (1970) estimated the proportion of inorganic carbon or "dead" carbon from the difference in ^{14}C values of modern atmospheric CO_2 and the dissolved carbonate. Wallick (1975) used a combination of the two methods.

In all of these methods, the final age estimation must account for the actual age of carbon being less than that observed as a function of dead carbon entering the system from inorganic sources. Thus a corrected age of carbon, t_k, may be calculated by introducing an adjustment Q into Equation (3.13):

$$t_k = -8270(\ln R - \ln Q) \qquad (3.1[illegible])$$

where Q is interpreted as the fraction of modern carbon in the system. As carbon is added beneath the water table by dissolution of carbonate or oxidation of organic matter, Q is lowered as the result of dilution. While there are many problems with the simple application of a Q factor, empirical values of Q have been demonstrated to range between 0.5 and 1.0 (Freeze and Cherry 1979; Wigley 1975). Q is lower when $\delta^{13}C$ and alkalinity are higher.

Consequently, it was decided that Q values would be estimated as a function of alkalinity and $\delta^{13}C$. Table 3.3 shows the data from the current work: the R values expressed as pmc, the $\delta^{13}C$ values expressed versus the PDB standard, alkalinity and errors. The resulting information is very incomplete: out of the 20 ^{14}C samples sent to the lab, only two have a full set of values for ^{14}C, $\delta^{13}C$ and for alkalinity. Several samples did not react with CARBO-SORB®

SAMPLE	% MODERN CARBON	DEL C13 (VS PDB)	pH	ALKALINITY (mg/L)	Q FACTOR (ESTIMATED)
RCA-1	69 ±20	-- --	7.9	176	0.70 ±.20
RCA-6	80 ±20	-- --	7.7	358	0.95 ±.10
RCA-13	20 ±20	-- --	---	---	0.60 ±.20
RCA-20	92 ±20	-14.3	---	250	0.95 ±.10
RCA-23	98 ±20	-- --	8.2	325	1.00 ±.10
RCA-45	-- --	-12.7	---	---	-- --
RCA-46	43 ±20	-- --	7.8	482	0.85 ±.10
RCA-47	98 ±20	-15.2	---	170	1.00 ±.10
RCA-56	-- --	-13.0	8.3	488	-- --
RCB-1	27 ±20	-- --	7.7	646	0.75 ±.15
RCB-3	23 ±20	-- --	8.1	686	0.75 ±.15
RCB-22	7 ±20	-- --	---	---	0.75 ±.20
RCB-41	2 ±20	-5.9	7.9	508	0.60 ±.20
RCC-26	61 ±20	-- --	---	---	0.65 ±.20
RCC-31	42 ±20	-- --	8.3	264	0.90 ±.10
RCD-15	42 ±20	-- --	8.9	454	0.90 ±.10
RCE-15	43 ±20	-14.0	---	---	0.85 ±.10
RCE-27	66 ±20	-13.4	---	---	0.70 ±.20
RCE-28	-- --	-11.3	---	390	-- --
RCE-33	23 ±20	-13.0	---	---	0.70 ±.20

Table 3.2. Adjustment factors: Carbon-14 analyses.

and were lost; over half did not have CO_2 collected for $\delta^{13}C$ analysis; and water quality analyses were not performed on every sample taken. However, alkalinity and $\delta^{13}C$ appear to increase as R decreases, implying that carbonate is acquired throughout the length of flow paths in Ross Creek Basin. In addition, the size of the error attached to R is enormous: ±0.20 pmc. This far outweighs the effects of Q in most cases if Q is assumed to range between 0.5 and 1.0.

It was decided that an expedient method of adjusting R values was by estimating Q, using the examples cited by Wigley (1975) and Freeze and Cherry (1979) as a guideline. Q's were judged to be low, that is, close to 0.60 for high values of alkalinity and $\delta^{13}C$ approaching 0°/₀₀(PDB). Q's were judged to be near to unity with $\delta^{13}C$ close to -15°/₀₀ and low levels of alkalinity. In all cases, Q was attached to an uncertainty of estimation, which was propagated through the ^{14}C conversions by the methods of Taylor (1982), although a maximum error of R equal to 13300 years (-8270 ln 0.20) was assumed.

The values of Q and their associated error values are given in the last column of Table 3.2. A more sophisticated estimation of Q would have not have had a large bearing on the overall results due to the large precisional uncertainties.

3.4.4 Data and statistical processing

All samples were identified by the order in which they were collected for stable isotopic analysis. As five major field trips were made, all having unique reference codes (RCA, RCB, and so on), the samples were numbered sequentially with RCA-1 as number 1 and RCE-38 as number 238. An exception to this pattern are the six MT samples, collected in April, 1984; which are out of order chronologically. The MT samples are numbers 195-200. Table 3.3 lists the sampling trips that were made in Ross Creek Basin, with the reference codes. Data sorting and pairing procedures were done by computer.

Statistical procedures consisted of three basic types of analysis: 1) linear regression; 2) product moment correlation; and 3) cluster analysis. The basis for these techniques is well understood and is discussed in detail in statistics textbooks such as Sokal and Rohlf (1981) and Till (1974).

Linear regression was utilized to analyze the δD versus $\delta^{18}O$ relationship of samples. Classical methods of least-square regression were applied with the use of a standard statistical software package, SPSSx (SPSS Inc. 1983). δD was assumed to be the dependent variable. While not a totally valid assumption (Gat and Gonfiantini 1981; Freeman 1985), this has become an accepted technique in isotope hydrology and as such is applied in the current work.

SAMPLING TRIP	DATES	NUMBER AND TYPE OF SAMPLES
MI Series	April 4, 1984	6 (S)
RCA Series	May 23-24, 1984	71 (S)
RCB Series	July 11-13, 1984	53 (S)
RCC Series	July 30- August 3, 1984	41 (S)
RCD Series	October 16-19, 1984	29 (S) 15 (T) 13 (C)
RCE Series	March 25-26, 1985	38 (S) 23 (T) 7 (C)
	TOTALS:	238 (S) 38 (T) 20 (C)

(S) Stable Isotopes
(T) Tritium
(C) Carbon-14

Table 3.3. Sam[illegible] trips to Ross Creek Basin.

The statistical problem of dividing data into two separate regression lines is also an accepted method for isotope interpretation. For the current study, scattergrams of the stable isotope values were plotted and visual inspection utilized to separate samples that fall near the meteoric water line from those that did not. A partial justification of this technique might be to point out that improved correlation coefficients for two lines were noted, but this represents a circular argument and is probably not strictly true.

Pearson product moment correlation and cluster analysis were techniques incorporated in the present work to probe the data for groups of like variables and trends between variables. Pearson correlations were performed with SPSSx (SPSS Inc. 1983) and were attempted for all isotope, well and chemistry data. Any strong positive or negative correlations between variables would have demonstrated a covariance and perhaps helped to highlight the expected co-dependance of different data such as δ^{18}O and elevation (the altitude effect), or ^{14}C and percent milliequivalents chloride (age and hydrochemical facies relations). Pearson correlation tests were judged to be largely unproductive without a more detailed analysis of the actual data.

Cluster analysis was run using the MIDAS software package (University of Michigan) for δ^{18}O data. Different groupings of isotopic data, such as all the spring waters, or all well waters, were analyzed in a reconnaissance fashion in an attempt to cluster groups of similar data in the set. The groups were then visually examined to ascertain whether variabies such as well depth or geographical location could help to explain any patterns of clustering noted.

4. EXPERIMENTAL RESULTS

4.1 Stable Isotopes

In this chapter, the results of the isotopic analyses will be presented. These are listed in comprehensive tables and are plotted in a series of figures that demonstrate characteristic features of the data. In Chapter 5, these data are discussed more completely. The relationship between analytical results and models of groundwater flow in Ross Creek Basin are examined.

Table 4.1 lists the 238 samples that were analyzed for δD and $\delta^{18}O$ in Ross Creek Basin. Several points about the "owner" and "description" columns in Table 4.1 deserve clarification. The abbreviation CHPP stands for Cypress Hills Provincial Park. Sites within the Park were located as accurately as possible, but may not be exactly pinpointed. All notable points in the Park were named, either by an official name; such as "Nicholls spring" or by a name given by the author; as in the case of ~~the~~ "Ski Run Spring". "AE" stands for the wells put in by Alberta Environment; "Duke AE" wells were drilled as part of the Ophori/Alberta Environment aquifer delineation program. Some of the precipitation ("ppt") samples were given explicit labels: "o" is a firn snow sample taken during the RCE trip, "n" is a sample of week-old snow acquired at the same time. "Winter ppt" is snow, "summer ppt" is a rain sample.

Table 4.1. Results of stable isotope analyses.

SAMPLE	LOCATION	OWNER DESCRIPTION	TYPE OF WATER	DELTA O18 (RAW)	DELTA O18 (VS SMOW)	ERROR (1 SIGMA)	DELTA H/D (RAW)	DELTA H/D (VS SMOW)	ERROR (1 SIGMA)
RCA-1	13 11 8 3W4	CHPP-NICHOLLS	SPRING	2.41	-19.00	0.13	51.9	-146.4	1.48
RCA-2	4 14 8 3W4	CHPP-MITCHELL	SPRING	2.89	-18.53	0.14	58.3	-141.2	1.52
RCA-3	7 23 8 3W4	CHPP-FIREROCK	WELL	2.76	-18.66	0.15	52.6	-145.9	1.49
RCA-4	11 24 8 3W4	CHPP-ELKWATER	LAKE	12.00	-9.61	0.18	115.2	-93.7	1.86
RCA-5	12 23 8 3W4	CHPP	SEEP	2.63	-18.79	0.15	54.3	-144.5	1.50
RCA-6	7 24 8 3W4	ELKWATER-TOWN	WELL	2.06	-19.34	0.14	49.6	-148.4	1.47
RCA-7	11 25 8 3W4	A.PETER	WELL	1.87	-19.53	0.13	48.8	-149.1	1.47
RCA-8	4 36 8 3W4	A.PETER	SLOUGH	8.12	-13.41	0.14	86.8	-117.3	1.69
RCA-9	11 35 8 3W4	B.SCHORR	SLOUGH	15.87	-5.83	0.16	139.1	-73.7	2.00
RCA-10	13 14 9 3W4	B.WEISS-FIELD	SPRING	5.75	-15.73	0.18	67.1	-133.8	1.57
RCA-11	4 24 9 3W4	B.WEISS-HOMEST	SPRING	3.92	-17.52	0.13	59.4	-140.2	1.53
RCA-12	15 9 9 3W4	J.IGNATIUS	SPRING	2.02	-19.38	0.15	46.9	-150.7	1.46
RCA-13	1 22 9 3W4	B.WEISS-CORRAL	SPRING	2.97	-18.45	0.13	50.8	-147.4	1.48
RCA-14	7 26 9 3W4	W.SWADLING	F.WELL	2.58	-18.83	0.15	53.2	-145.4	1.49
RCA-15	4 25 9 3W4	C.HERMANN	S.SEEP	4.69	-16.77	0.14	62.6	-137.5	1.55
RCA-16	9 13 9 3W4	J.ENGLER	SPRING	3.95	-17.49	0.15	59.7	-140.0	0.75
RCA-17	4 30 9 2W4	E.MACK-CORRAL	SPRING	2.80	-18.62	0.13	51.1	-147.1	1.48
RCA-18	13 8 9 2W4	E.MACK-FIELD	DUGOUT	4.13	-17.32	0.15	59.6	-140.1	1.53
RCA-19	1 19 9 2W4	E.MACK-HOMESTE	SPRING	2.66	-18.76	0.15	48.0	-149.7	1.46
RCA-20	9 19 9 2W4	D.NEUBAUER	SPRING	2.34	-19.07	0.15	47.2	-150.4	1.46
RCA-21	13 7 10 2W4	A.SCHORR	WELL	0.64	-20.73	0.17	32.1	-163.0	1.38
RCA-22	1 14 10 3W4	F.BOLLINGER	WELL	9.01	-12.54	0.13	84.7	-119.1	1.67
RCA-23	6 24 10 3W4	KRAUSS	F.WELL	8.61	-12.93	0.13	83.0	-120.5	1.66
RCA-24	9 26 10 3W4	C.JANS	DUGOUT	7.61	-13.91	0.13	75.9	-126.4	1.62
RCA-25	12 35 10 3W4	B.OTTO	DUGWELL	5.01	-16.46	0.14	58.4	-141.1	1.52
RCA-26	16 36 10 3W4	G.V.M.RANCH	WELL	6.52	-14.98	0.13	72.4	-129.3	1.60
RCA-27	12 18 10 2W4	ROSS	CREEK	7.93	-13.60	0.15	79.6	-123.3	1.64
RCA-28	16 30 10 2W4	B.SCHORR	DUGWELL	3.70	-17.74	0.14	53.5	-145.1	1.49
RCA-29	11 31 11 2W4	IRVINE P-CAN	WELL	3.42	-18.01	0.15	49.9	-148.2	1.47
RCA-30	1 1 12 3W4	H.AMAN	WELL	2.98	-18.44	0.15	50.6	-147.5	1.48
RCA-31	16 32 11 2W4	A.BROST	DUGOUT	13.80	-7.85	0.16	116.1	-92.9	1.86
RCA-32	16 7 12 2W4	M.BROST	WELL	4.07	-17.38	0.15	63.2	-137.1	1.55
RCA-33	5 15 12 3W4	R.FRANZ	WELL	2.36	-19.05	0.17	41.0	-155.6	1.42
RCA-34	11 24 12 3W4	A.ZELLER	WELL	10.32	-11.26	0.46	96.1	-109.6	1.74
RCA-35	11 24 12 3W4	A.ZELLER	DUGOUT	16.78	-4.93	0.16	123.6	-86.6	1.91
RCA-36	8 24 12 3W4	J.ZELLER	SPRING	9.55	-12.01	0.15	80.8	-122.4	1.65
RCA-37	1 30 12 2W4	C.ZIEGLER	WELL	5.89	-15.59	0.15	73.2	-128.7	1.61
RCA-38	4 36 12 3W4	R.HAUSAUER	WELL	4.50	-16.96	0.15	56.4	-142.7	1.51
RCA-39	9 27 12 3W4	H.BROST	WELL	1.47	-19.92	0.15	36.0	-159.7	1.40
RCA-40	8 20 12 3W4	R.ROTH	WELL	6.79	-14.71	0.15	66.3	-134.5	1.57
RCA-41	12 33 12 3W4	E.MILLER	WELL	4.20	-17.25	0.14	51.6	-146.7	1.48
RCA-42	15 31 12 3W4	W.DRISCOLL	WELL	1.94	-19.46	0.15	40.8	-155.7	1.42
RCA-43	16 13 12 4W4	B.ZIEGENHAGEL	WELL	2.90	-18.52	0.15	37.4	-158.6	1.40
RCA-44	1 18 12 3W4	G.ZIEGENHAGEL	PUDDLE	13.13	-8.51	0.16	109.2	-98.6	1.82
RCA-45	1 5 12 3W4	R.PFAFF	SPRING	0.75	-20.63	0.14	31.0	-163.9	1.37
RCA-46	3 35 11 3W4	K.FRIEMARK	SPRING	3.23	-18.20	0.15	50.4	-147.7	1.48
RCA-47	3 13 8 3W4	CHPP-MITCHELL	SPRING	2.66	-18.76	0.15	52.8	-145.7	1.49
RCA-48	12 12 8 3W4	SUMMER	PPT.	4.94	-16.52	0.15	60.7	-139.1	1.53
RCA-49	4 7 8 2W4	CHPP	PUDDLE	13.61	-8.04	0.16	117.0	-92.1	1.87
RCA-50	7 7 8 2W4	CHPP	SEEP	3.13	-18.30	0.15	56.2	-142.9	1.51
RCA-51	7 7 8 2W4	CHPP	DUGOUT	5.73	-15.75	0.15	68.8	-132.3	1.58
RCA-52	2 21 8 2W4	CHPP-PINES	SPRING	2.92	-18.50	0.13	55.6	-143.4	1.51
RCA-53	14 30 8 2W4	FELESKY	WELL	0.37	-21.00	0.13	35.4	-160.2	1.39
RCA-54	14 30 8 2W4	SUMMER	PPT.	6.32	-15.17	0.15	70.7	-130.7	1.59
RCA-55	14 2 9 3W4	D.LYALL	WELL	6.88	-12.67	0.15	79.5	-123.4	1.64
RCA-56	15 15 9 3W4	H.SEITZ	SPRING	0.84	-20.54	0.15	37.1	-158.9	1.40
RCA-57	7 4 10 3W4	R.JANS-HOUSE	F.WELL	2.10	-19.30	0.15	46.5	-150.9	1.45
RCA-58	6 4 10 3W4	R.JANS-STOCK	WELL	4.73	-16.73	0.15	63.6	-136.7	1.55
RCA-59	1 30 9 3W4	D.SCHORR	SEEP	2.89	-18.53	0.15	48.0	-149.7	1.46
RCA-60	1 1 10 4W4	M.RATH-OLD HOU	WELL	4.89	-16.57	0.15	58.1	-141.3	1.52
RCA-61	1 14 10 4W4	M.REIGER	SPRING	3.51	-17.92	0.15	51.3	-146.9	1.48
RCA-62	13 18 10 3W4	J.LENTZ	DUGOUT	12.51	-9.12	0.24	105.7	-101.6	1.80
RCA-63	13 18 10 3W4	SUMMER	PPT.	9.32	-12.24	0.21	85.3	-118.6	1.68
RCA-64	10 30 10 3W4	C.GILL	WELL	1.17	-20.21	0.19	38.0	-158.1	1.41
RCA-65	1 6 11 3W4	G.RETELBACK	DUGOUT	11.21	-10.39	0.16	93.9	-111.4	1.73
RCA-66	15 5 11 3W4	W.STUBER	DUGOUT	10.41	-11.17	0.16	88.1	-116.2	1.69
RCA-67	9 33 10 3W4	L.ZIEGLER	WELL	0.96	-20.42	0.15	32.4	-162.7	1.38
RCA-68	3 15 11 3W4	SUMMER	PPT.	7.92	-13.61	0.14	64.9	-135.6	1.56
RCA-69	13 17 11 3W4	R.DEERING	WELL	2.66	-18.76	0.27	44.1	-153.0	0.76
RCA-70	5 23 11 3W4	R.RESCH	WELL	6.07	-15.42	0.15	69.6	-131.7	1.58
RCA-71	14 8 9 2W4	E.MACK-FIELD	SEEP	3.93	-17.51	0.15	57.8	-141.6	1.52
RCB-1	2 24 9 4W4	K.SAILER	SPRING	3.48	-17.95	0.15	57.0	-142.2	1.51
RCB-2	13 5 9 3W4	L.PFIEFFER	WELL	0.67	-20.70	0.13	34.7	-160.8	1.39
RCB-3	11 30 8 3W4	BROWN EST.-H	SPRING	1.86	-19.54	0.15	44.6	-152.6	1.44
RCB-4	6 29 8 3W4	BROWN EST.-F	SPRING	3.52	-17.91	0.15	55.9	-143.1	1.51
RCB-5	14 12 9 4W4	FLAIG	F.WELL	1.58	-19.81	0.15	41.8	-154.9	1.43
RCB-6	16 2 9 4W4	A.RATH	WELL	1.43	-19.96	0.15	40.1	-156.3	1.42
RCB-7	10 4 9 4W4	DRAUDSON#1	WELL	12.15	-9.47	0.14	111.5	-98.7	1.83
RCB-8	1 16 9 4W4	DRAUDSON#2	WELL	5.35	-16.12	0.15	66.7	-134.1	1.57
RCB-9	1 20 9 4W4	BURGEVITZ	DUGWELL	1.04	-20.34	0.15	36.8	-159.0	1.71
RCB-10	13 23 9 4W4	BOSCHEE	F.WELL	1.83	-19.57	0.15	44.0	-153.1	1.44
RCB-11	8 23 9 4W4	GEIGLE	WELL	5.08	-16.39	0.15	62.[illegible]	-137.3	1.55
RCB-12	5 3 10 4W4	FALCON RANCH	F.WELL	1.14	-20.24	0.13	38.9	-157.3	1.41

Table 4.1. (con.)

SAMPLE	LOCATION	OWNER DESCRIPTION	TYPE OF WATER	DELTA O18 (RAW)	DELTA O18 (VS SMOW)	ERROR (1 SIGMA)	DELTA H/D (RAW)	DELTA H/D (VS SMOW)	ERROR (1 SIGMA)
RCB-13	16 9 10 4W4	SCHEFFELMEIR	WELL	5.39	-16.08	0.15	64.1	-136.3	1.55
RCB-14	11 28 9 4W4	R.REIGER	WELL	3.49	-17.94	0.14	55.8	-143.[illegible]	1.51
RCB-15	8 28 9 4W4	R.REIGER	DUGOUT	13.79	-7.86	0.16	108.3	-99.4	1.81
RCB-16	5 36 9 5W4	G.SEITZ	WELL	9.39	-12.27	0.15	88.1	-116.3	1.69
RCB-17	13 12 10 5W4	D.SCHORR	DUGOUT	17.00	-4.72	0.16	123.1	-87.1	1.91
RCB-18	4 6 10 4W4	CLARK	WELL	3.67	-17.77	0.15	59.3	-140.3	1.53
RCB-19	7 18 10 4W4	LANGE	WELL	0.47	-20.90	0.15	31.9	-163.2	1.38
RCB-20	5 28 10 4W4	I.NEITZ	WELL	2.78	-18.64	0.15	49.0	-148.9	1.47
RCB-21	8 31 10 4W4	A.WUTZKE	WELL	0.83	-20.55	0.15	33.1	-162.1	1.38
RCB-22	4 27 8 3W4	RUSSIL	SPRING	[illegible].76	-19.64	0.15	44.0	-153.0	1.44
RCB-23	7 24 8 3W4	ELKWATER TOWN	WELL	[illegible].72	-19.68	0.13	47.0	-150.6	1.46
RCB-24	3 22 10 3W4	J.GILL	SPRING	2.54	-18.87	0.15	47.7	-149.9	1.46
RCB-25	11 2 11 4W4	E.YANKE	WELL	6.07	-15.42	0.15	64.8	-135.7	1.56
RCB-26	16 27 10 4W4	WILDE	WELL	5.25	-16.22	0.15	68.2	132.9	1.58
RCB-27	5 5 11 4W4	RENKE	WELL	1.88	-19.52	0.15	41.5	-155.1	1.43
RCB-28	1 8 11 4W4	A.RIEGER	WELL	5.48	-16.00	0.15	64.1	-136.2	1.55
RCB-29	13 30 11 4W4	E.JANS	WELL	2.42	-18.99	0.15	46.2	151.2	1.45
RCB-30	8 21 11 4W4	W.LENTZ	SPRING	1.29	-20.10	0.15	34.5	-161.0	1.39
RCB-31	5 34 11 4W4	G.LENTZ	WELL	3.83	-17.61	0.16	50.5	-147.7	1.48
RCB-32	13 24 11 4W4	WUTCH	SLOUGH	23.97	2.10	0.14	181.5	-38.3	2.27
RCB-33	5 7 12 4W4	DIETELBACH	WELL	4.93	-16.53	0.15	51.6	-146.7	1.48
RCB-34	1 11 12 4W4	PASH[illegible]Y	WELL	[illegible]0.60	-10.98	0.15	97.2	-108.6	1.75
RCB-35	3 14 12 4W4	B.SCHNEIDER	SPRING	3.50	-17.93	0.15	51.5	-146.8	1.48
RCB-36	4 10 12 4W4	DAVIES	WELL	-0.88	-22.22	0.15	16.7	-1[illegible]5.8	1.30
RCB-37	3 9 12 4W4	DUNMORE CAMPGND	WELL	4.37	-17.08	0.15	62.7	-137.5	1.55
RCB-38	6 12 12 5W4	CAVAN	WELL	-0.65	-22.00	0.15	18.8	-174.1	1.31
RCB-39	1 19 12 4W4	LA POULET FARM	WELL	1.56	-19.83	0.30	36.3	-159.5	1.40
RCB-40	11 32 12 4W4	SCHMIPF	WELL	1.36	-20.03	0.15	34.0	-161.4	1.39
RCB-41	14 24 12 5W4	HOFFMAN	SEEP	2.52	-18.85	0.15	43.6	-153.4	1.44
RCB-42	11 24 12 5W4	HOFFMAN	F.WELL	4.34	-17.11	0.23	70.1	-131.2	1.59
RCB-43	7 23 12 5W4	J.STOCK	WELL	0.77	-20.61	0.15	32.2	-162.9	1.38
RCB-44	15 36 11 4W4	A.ELHART	WELL	1.32	-20.07	0.15	31.7	-163.3	1.37
RCB-45	7 7 8 2W4	CHPP	DUGOUT	10.30	-11.28	0.13	92.6	-112.5	1.72
RCB-46	7 7 8 2W4	CHPP	SEEP	2.45	-18.96	0.15	50.9	-147.3	1.48
RCB-47	10 19 8 2W4	CHPP-GROUP CAMP	WELL	2.07	-19.33	0.14	48.6	-149.2	1.47
RCB-48	15 18 8 2W4	CHPP-SKI HILL	STREAM	3.05	-18.37	0.15	62.9	-137.3	1.55
RCB-49	11 24 8 3W4	CHPP-ELKWATER	LAKE	12.72	-8.91	0.16	119.7	-89.9	1.88
RCB-50	3 15 11 3W4	ACREAGE	WELL	3.67	-17.77	0.15	54.1	-144.7	1.50
RCB-51	15 28 11 3W4	COUILLARD	WELL	5.98	-15.51	0.14	73.6	-128.4	1.61
RCB-52	4 8 12 4W4	VEHICLE INSP ST	WELL	-1.78	-23.10	0.15	11.3	-180.4	1.27
RCB-53	11 2 12 5W4	DUNMORE TOWN	WELL	-0.85	-22.20	0.15	25.1	-168.8	1.34
RCC-1	12 12 8 3W4	SUMMER	PPT.	11.72	-9.89	0.24	137.0	-75.4	1.99
RCC-2	13 23 8 2W4	CHPP-SPRUCE	CREEK	3.20	-18.23	0.15	61.0	-138.8	1.54
RCC-3	3 26 8 2W4	CHPP-MUSKEG	SEEP	2.66	-18.76	0.15	58.1	-141.3	1.62
RCC-4	10 27 8 2W4	CHPP-S. COULEE	SPRING	3.04	-18.38	0.15	59.4	-140.2	1.53
RCC-5	2 21 8 2W4	CHPP-PINES	SPRING	3.06	-18.36	0.16	60.7	-139.1	1.53
RCC-6	7 7 8 2W4	CHPP	SEEP	5.20	-16.27	0.15	74.4	-127.7	1.61
RCC-7	3 13 8 3W4	CHPP-MITCHELL	SPRING	2.50	-18.91	0.15	54.8	-144.1	1.50
RCC-8	13 11 8 3W4	CHPP-NICHOLLS	SPRING	2.2[illegible]	-19.21	0.15	51.5	-146.[illegible]	1.48
RCC-9	2 18 8 2W4	CHPP-MOOSE PAST	SEEP	3.17	-18.26	0.15	56.9	-142.3	1.51
RCC-10	6 18 8 2W4	CHPP-SKI RUN	SPRING	2.70	-18.72	0.13	54.7	-144.2	1.50
RCC-11	11 24 8 3W4	CHPP-ELKWATER	LAKE	12.91	-8.72	0.16	122.9	-87.1	1.90
RCC-12	7 24 8 3W4	ELKWATER TOWN	WELL	1.88	-19.52	0.15	48.8	-149.1	1.47
RCC-13	2 28 8 2W4	CHPP-BENCHES	SPRING	4.10	-17.35	0.15	66.7	-134.1	1.57
RCC-14	7 23 8 3W4	CHPP-FIREROCK	WELL	2.63	-18.79	0.15	52.4	-146.1	1.49
RCC-15	9 33 10 3W4	SUMMER-CLOUDB	PPT.	10.53	-11.05	0.16	130.4	-81.0	1.95
RCC-16	16 32 10 3W4	SUMMER-CLOUDB	RUNOFF	8.56	-12.98	0.16	112.6	-95.8	1.84
RCC-17	1 24 11 4W4	E.PINDER	WELL	2.01	-19.39	0.15	39.6	-156.8	1.42
RCC-18	15 31 12 3W4	W.DRISCOLL	WELL	1.32	20.07	0.15	34.7	-160.9	1.39
RCC-19	9 27 12 3W4	H.BROST	WELL	1.18	20.21	0.15	34.9	-160.6	1.39
RCC-20	5 15 12 3W4	R.FRANZ	WELL	2.21	-19.20	0.15	41.3	-155.3	1.43
RCC-21	16 7 12 2W4	M.BROST	WELL	4.89	-16.57	0.15	61.3	-138.7	1.54
RCC-22	11 31 11 2W4	IRVINE P-CAN	WELL	3.02	-18.40	0.14	51.7	-146.7	1.48
RCC-23	14 8 8 2W4	SUMMER	PPT.	13.98	-7.68	0.16	136.8	-75.6	1.99
RCC-24	9 27 8 2W4	SUMMER	PPT.	13.60	-8.05	0.16	153.2	-61.9	2.09
RCC-25	14 30 8 2W4	FELESKY	WELL	0.27	-21.10	0.13	37.0	-158.9	1.40
RCC-26	10 16 8 3W4	KAJEWSKY	SPRING	2.48	-18.93	0.15	53.5	-145.1	1.49
RCC-27	15 9 9 3W4	J.IGNATIUS	SPRING	2.04	-19.36	0.15	47.1	-150.5	1.46
RCC-28	15 15 9 3W4	H.SEITZ	SPRING	1.02	-20.36	0.15	38.7	-157.5	1.41
RCC-29	22 9 3W4	B.WEISS-CORRAL	SPRING	2.96	-18.46	0.15	52.4	-146.1	1.49
RCC-30	9 19 9 2W4	D.NEUBAUER	SPRING	2.56	-18.85	0.15	51.0	-147.2	1.48
RCC-31	1 4 9 2W4	ROAD ALLOWANCE	F.WELL	2.64	-18.78	0.15	51.2	-147.0	1.48
RCC-32	8 5 9 2W4	E.NEUBAUER	SPRING	2.65	-18.77	0.15	52.9	-145.6	1.49
RCC-33	4 1 10 4W4	M.RATH-STOCK	WELL	7.96	-13.57	0.15	79.4	-123.5	1.64
RCC-34	13 36 9 4W4	M.RATH-GARDEN	WELL	6.16	-15.33	0.15	76.9	-125.6	1.63
RCC-35	7 4 10 3W4	R.JANS-HOUSE	F.WELL	1.83	-19.57	0.15	47.7	-150.3	1.46
RCC-36	10 30 10 3W4	C.GILL	WELL	1.13	-20.25	0.15	39.1	-157.2	1.41
RCC-37	13 7 10 2W4	A.SCHORR	WELL	0.93	-20.45	0.15	36.8	-159.0	1.40
RCC-38	16 30 10 2W4	B.SCHORR	DUGWELL	2.95	-18.47	0.14	49.9	-148.1	1.47
RCC-39	12 35 10 3W4	B.OTTO	DUGWELL	5.11	-16.36	0.15	59.5	140.2	1.53
RCC-40	13 23 11 3W4	R.HESCH	WELL	7.17	-14.34	0.15	77.8	124.9	1.63
RCC-41	3 35 11 3W4	K.FRIEMARK	SPRING	3.24	-18.19	0.15	51.2	147.1	1.48

Table 4.1. (con.)

SAMPLE	LOCATION				OWNER DESCRIPTION	TYPE OF WATER	DELTA O18 (RAW)	DELTA O18 (VS SMOW)	ERROR (1 SIGMA)	DELTA H/D (RAW)	DELTA H/D (VS SMOW)	ERROR (1 SIGMA)
RCD 1	9	27	8	2W4	WINTER	PPT	-7.18	-28.39	0.15	33.3	217.6	1.07
RCD 2	7	7	8	2W4	CHPP	DUGOUT	10.20	-11.38	0.16	97.1	-108.8	1.75
RCD-3	7	7	8	2W4	CHPP	SEEP	4.25	-17.20	0.15	59.2	-140.4	1.53
RCD-4	12	12	8	3W4	WINTER	PPT	-7.45	-28.65	0.15	-37.2	-220.8	1.06
RCD-5	13	11	8	3W4	CHPP-NICHOLLS	SPRING	2.26	-19.15	0.15	54.3	-144.5	1.50
RCD-6	7	23	8	3W4	CHPP-FIREROCK	WELL	2.80	-18.62	0.13	52.1	-146.3	1.49
RCD-7	7	23	8	3W4	WINTER	PPT	-7.25	-28.46	0.15	-34.4	-218.5	1.07
RCD-8	3	13	8	3W4	CHPP-MITCHELL	SPRING	2.53	-18.88	0.15	52.6	-145.9	1.49
RCD-9	7	24	8	3W4	ELKWATER TOWN	WELL	2.10	-19.30	0.15	49.4	-148.5	1.37
RCD-10	10	16	8	3W4	KAJEWSKY	SPRING	2.83	-18.59	0.15	54.3	-144.4	1.50
RCD-11	4	27	8	3W4	RUSSIL	SPRING	1.79	-19.61	0.14	45.1	-152.2	1.45
RCD-12	15	16	9	3W4	H. SEITZ	SPRING	0.69	-20.68	0.15	36.9	-159.0	1.40
RCD-13	15	16	9	3W4	WINTER	PPT.	-6.89	-28.10	0.15	-28.2	-213.3	1.09
RCD-14	1	22	9	3W4	B. WEISS-CORRAL	SPRING	2.80	-18.62	0.15	51.6	-146.7	1.48
RCD-15	5	18	9	2W4	J. MACK	SPRING	3.28	-18.15	0.15	54.4	-144.4	1.50
RCD-16	1	4	9	2W4	ROAD ALLOWANCE	F. WELL	2.35	-19.06	0.15	50.2	-147.9	1.48
RCD-17	13	7	10	2W4	A. SCHORR	WELL	1.35	-20.04	0.14	40.3	-156.1	1.42
RCD-18	6	24	10	3W4	KRAUSS	F. WELL	10.03	-11.54	0.15	91.2	-113.7	1.71
RCD-19	11	30	8	3W4	BROWN EST. -H	SPRING	2.08	-19.32	0.15	43.6	-153.4	1.44
RCD-20	2	24	9	4W4	K. SAILER	SPRING	3.40	-18.03	0.13	55.1	-143.8	1.50
RCD-21	9	19	9	2W4	D. NEUBAUER	SPRING	2.47	-18.94	0.15	51.3	-146.9	1.48
RCD-22	1	30	12	5W4	WINTER	PPT.	-7.00	-28.21	0.15	-33.7	-217.9	1.07
RCD-23	12	34	11	3W4	WINTER	PPT.	-7.81	-29.00	0.15	-39.0	-222.4	1.05
RCD-24	1	4	11	3W4	WINTER	PPT	-6.99	-28.20	0.15	-26.6	-212.0	1.10
RCD-25	8	24	8	3W4	WINTER	PPT.	-6.15	-27.38	0.15	-21.4	-207.7	1.12
RCD-26	2	18	8	2W4	WINTER	PPT	-5.61	-26.85	0.15	-17.3	-204.2	1.14
RCD-27	8	7	8	2W4	WINTER	PPT.	-6.18	-27.41	0.15	-22.3	-208.4	1.12
RCD-28	11	24	8	3W4	CHPP-ELKWATER	LAKE	11.17	-10.43	0.19	108.6	-99.1	1.82
RCD-29	4	25	9	3W4	ROSS	CREEK	[illegible]	---	--	---	---	--
MT-1	10	35	12	6W4	SOUTH SASK-MH	RIVER	3.23	-18.20	0.15	57.2	-142.0	1.51
MT-2	13	27	10	3W4	SNOWBANK	PPT.	-2.15	-23.46	0.15	8.6	-182.6	1.26
MT-3	13	10	11	3W4	SNOWMELT	PUDDLE	-0.71	-22.05	0.15	21.2	-172.1	1.32
MT-4	16	33	9	3W4	VOSSLER	S. SEEP	[illegible].27	-8.37	0.16	103.6	-103.3	1.79
MT-5	7	24	8	3W4	ELKWATER TOWN	WELL	2.05	-19.35	0.15	47.1	-150.5	1.46
MT-6	7	7	8	2W4	CHPP	DUGOUT	2.51	-18.90	0.15	54.5	-144.3	1.50
RCE-1	10	12	12	4W4	WINTER(N)	PPT.	-1.69	-23.01	0.15	7.4	-183.6	1.25
RCE-2	10	12	12	4W4	SNOW	MELT	1.05	-20.33	0.15	38.5	-157.7	1.41
RCE-3	9	9	1[illegible]	[illegible]W4	WINTER(N)	PPT	-5.47	-26.71	0.15	-18.4	-205.1	1.13
RCE-4	16	26	8	3W4	WINTER(O)	PPT.	2.81	-18.51	0.15	57.2	-142.1	1.51
RCE-5	5	19	8	2W4	WINTER(N)	PPT.	0.33	-21.04	0.15	35.1	-160.5	1.39
RCE-6	6	24	8	3W4	CHPP AE#2094E	WELL	2.54	-18.87	0.15	53.3	-145.3	1.49
RCE-7	12	8	8	2W4	DUKE AE#2093E	WELL	2.49	-18.92	0.15	54.2	-144.6	1.50
RCE-8	12	8	8	2W4	DUKE AE#2084E	WELL	3.78	-17.66	0.15	62.6	-137.5	1.55
RCE-9	12	8	8	2W4	WINTER(N)	PPT	3.97	-17.47	0.13	73.4	-128.5	1.61
RCE-10	12	8	8	2W4	WINTER(O)	PPT.	-5.28	-26.53	0.15	-12.5	-200.3	1.16
RCE-11	11	34	11	3W4	ROSS	CREEK	-0.58	-21.93	0.15	25.7	-168.3	1.34
RCE-12	14	31	11	2W4	IRVINE P-CAN	WELL	2.96	-18.46	0.15	50.8	-147.4	1.48
RCE-13	4	35	11	3W4	K. FRIEMARK	SPRING	2.83	-18.59	0.15	51.0	-147.2	1.48
RCE-14	1	5	12	3W4	R. PFAFF	SPRING	0.46	-20.91	0.17	28.7	-165.8	1.36
RCE-15	8	15	12	4W4	B. SCHNEIDER	SPRING	2.59	-18.82	0.15	49.5	-148.5	1.47
RCE-16	16	10	12	4W4	DUKE AE#2088E	WELL	1.55	-19.84	0.15	42.2	-154.6	1.43
RCE-17	16	10	12	4W4	DUKE AE#2087E	WELL	3.00	-18.42	0.15	37.1	-158.9	1.40
RCE-18	16	10	12	4W4	DUKE AE#2086E	WELL	1.34	-20.05	0.15	38.6	-157.5	1.41
RCE-19	8	15	12	4W4	SNOW	MELT	1.49	-19.90	0.13	41.5	-155.2	1.43
RCE-20	8	15	12	4W4	WINTER(N)	PPT	1.20	-20.19	0.15	41.3	-155.3	1.43
RCE-21	16	25	11	4W4	DUKE AE#2080E	WELL	2.00	-19.40	0.15	41.1	-155.5	1.43
~~RCE-22~~	~~16~~	~~25~~	11	4W4	DUKE AE#2081E	WELL	10.03	-11.54	0.15	96.0	-109.7	1.74
RCE-23	1	25	11	3W4	SNOW	MELT	2.25	-19.16	0.15	40.9	-155.6	1.42
RCE-24	13	24	11	4W4	WUTCH	SLOUGH	5.69	-15.79	0.15	66.4	-134.4	1.57
RCE-25	8	9	11	4W4	DUKE AE#2092E	WELL	3.20	-18.23	0.13	55.6	-143.4	1.51
RCE-26	8	9	11	4W4	DUKE AE#2091E	WELL	2.81	-18.61	0.15	51.1	-147.1	1.30
RCE-27	13	35	10	4W4	C. ZEIGLER	WELL	3.38	-18.05	0.15	46.2	-151.3	1.45
RCE-28	7	20	11	4W4	C. SCHMIDEK	SPRING	1.05	-20.33	0.15	34.2	-161.2	1.39
RCE-29	8	35	12	6W4	SOUTH SASK-MH	RIVER	2.20	-19.21	0.15	48.6	-149.2	1.47
RCE-30	11	24	12	5W4	HOFFMAN	F. WELL	2.80	-18.62	0.13	47.5	-150.1	1.46
RCE-31	8	33	10	3W4	DUKE AE#2089E	WELL	9.09	-12.46	0.15	81.3	-122.0	1.65
RCE-32	8	33	10	3W4	DUKE AE#2079E	WELL	9.25	-12.31	0.15	95.6	-110.0	1.74
RCE-33	12	25	10	4W4	D. MEIER	WELL	-0.70	-22.05	0.15	23.2	-170.4	1.33
RCE-34	2	4	11	3W4	SNOW	MELT	1.74	-19.66	0.15	39.6	-156.7	1.42
RCE-35	2	4	11	3W4	WINTER(N)	PPT	2.66	-18.76	0.13	55.7	-143.3	1.51
RCE-36	7	24	8	3W4	ELKWATER TOWN	WELL	1.80	-19.60	0.15	48.1	-149.7	1.46
RCE-37	12	11	9	3W4	H. SEITZ	SLOUGH	0.08	-21.28	0.15	30.0	-164.7	1.37
RCE-38	12	11	9	3W4	WINTER(O)	PPT	-1.72	-23.04	0.15	14.1	-178.0	1.28

4.1.1 Meteoric and surface waters

Wide variations in the $\delta^{18}O$ and δD of precipitation were noted; over 20°/₀₀ and 160°/₀₀, respectively. These enormous variations are typically found in the region, but make Alberta a unique location worldwide in this regard. The differences reflect both seasonal variations and the fact that the eastern side of the Rockies derives its weather patterns from four separate sources: the Pacific Ocean, Hudson's Bay, the Arctic Ocean, and the Gulf of Mexico. Figure 4.1 shows the variations in $\delta^{18}O$ of precipitation samples collected in Ross Creek Basin during the various sampling trips. For contrast, the range of non-evaporated groundwaters containing "bomb" levels of tritium is included in Figure 4.1. Clearly, recent groundwaters show little variation in $\delta^{18}O$ values in comparison to the precipitation.

Examinations of precipitation data from the RCA sampling trip showed that an altitude effect can be found for a single rainstorm (Figure 4.2). The slope of 0.0046°/₀₀ per meter is well within the range of values reported in the literature (Table 2.1). However, results from subsequent precipitation events, such as the major October storm collected during the RCD trip (Figure 4.3) did not give further evidence of a significant altitude effect in Ross Creek Basin. Similarily, no altitude effect was noted in 11 non-evaporated groundwaters containing post-1952 levels of tritium (Fig. 4.4).

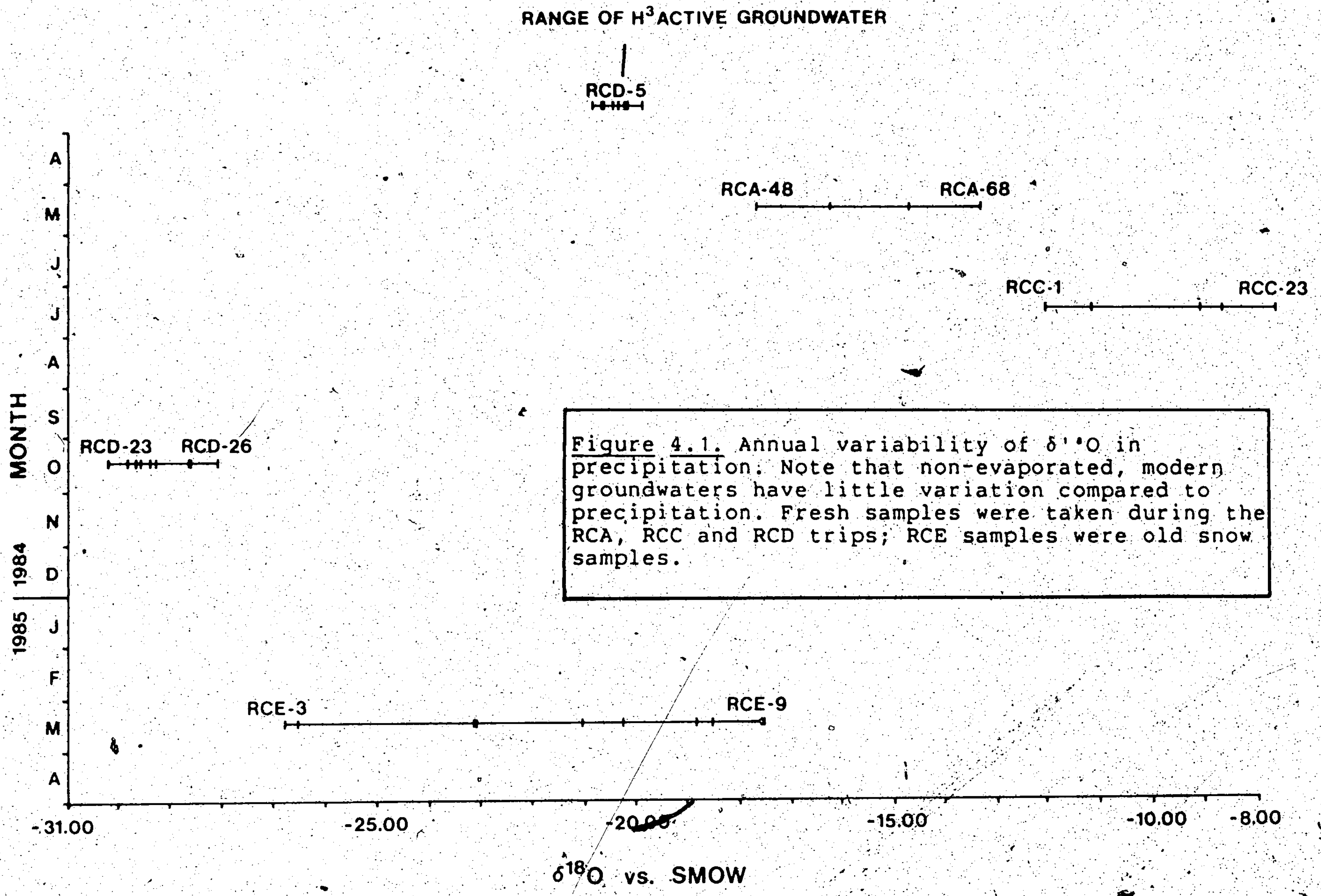


Figure 4.1. Annual variability of δ^{18}O in precipitation. Note that non-evaporated, modern groundwaters have little variation compared to precipitation. Fresh samples were taken during the RCA, RCC and RCD trips; RCE samples were old snow samples.

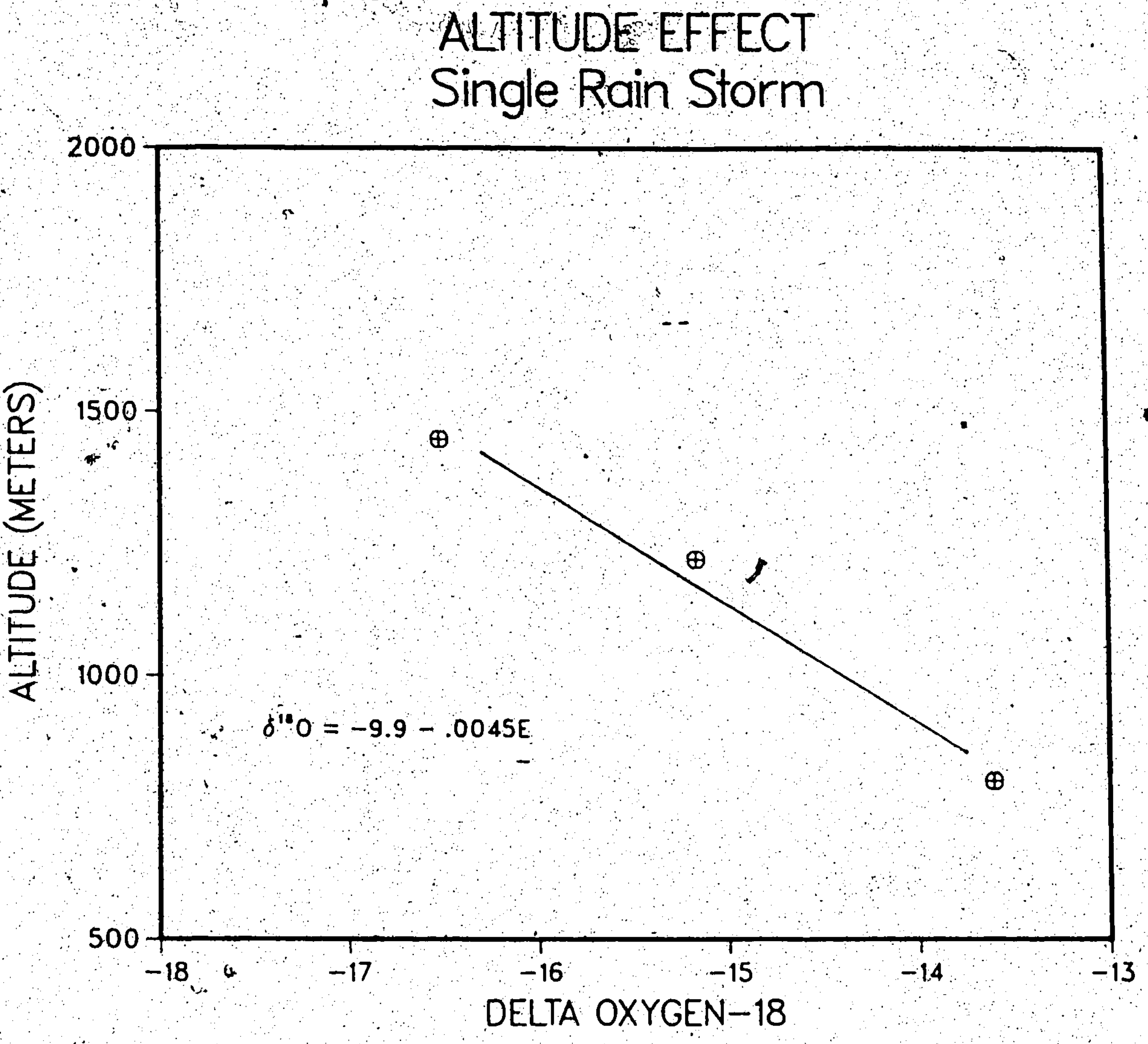


Figure 4.2. Altitude effect in a single rain storm. Samples taken during May, 1984 rain; RCA sampling trip.

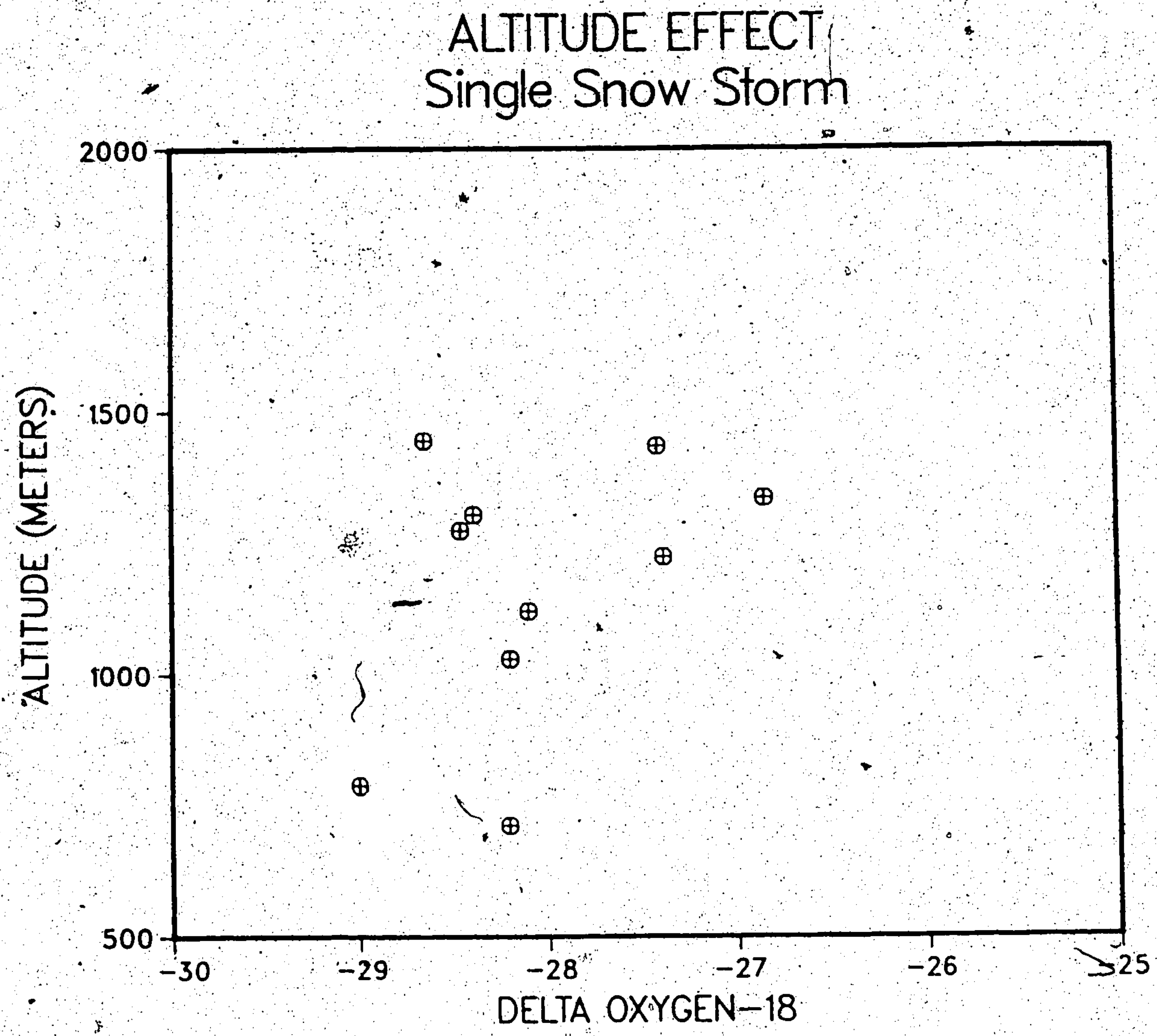


Figure 4.3. No altitude effect was found in a October, 1984 snow storm. Samples taken during RCD sampling trip.

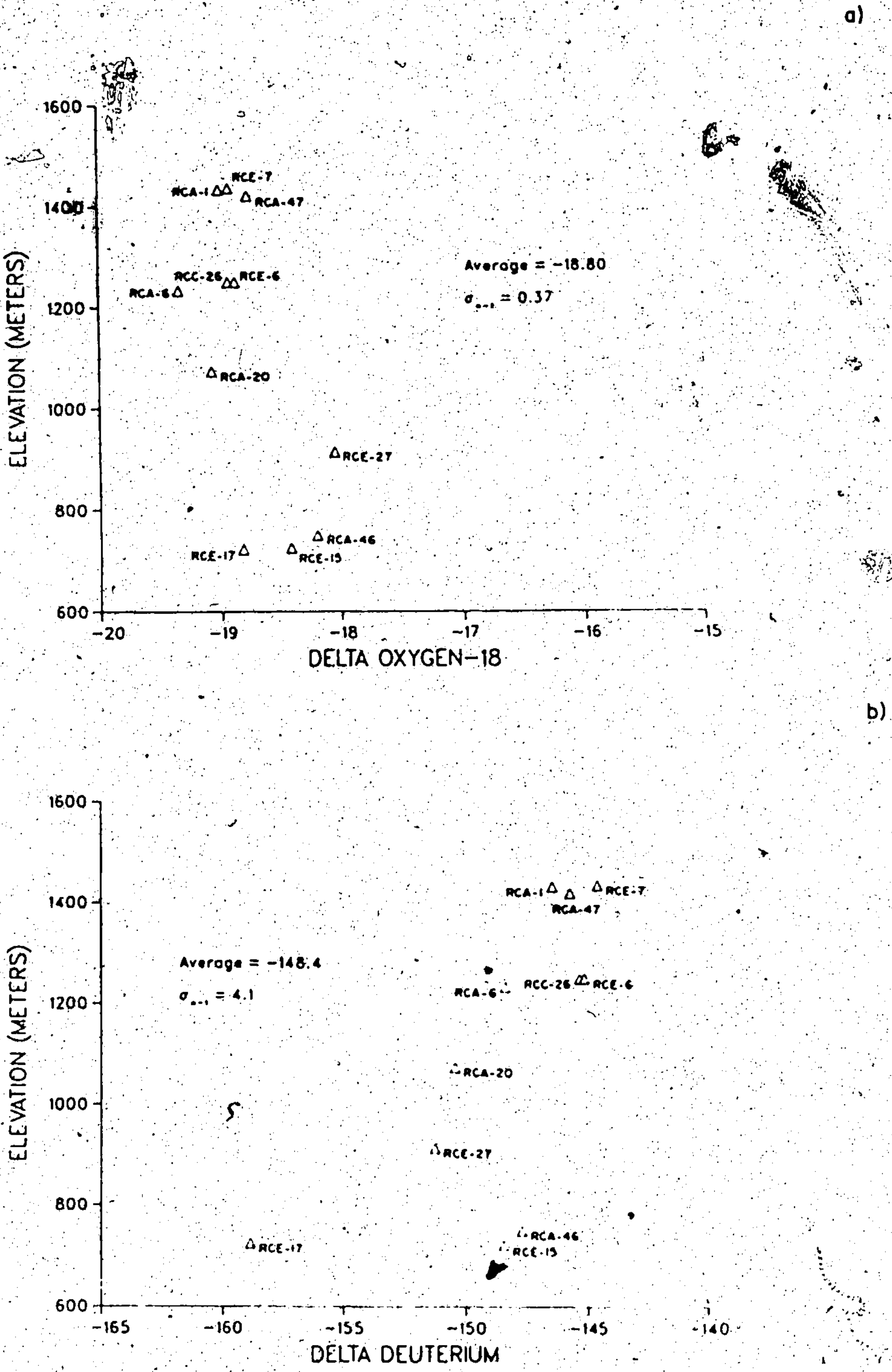


Figure 4.4. No altitude effect was found in 11 non-evaporated modern groundwaters. a) elevation vs. $\delta^{18}O$; b) elevation vs. δD.

With the exception of the RCA rain samples and one sample from the RCC storm, stable isotope values of precipitation from Ross Creek Basin can be plotted along a straight line which is interpreted as an approximate meteoric water line for the area. The equation of the meteoric water line, calculated for the 24 non-evaporated samples is:

$$\delta D = 7.7 \cdot \delta^{18}O + 2.00\,^{\circ}/_{\circ\circ} \tag{4.1}$$

$r^2 = .99741$. A diagram of the Ross Creek meteoric waterline and all of the precipitation points is given in Figure 4.5.

δD levels of surface water samples were plotted against $\delta^{18}O$ and are shown in Figure 4.6. These results also fit a straight line with the equation:

$$\delta D = 5.1 \cdot \delta^{18}O - 52.47\,^{\circ}/_{\circ\circ} \tag{4.2}$$

with an $r^2 = .96773$. Because the surface water samples are from locations where evaporation occurred during the summer, it is assumed that Equation 4.2 describes an evaporative water line for Ross Creek Basin.

4.1.2 Groundwaters

As indicated by Figure 4.1, modern groundwater samples from the basin occupy a much narrower range of values on an isotopic plot than does the precipitation. However, the

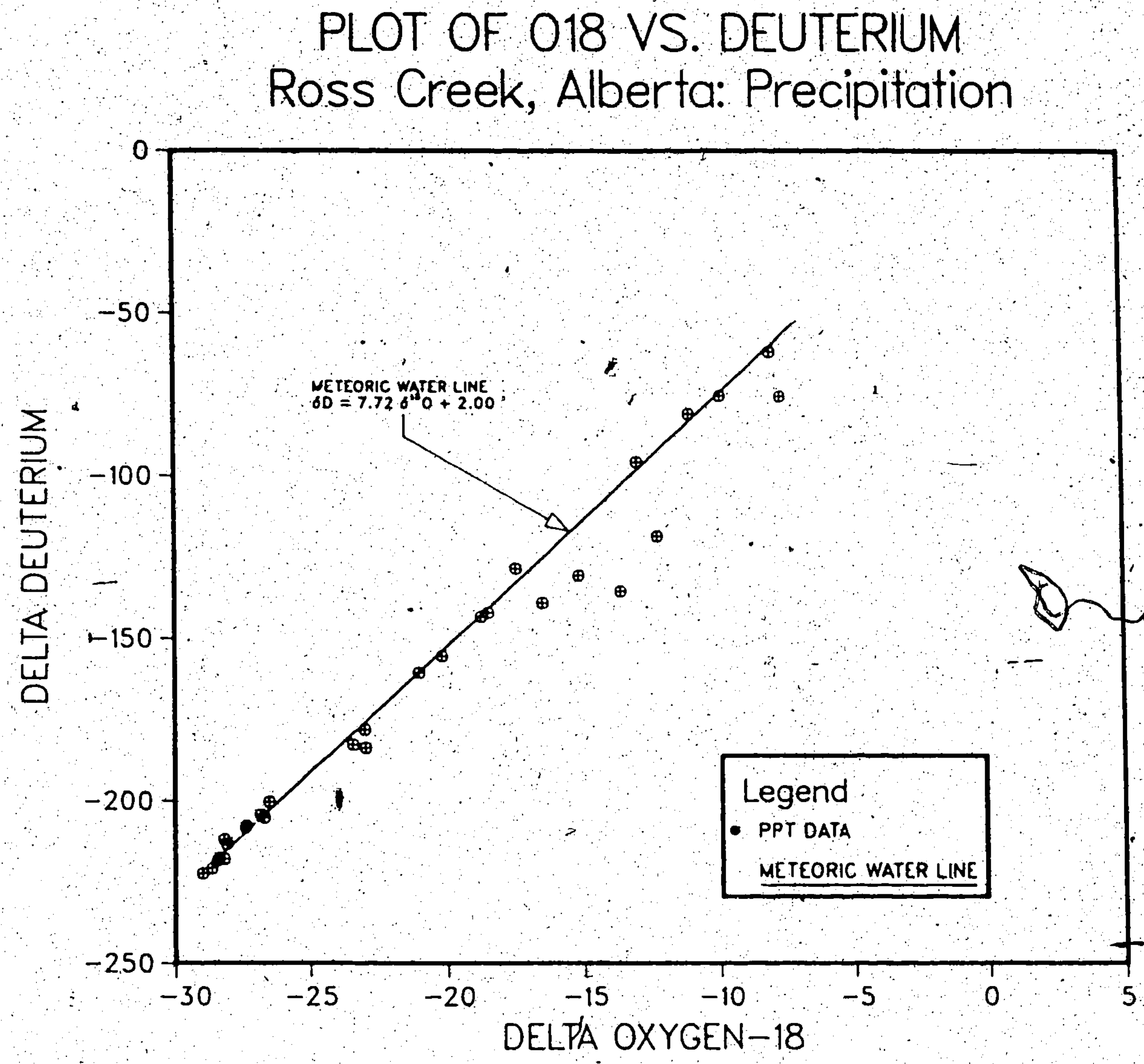


Figure 4.5. Meteoric water line in Ross Creek Basin. The 5 samples that plot to the right of the line were not considered in the regression analysis.

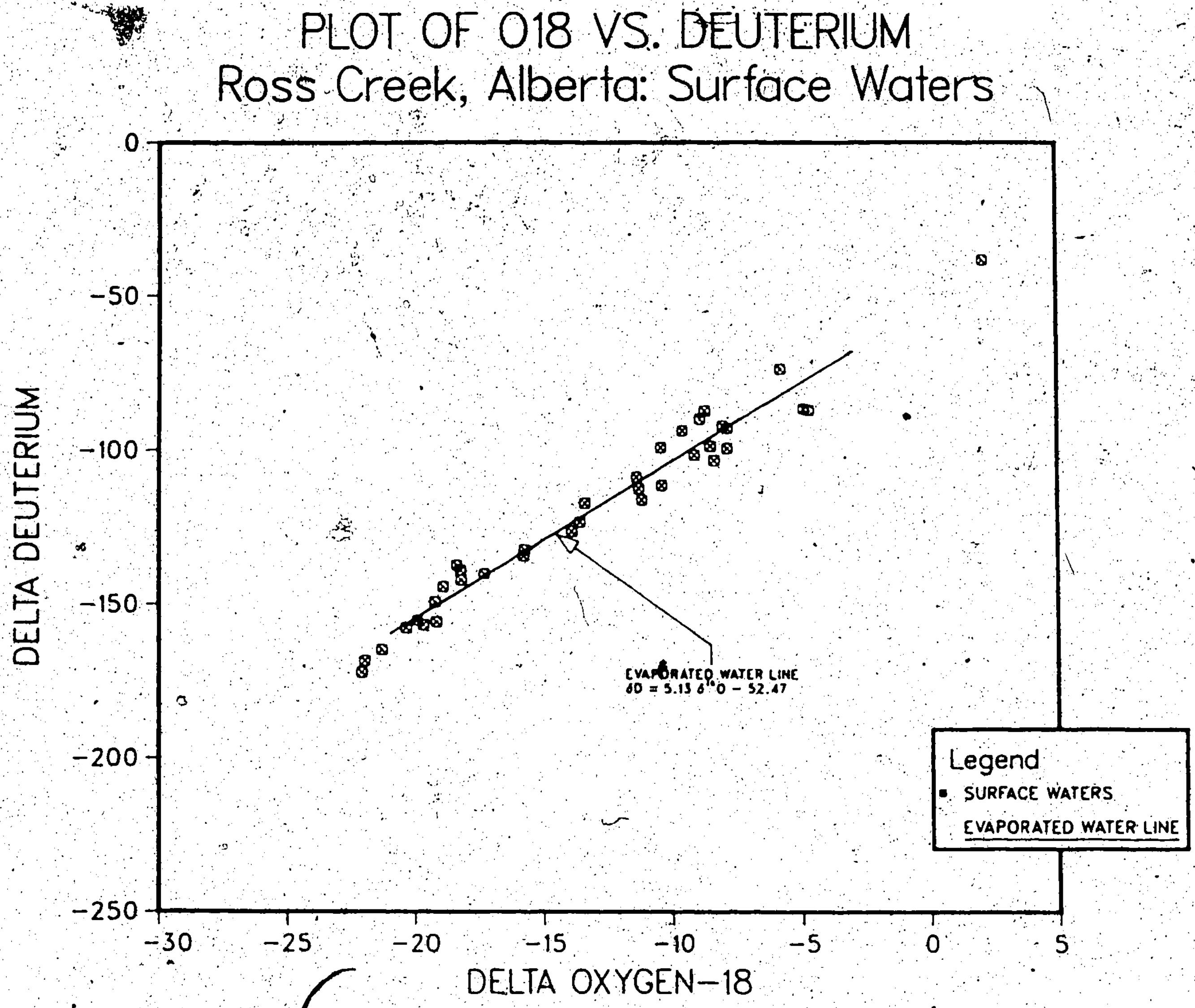


Figure 4.6. Evaporated water line in Ross Creek Basin. The isotope values of 38 surface water samples are shown.

range of all samples is still extreme: over $12^{\circ}/_{oo}$ for $\delta^{18}O$ and $80^{\circ}/_{oo}$ for δD. Fritz et al. (1978) noted an $11^{\circ}/_{oo}$ variation in groundwater samples from the Winnipeg area; while Schwartz and Muehlenbachs (1979) noted shifts of $12^{\circ}/_{oo}$ ($\delta^{18}O$) and $70^{\circ}/_{oo}$ (δD) in the Milk River aquifer. Therefore to a first approximation, the Ross Creek Basin samples would appear to mirror processes occurring elsewhere on the prairies. However, Figure 4.7 shows that only the more isotopically depleted groundwater samples from Ross Creek plot on the meteoric water line described by Equation 4.1. The isotope data from Ross Creek Basin groundwater that do not fall on the meteoric water line plot close to the evaporative line (Fig. 4.7). No differences between the enriched waters of any particular type of groundwater feature were noted: if graphed alone, evaporated springs have a slope of 4.7 and an $r^2=.87987$; while wells have a slope of 5.5 and an $r^2=.92748$. This does not imply that all groundwater is evaporated; a significant number of samples cluster near the meteoric water line, (Figure 4.7), but many are clearly enriched relative to meteoric water.

It was thought that the limited number of precipitation samples collected in 1984 might not give a representative meteoric line for Ross Creek Basin over the long term. As shallow groundwater samples are often utilized in isotopic studies to delineate a local meteoric waterline for an area, all of the waters sampled in Ross Creek Basin were used to distinguish both composite meteoric and evaporated lines.

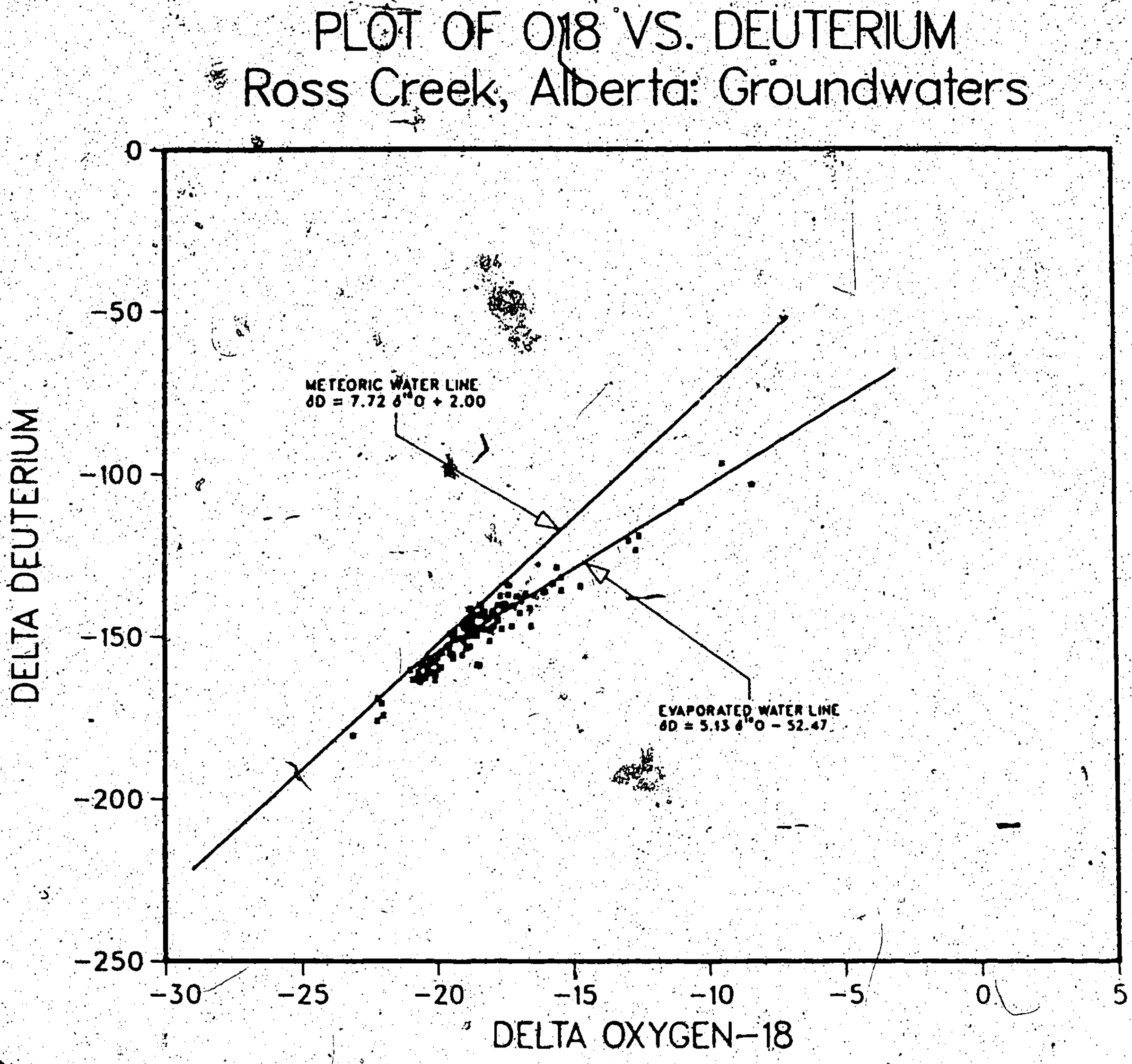


Figure 4.7. Plot of all groundwater samples in Ross Creek Basin. Also shown are the meteoric and evaporated water lines from Figures (4.5) and (4.6).

The composite meteoric water line found for Ross Creek Basin has an equation of:

$$\delta D = 7.5 \cdot \delta^{18}O - 6.14‰ \qquad (4.3)$$

and an $r^2 = .98283$. The composite evaporated line can be described by the equation:

$$\delta D = 5.4 \cdot \delta^{18}O - 50.23‰ \qquad (4.4)$$

The $r^2 = .94407$. These two trends are very close to those calculated by Equations 4.1 and 4.4. The plot of all Ross Creek Basin isotopic samples is given in Figure 4.8. All of the sample values fall very close to either the evaporated or the meteoric water line for the basin.

Cluster analysis of $\delta^{18}O$ values of samples allowed for further delineation of different groups of groundwater in Ross Creek Basin. These groupings reflect a bias towards evaporative effects because clustering was performed only on the $\delta^{18}O$ variable. This bias would not have been as marked if cluster analysis had involved δD. However, it was thought that such an analysis could be more easily made using $\delta^{18}O$ because the variation in samples was proportionally larger than for δD. The resultant clusters were numbered in order of increasing $\delta^{18}O$ content. The characteristics may be summarized as follows:

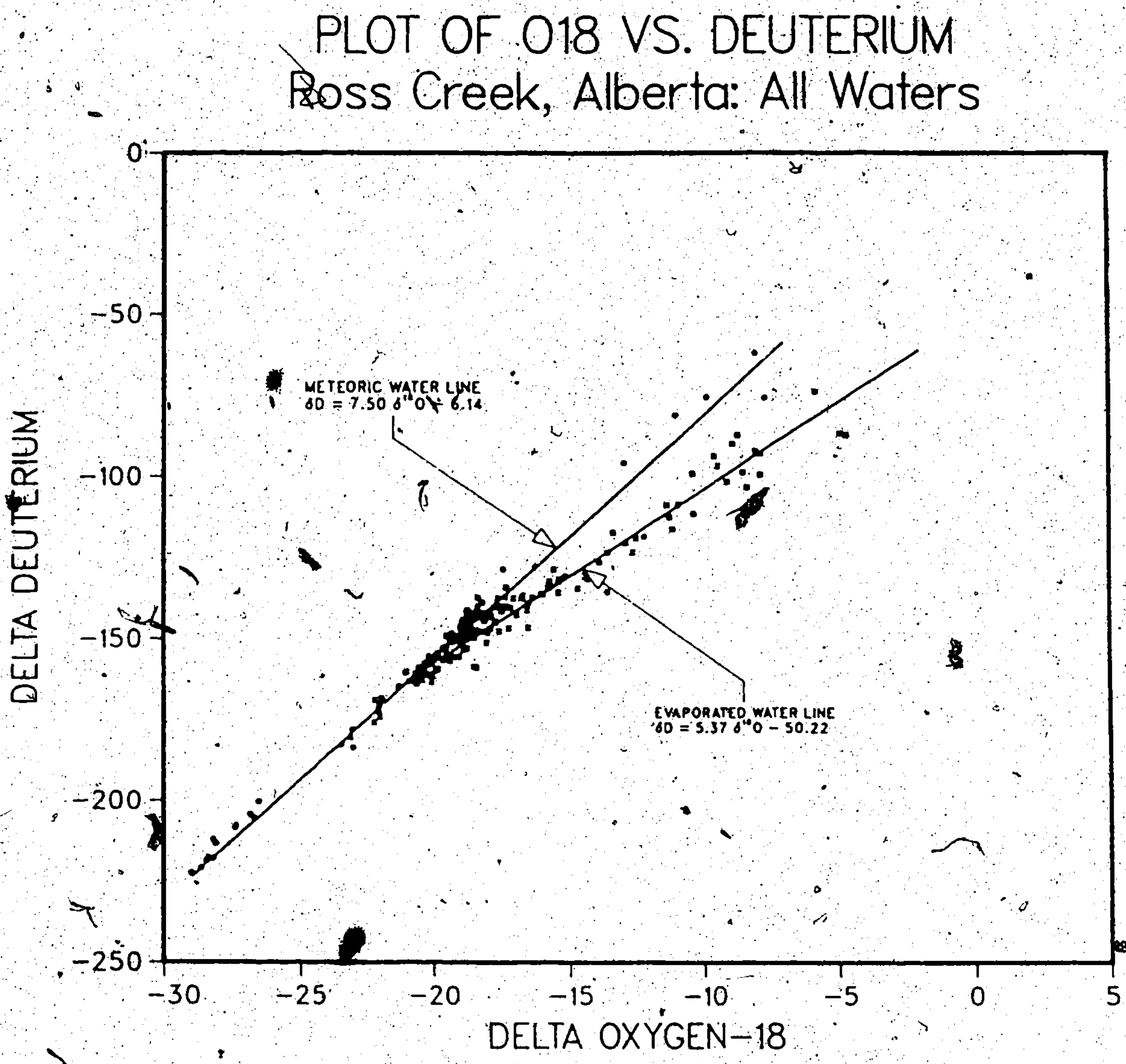


Figure 4.8. The composite meteoric and evaporated water lines in Ross Creek. The lines are very similar to those shown in Figures (4.5) and (4.6), but the meteoric line describes the trend of non-evaporated groundwaters more closely.

1. -22.00 to -23.10 °/oo. Five wells, "extremely depleted" in δ^{18}O relative to the rest of the groundwater groupings. This group of waters occurs only near the town of Dunmore and in the center of the basin (Fig. 4.9).

2. -20.24 to -21.00 °/oo. Thirteen wells and springs "very depleted" in δ^{18}O relative to the rest of the groundwater groupings. This group of waters occurs largely on the western side of Ross Creek Basin (Fig. 4.9).

3. -19.83 to -20.10 °/oo. Nine groundwaters "depleted" in δ^{18}O relative to the average grouping. This group of waters occurs on the western side of the basin with many points near the town of Dunmore (Fig. 4.9).

4. -19.30 to -19.64 °/oo. Twelve wells and springs "slightly depleted" relative to the average. This group of waters is more evenly distributed throughout the basin than Groups 1 to 3, but is found more often on the western side than on the eastern (Fig. 4.9).

5. -16.93 to -19.07 °/oo. Fifty-six groundwater samples that represent the average groundwaters in Ross Creek. Some slightly evaporated samples were thought to be included in this group, but cluster analysis does not distinguish these.

6. -14.47 to -16.53 °/oo. Sixteen "enriched" samples. These

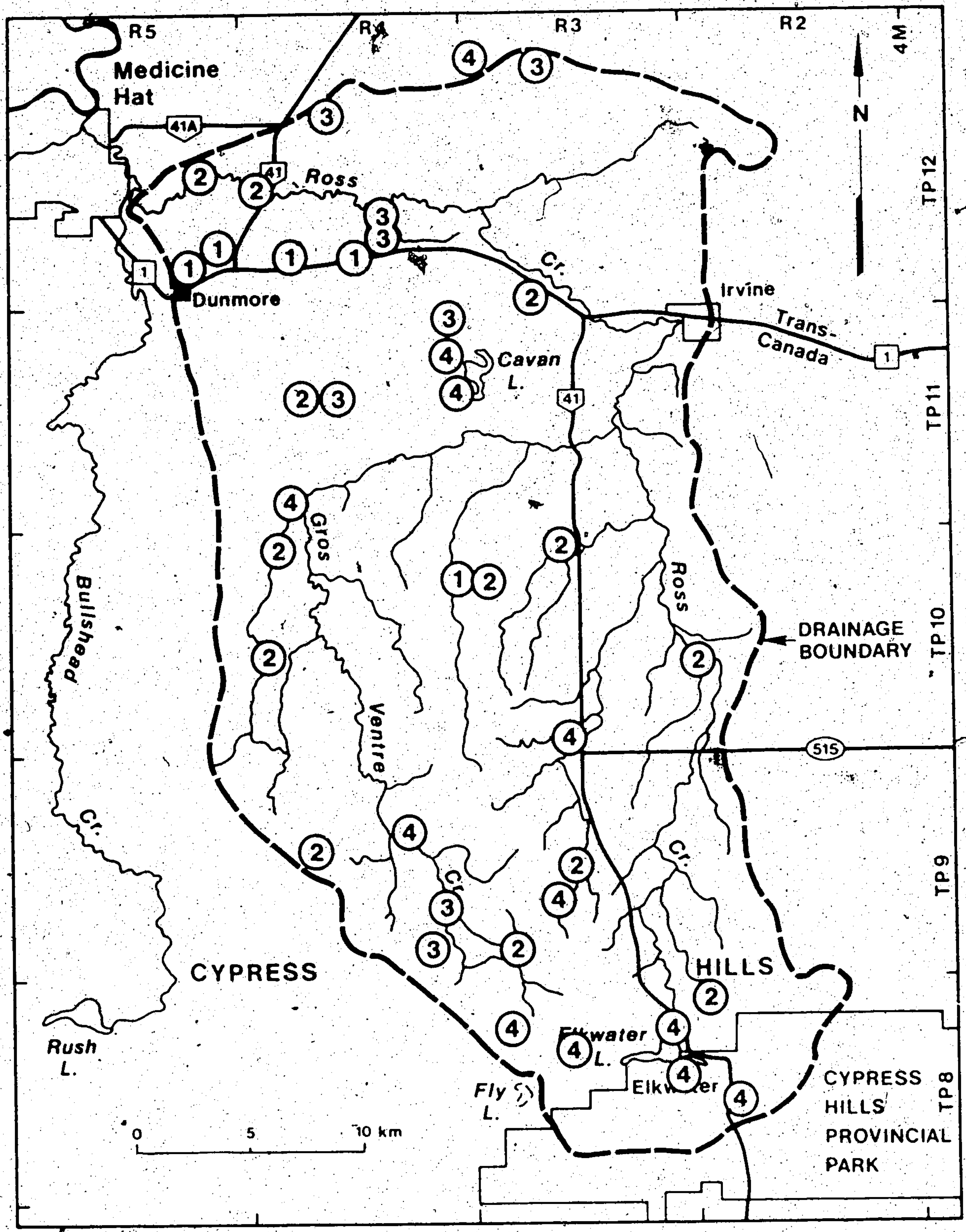


Figure 4.9. Location map of Groups 1 to 4 waters. These are groundwaters which are depleted in ^{18}O relative to the average. Virtually all are found to the west of Highway 41, with the most depleted, Groups 1 [illegible] 2, found near the town of Dunmore and in the center of the basin.

are interpreted as having undergone evaporation.

7. -9.47 to -13.57. Five "very enriched" samples from wells. These have undergone a great deal of evaporation.

As shown in Figure 4.9, Group 1 waters occur in the northwestern portion of the basin near the town of Dunmore and in the center of the basin near an area of high TDS (Ophori and Tóth 1983). Groups 2 and 3 waters are predominantly found in the northern and western portions of the basin. Groups 4 to 7 waters occur uniformly throughout Ross Creek Basin; Groups 6 and 7 are plotted in Figure 4.10. Group 5 waters are not represented because of the great number of samples in this cluster, but they are found throughout the basin.

Of the 30 groundwater sites that were sampled more than one time during the field collection program, only 4 showed significant changes in $\delta^{18}O$ content between collection trips[3]. Variations over the course of the year are shown in Figure 4.11. The seep at the top of the Cypress Hills (7-7-8-2W4) shows the largest variation of groundwater over the year, the source of water for the seep is local and thus subject to seasonal effects in precipitation. The three wells (Resch, Krauss and Schorr) reflect much more modest $\delta^{18}O$ variations, but these were also borne out in δD data (Table 4.1). Also shown on Figure 4.11 is the contrast

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[3] Significant changes were assumed to be shifts that were greater than 1°/oo

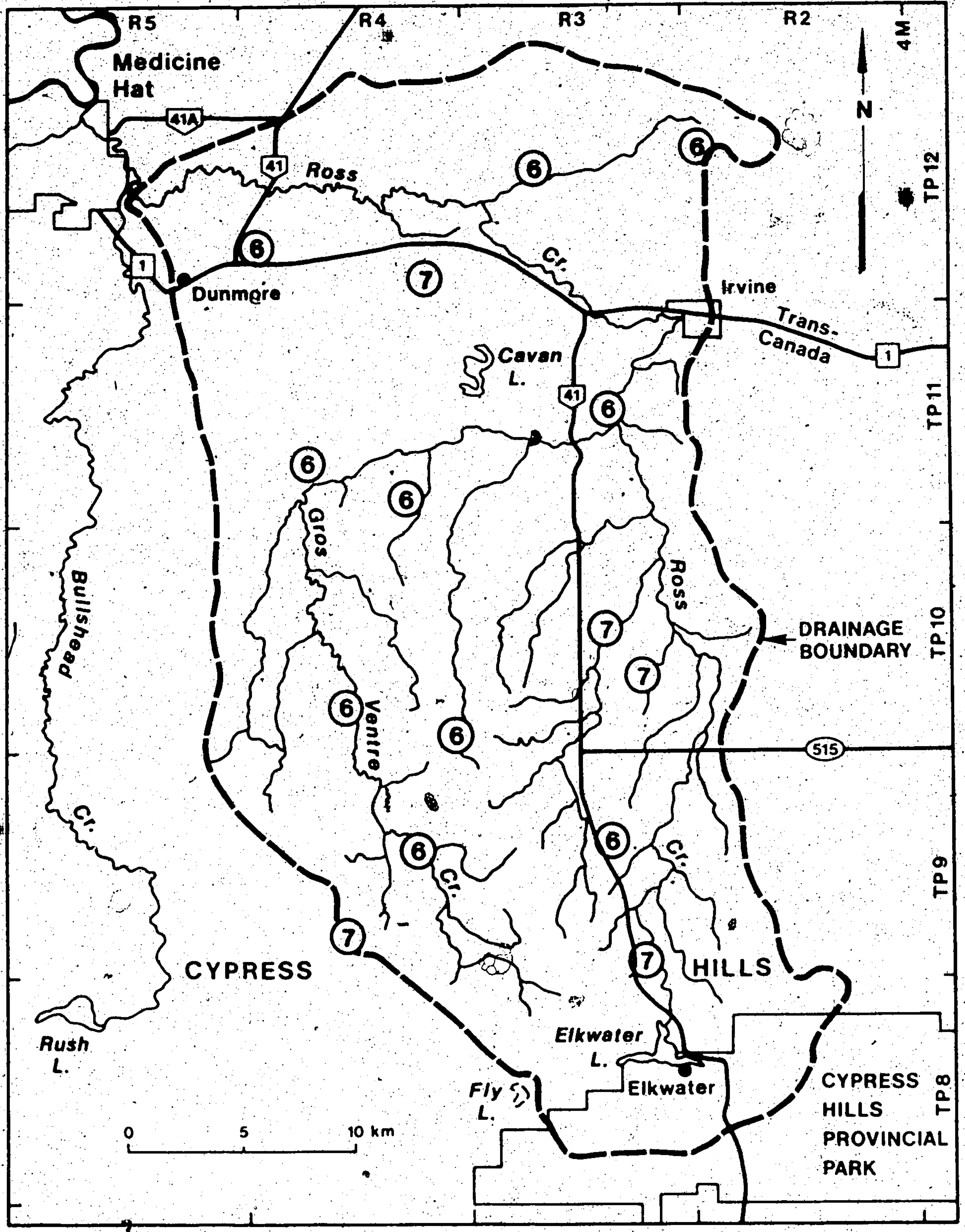


Figure 4.10. Location map of Groups 6 and 7 waters. These are groundwaters which are enriched in ^{18}O relative to the average. These are distributed throughout Ross Creek Basin.

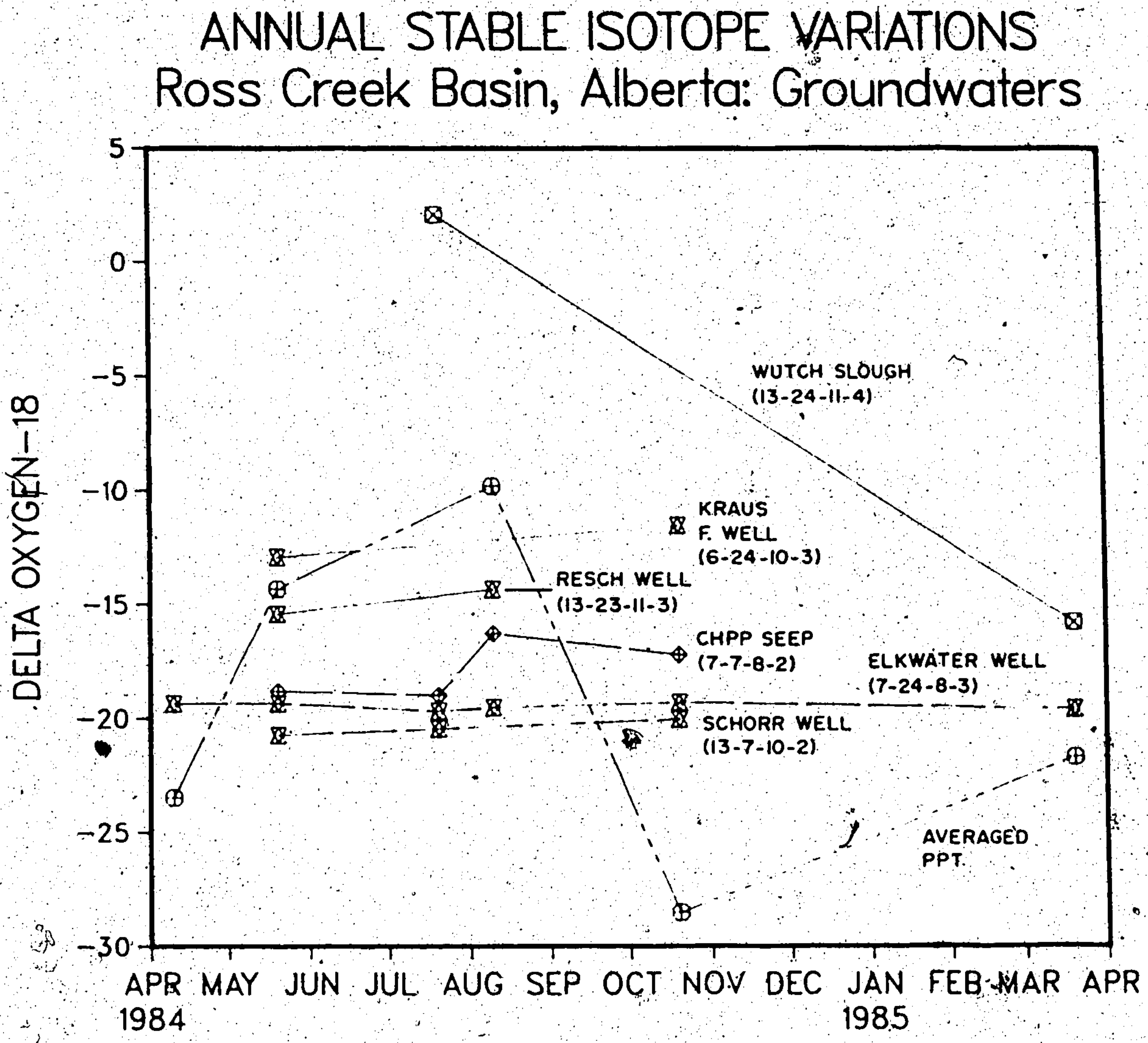


Figure 4.11. Annual variations in some groundwaters from Ross Creek Basin. The Resch, Krauss and Schorr wells demonstrate slight changes in ^{18}O when compared to the Elkwater well. The seep in Cypress Hills Provincial Park had a large shift, however. The annual variability in groundwaters were very small compared to the precipitation and the Wutch slough.

between these annual groundwater fluctuations and the variations in precipitation values and the Wutch slough. The latter had the most enriched values of $\delta^{18}O$ and δD that were sampled in Ross Creek Basin in July, 1984, but showed a dilution effect because of mixing with isotopically depleted snowmelt when sampled and analyzed in March, 1985.

4.2 Tritium Results

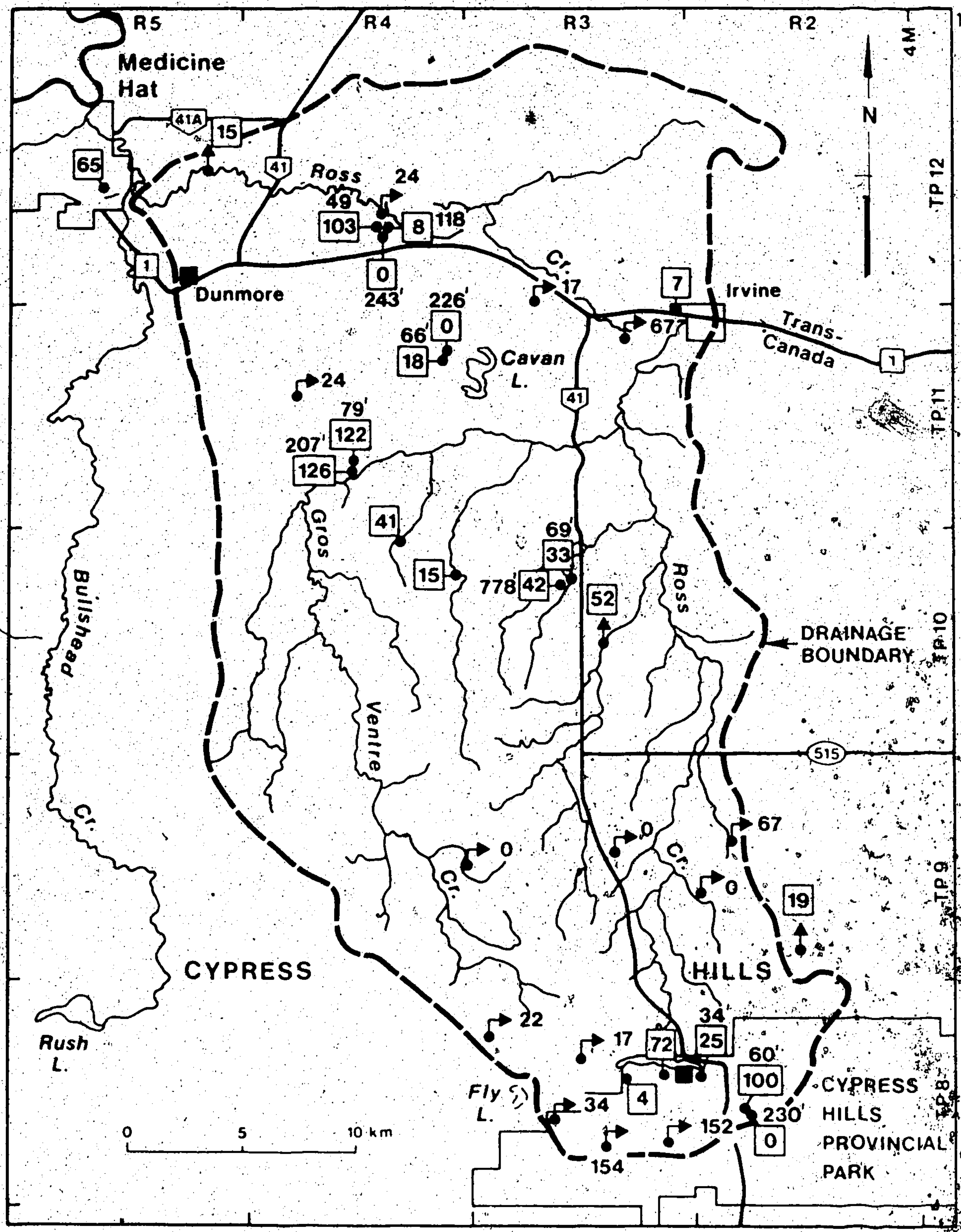
Twenty samples were collected for tritium analysis in Ross Creek Basin and are presented in Table 4.2. The results vary from 0 (below detectable limits) to 154 TU; spanning a wide range of waters including pre-1952, 1960-1970's water and 1980's levels of tritium, as described by the tritium input function for Alberta (Table 3.1).

Table 4.2 and Figure 4.12 indicate that tritium levels are not constant for any particular type of feature; the levels in wells, springs and precipitation all vary widely. Tritium levels do not appear to be geographically controlled.

Laboratory error values for tritium analyses are also quoted on Table 4.2. The indicated precisional errors are high and often equal to or greater than the level of tritium present. Tritium errors are due to variations in the counting vial walls; background vial activity; variations in laboratory technique and from background levels of radiation in the environment (Egboka et al. 1983). Levels of background activity at the Environmental Centre are higher

SAMPLE	LOCATION	OWNER DESCRIPTION	TYPE OF WATER	H3 ACTIVITY (TRITIUM UNITS)	ERROR (2 SIGMA)
RCA-1	13 11 8 3W4	CHPP-NICHOLLS	SPRING	154	32
RCA-3	7 23 8 3W4	CHPP-FIREROCK	WELL	4	14
RCA-6	7 24 8 3W4	ELKWATER TOWN	WELL	25	16
RCA-13	1 22 9 3W4	B.WEISS-CORRAL	SPRING	0	16
RCA-20	9 19 9 2W4	D.NEUBAUER	SPRING	67	29
RCA-23	6 24 10 3W4	KRAUSS	F.WELL	52	10
RCA-29	11 31 11 2W4	IRVINE P-CAN	WELL	7	16
RCA-45	1 5 12 3W4	R.PFAFF	SPRING	17	19
RCA-46	3 35 11 3W4	K.FRIEMARK	SPRING	67	15
RCA-47	3 13 8 3W4	CHPP-MITCHELL	SPRING	152	16
RCB-1	2 24 9 4W4	K.SAILER	SPRING	0	10
RCB-3	11 30 8 3W4	BROWN EST.-H	SPRING	22	10
RCB-22	4 27 8 3W4	RUSSIL	SPRING	17	10
RCB-41	14 24 12 5W4	HOFFMAN	SEEP	15	18
RCC-26	10 16 8 3W4	KAJEWSKY	SPRING	34	18
RCC-31	1 4 9 2W4	ROAD ALLOWANCE	F.WELL	19	9
RCD-4	12 12 8 3W4	WINTER	PPT.	27	18
RCD-15	5 18 9 2W4	J.MACK	SPRING	0	18
RCD-29	4 25 9 3W4	ROSS	CREEK	49	23
RCE-6	6 24 8 3W4	CHPP AE#2094E	WELL	72	11
RCE-7	12 8 8 2W4	DUKE AE#2093E	WELL	100	16
RCE-8	12 8 8 2W4	DUKE AE#2084E	WELL	0	17
RCE-9	12 8 8 2W4	WINTER(N)	PPT.	9	16
RCE-15	8 15 12 4W4	B.SCHNEIDER	SPRING	124	16
RCE-16	16 10 12 4W4	DUKE AE#2088E	WELL	8	11
RCE-17	16 10 12 4W4	DUKE AE#2087E	WELL	103	17
RCE-18	16 10 12 4W4	DUKE AE#2086E	WELL	0	17
RCE-21	16 25 11 4W4	DUKE AE#2080E	WELL	0	17
RCE-22	16 25 11 4W4	DUKE AE#2081E	WELL	18	17
RCE-25	8 9 11 4W4	DUKE AE#2092E	WELL	122	19
RCE-26	8 9 11 4W4	DUKE AE#2091E	WELL	126	20
RCE-27	13 35 10 4W4	C.ZEIGLER	WELL	41	22
RCE-28	7 20 11 4W4	C.SCHMIDEK	SPRING	24	18
RCE-29	8 35 12 6W4	SOUTH SASK/MH	RIVER	65	19
RCE-31	8 33 10 3W4	DUKE AE#2089E	WELL	32	19
RCE-32	8 33 10 3W4	DUKE AE#2079E	WELL	42	18
RCE-33	12 25 10 4W4	D.MEIER	WELL	15	21
RCE-36	7 24 8 3W4	ELKWATER TOWN	WELL	34	17

Table 4.2. Results of tritium analyses.



Sampling Points

15 Flowing Well with Tritium Level (Tu)

24 Spring with Tritium Level (Tu)

69' 33 Well with Depth in Feet Tritium Level (Tu)

Figure 4.12. Geographic distribution of tritium values.

than in many other institutions (D. Arnold, pers. comm.) and the detection limits are between 25 and 40 TU for any given counting day. This threshold is established by the daily background activity. Numbers that are quoted at less than the detection limit then, are considered to be useful only as a rough indicator. On Table 4.2 these values have been reported as raw values.

The problem with using reported values less than a given detection limit has been discussed by Egboka et al. (1983) who determined that values obtained by standard counting techniques that were recorded at less than 15 TU invariably contained less than 1 or 2 TU when analyzed by tritium enrichment. A similar result is anticipated with the Ross Creek Basin samples. RCB-22 and RCC-31 are both reported to contain slightly less than 20 TU which is under the detection limit, but greater than 1 TU, the assumed value of tritium "dead" water. Both samples have very low values of ^{14}C, 7 and 42 pmc respectively, indicating that they have been out of contact with the atmosphere for much longer than 35 years. Although enrichment would help to verify this hypothesis, it is evident that values of tritium less than 20 TU may be considered to be dead, while values between 20 and 30 TU should be examined carefully before a decision is made as to whether or not the sample contains a significant post-1952 component of tritium.

Three groundwater samples (RCA-6, RCB-3 and RCE-28) have tritium levels of between 20 and 30 TU (Table 4.2).

RCA-6 is from the Elkwater Town well, which when resampled had a value of 34 TU. It is assumed that RCA-6 represents a modern level of tritium of around 30 TU. In contrast, the value of 22 TU for the Brown estate spring (RCB-3) does not appear to be modern, as a value of 23 pmc for ^{14}C suggests that this water was recharged prior to the 1950's. Similarily, the Schneider spring (RCE-28) is a Group 2 water and is seen to represent recharge during an earlier climate and is probably dead.

The difficulty with eliminating all values below 20 TU is that no provision is made for mixing of post- and pre-1952 waters, as required by the modeling technique proposed in Section 3.3. This is unfortunate; a more accurate method of analysis would be advantageous for future tritium studies.

It was important that some quality control work be included with samples delivered to the laboratory. For this study, two replicate samples were taken at the Elkwater Town well on successive sampling trips. Seasonal variations might be expected to cause variations in the tritium content, but as fluctuations in the δ^{18}O content were not noted, it may be that tritium levels also remained constant in the well. The tritium levels detected for the two samples are similar: 25 TU(RCA-6) and 34 TU(RCE-36), indicating that the quality control test was positive.

Except for groundwater from the Eastend Springs (Fig. 4.12), tritium in Ross Creek groundwaters show few significant spatial trends. This line of springs originate at the contact between the Eastend and Bearpaw Formations and of the six springs sampled, five contain no appreciable levels of tritium. This is consistent with the concept that intermediate-level discharge occurs because low permeability in the underlying Bearpaw Formation causes horizontal groundwater flow in the Eastend Formation. The one sample that did contain post-1952 tritium levels (RCA-20) appears to derive a substantial amount of local recharge from the sides of the distinct coulee through which Ross Creek flows and in which the Neubauer spring is located.

In contrast, three of the four groundwaters collected from sites at the top of the Cypress Hills contain high (100-154 TU) levels of tritium, indicating water with an average age of 10-25 years (see Table 3.1). As the Cypress Hills Formation is very permeable and the hills are clearly a source of recharge, it is not at all surprising that shallow groundwater samples would contain post-1952 tritium. The fourth sample (RCE-8) was taken from a 70m deep well on top of the hill and contained no measurable tritium. Since the sample at 15m contained 100 TU (approximately 12-18 years average age: Table 3.1), this suggests that the vertical component of recharge has a rate that is at least 1m/year near the top of the profile, but is less than 2m/year further down in the section (0 TU, implying at least 35 years since recharge, at 70m). Groundwater movement through the Cypress Hills gravels will be discussed in more detail in Section 5.3.

The Krauss flowing well (RCA-23), which exhibits seasonal fluctuations in stable isotope values (Fig. 4.11), was observed to contain a significant level of tritium. This indicates that water is derived from a very shallow source and that the short transit time involved does not permit mixing in the subsurface.

Tritium results may also be utilized to eliminate four of the Ophori/Alberta Environment samples (RCE-25, RCE-26, RCE-31 and RCE-32) from further consideration in an analysis of isotopic values. While these samples contain post-1952 levels of tritium, two of the wells (RCE-31 and RCE-32) appear to be significantly evaporated (Table 4.1). Further, because the well which supplied sample RCA-32 is 237m deep and completed into the Oldman Formation (Table A.2.2), it is thought that sufficient vertical gradient and permeability do not exist at this site to result in downward movement at such a rate. Similar indicators eliminate the other three wells also. An analysis of sampling and completion techniques is required; it is likely that the purging of several well volumes of water prior to sampling would have maximized the reliability of the tritium results in these wells. It is also possible that the Ophori/Alberta Environment wells were poorly developed and that not all of the drilling fluids were removed from the immediate well bore vicinity.

4.3 Carbon-14 Results

20 groundwater samples were collected in Ross Creek Basin for ^{14}C analysis and are listed in Table 4.3. The sampling was difficult and only two of the original samples had complete sets of data describing chemistry, $\delta^{13}C$ and ^{14}C levels that would aid one in making reasonable hypotheses about the contribution of inorganic carbon to the system. In addition, fractionation of carbon due to the exsolution of CO_2 during collection may have affected several of the samples with reported low pmc values. Apparent discrepancies between tritium and ^{14}C levels were found to exist which caused several of the ^{14}C samples to be eliminated from consideration.

Nevertheless, projected Q values were utilized to calculate ^{14}C age. Groundwater ages are interpreted to fall within a large range: from 200 to 30000 years. Figure 4.13 shows a map view of the uncorrected ^{14}C values.

Most of the values appear to fit the concepts of flow visualized so far for the basin. Five of the six springs sampled at the Eastend/Bearpaw contact have ages between 6000 and 10000 years before present (ybp) which is consistent with an intermediate groundwater flow system. The sixth spring, RCA-20, is interpreted as modern although the expected level of ^{14}C is less than expected. Because the water contains high levels of tritium, it is thought that this sample should contain more than 100 pmc, but it has possibly become diluted.

SAMPLE	LOCATION	OWNER DESCRIPTION	TYPE OF WATER	% MODERN CARBON	Q FACTOR (ESTIMATED)	C14 AGE YBP (UNADJUSTED)	C14 AGE YBP (ADJUSTED)	ERROR (2 SIGMA)
RCA-1	13 11 8 3W4	CHPP-NICHOLLS	SPRING	69 ±20	0.70 ± .20	3069	200	3200
RCA-6	7 24 8 3W4	ELRWATER TOWN	WELL	80 ±20	0.95 ± .10	1845	1400	2200
RCA-13	1 22 9 3W4	B.WEISS-CORRAL	SPRING	20 ±20	0.60 ± .20	13370	10000	8700
RCA-20	9 19 9 2W4	D.NEUBAUER	SPRING	92 ±20	0.95 ± .10	690	300	2000
RCA-23	6 24 10 3W4	KRAUSS	F.WELL	98 ±20	1.00 ± .10	167	200	1900
RCA-45	1 5 12 3W4	R.PFAFF	SPRING	-- --	-- --	---	---	---
RCA-46	3 35 11 3W4	K.FRIEMARK	SPRING	43 ±20	0.85 ± .10	6980	5500	4000
RCA-47	3 13 8 3W4	CHPP-MITCHELL	SPRING	98 ±20	1.00 ± .10	167	200	1900
RCA-56	15 15 9 3W4	H.SEITZ	SPRING	-- --	-- --	---	---	---
RCB-1	2 24 9 4W4	K.SAILER	SPRING	27 ±20	0.75 ± .15	10828	8500	6300
RCB-3	11 30 8 3W4	BROWN EST.-H	SPRING	23 ±20	0.75 ± .15	12154	10000	7400
RCB-22	4 27 8 3W4	RUSSIL	SPRING	7 ±20	0.75 ± .20	21992	20000	13300
RCB-41	14 24 12 5W4	HOFFMAN	F.WELL	2 ±20	0.60 ± .20	32352	30000	13300
RCC-26	10 16 8 3W4	KAJEWSKY	SPRING	61 ±20	0.65 ± .20	4088	500	3700
RCC-31	1 4 9 2W4	ROAD ALLOWANCE	F.WELL	42 ±20	0.90 ± .10	7174	6500	4000
RCD-15	5 18 9 2W4	J.MACK	SPRING	42 ±20	0.90 ± .10	7174	6000	4100
RCE-15	8 15 12 4W4	B.SCHNEIDER	SPRING	43 ±20	0.85 ± .10	6980	5500	4000
RCE-27	13 35 10 4W4	C.ZEIGLER	WELL	66 ±20	0.70 ± .20	3436	500	3400
RCE-28	7 20 11 4W4	C.SCHMIDEK	SPRING	-- --	-- --	---	---	---
RCE-33	12 25 10 4W4	D.MEIER	WELL	23 ±20	0.70 ± .20	12154	9000	7600

Table 4.3. Results of Carbon-14 analyses. Unadjusted age values do not take Q into account. Adjusted age values take Q into account (see text).

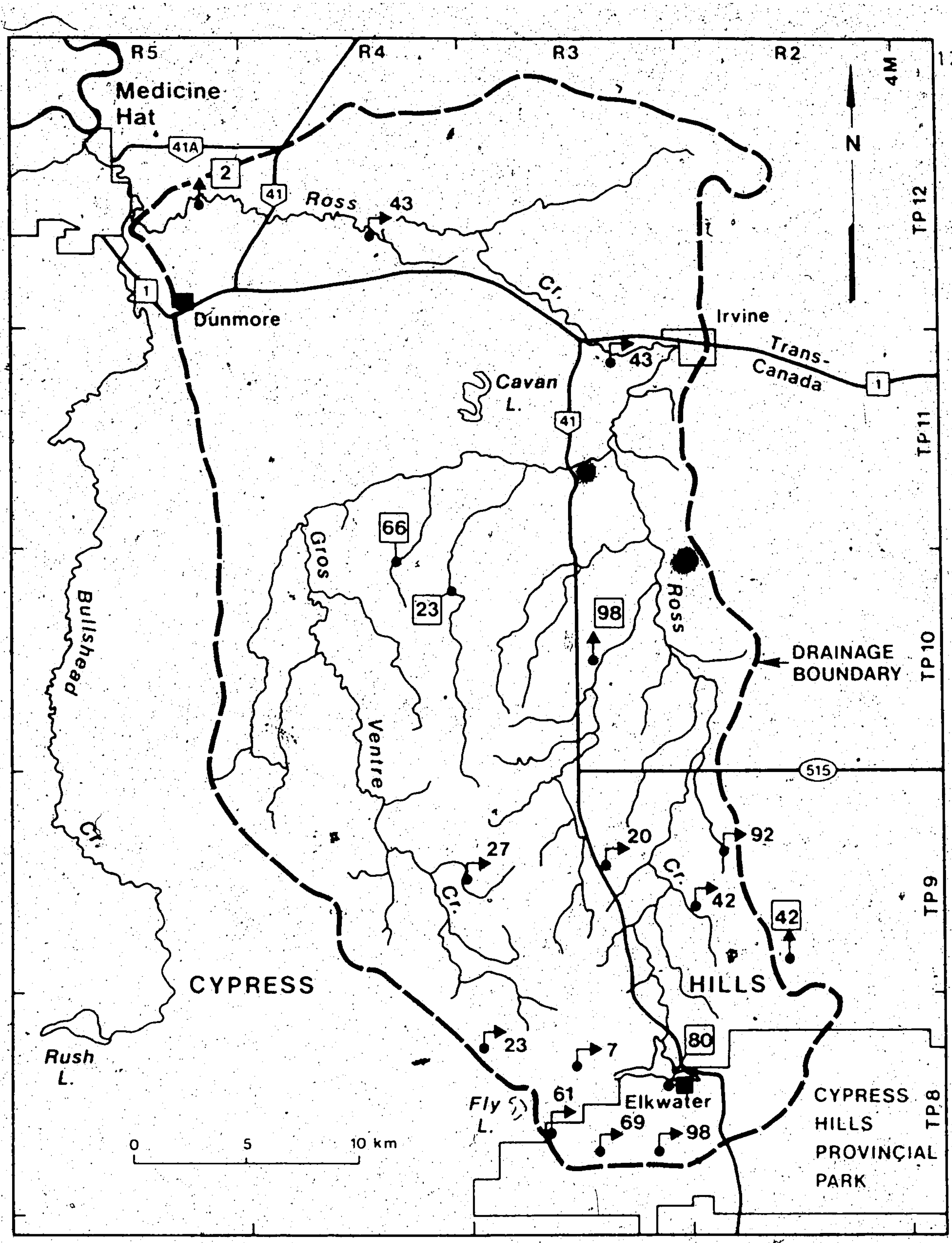


Figure 4.13. Geographic distribution of Carbon-14 values.

Most of the points sampled near the Cypress Hills yield ^{14}C ages of less than 3000 years; consistent with a model of local flow systems in this region. Groundwater in the immediate Cypress Hills area appears to have a short transit time after recharge.

Water from the Meier well (RCE-33), in the middle of Ross Creek Basin, and from the Hoffman flowing well (RCB-41) in the extreme northwestern corner of the area, contain extremely low levels of ^{14}C. The ages are interpreted as being 9000 ybp and 30000 ybp respectively. However, RCB-41 appears to have undergone fractionation and it is thought that this may have occurred during sampling. The NaOH solution was not added to the containers before they were filled and the sample took a long time to fill, as the well outflow has an exceedingly low flow rate. Agitation of the water by the sampling process and the fact that the bottles were left open to the atmosphere for 10 - 20 minutes during collection could have resulted in the exsolution of a significant amount of bicarbonate as CO_2. This is borne out by the unusually high $\delta^{13}C$ value for RCB-41 (-5.9 $^{o}/_{oo}$) which suggests a fractionation of at least 7 to 9 $^{o}/_{oo}$ when compared to RCA-47 (-15.2 $^{o}/_{oo}$; Table 3.2). RCA-47 was taken directly from a reservoir that has been built around the spring, and little agitation of the sample occurred.

Nevertheless, RCB-41 probably represents a water that has been recharged at considerable distance. Discharging of regional or intermediate flow systems around Dunmore cause the water of that vicinity to contain low values of modern carbonate. The Meier well (RCE-33) also appears to derive its recharge at considerable distance.

Another sample that has a suspiciously low value of ^{14}C is RCB-22. While this spring did not contain an appreciable level of tritium (Table 4.2), the reported value of 7 pmc would place the transit time of the groundwater at 20000 years. The Russill spring is a very low-yielding spring (approximately 0.02L/s) on the side of a large hummock which is located immediately north of the Cypress Hills Plateau. Discharge of a regional groundwater flow system at this point would be highly unlikely because of its proximity to the Hills. Westgate (1968) mentions that several high angle normal faults in the bedrock may be present on this side of Ross Creek Basin and this could provide a means for hydraulic connection with more deeply seated flow systems. However, it is thought that faults do not cause this low value of ^{14}C and that exsolution of CO_2 during the sample collection is a more likely explanation.

Values of 43 pmc at the Friemark (RCA-46) and Schneider (RCE-15) springs also reflect unusually low amounts of ^{14}C in view of the fact that both contain bomb tritium and that both springs are localized discharge features. Sampling techniques are a likely culprit in causing exsolution of CO_2 during collection of these samples.

4.4 Hydrochemistry

The results of groundwater quality analyses from the Ross Creek Basin are given in Appendix III (Tables A.3.1 and A.3.2). These data have been taken from Ophori and Tóth (1983, 1985) and the records of the Groundwater Information Centre. Appendix III also contains the results of several hydrochemical facies analyses (Table A.3.3). Ophori and Toth (1983) performed chemical balances on the data published in their report, but besides this, no attempt has been made to assess the accuracy of these data, and they are included solely for the purpose of completeness.

5. DISCUSSION OF RESULTS

5.1 Introduction

From the results presented in Section 4 it is apparent that data collected in Ross Creek Basin reflect very complex processes of mixing, evaporation and chemical reactions. No simple patterns, such as those noted by Schwartz and others in the Milk River Aquifer or by Fritz et al. (1978) in the Carbonate aquifer of Winnipeg are found in Ross Creek Basin. The complexity is partially a function of the basinal stratigraphy; few discrete aquifers exist in the region and even these are so small that they have very mixed sources of recharge. Applying an integrated approach to this area becomes a necessity as no simple model can explain the hydrochemical and hydrodynamic patterns observed.

Despite these complexities, the isotope data are worthwhile and help to evaluate the patterns of groundwater flow in the basin. Conceptually, isotope-based interpretations of groundwater flow conditions may be represented by Figure 5.1. All of the isotopes may be utilized to distinguish the mechanisms, the location and the conditions of groundwater recharge. Stable isotopic arguments may be based on altitude, evaporative and paleoclimatic principles. These data may help to pinpoint sources of groundwater recharge. Similarly, stable isotopes can be used to distinguish between flow systems. This type of delineation may be applied over the entire spectrum of

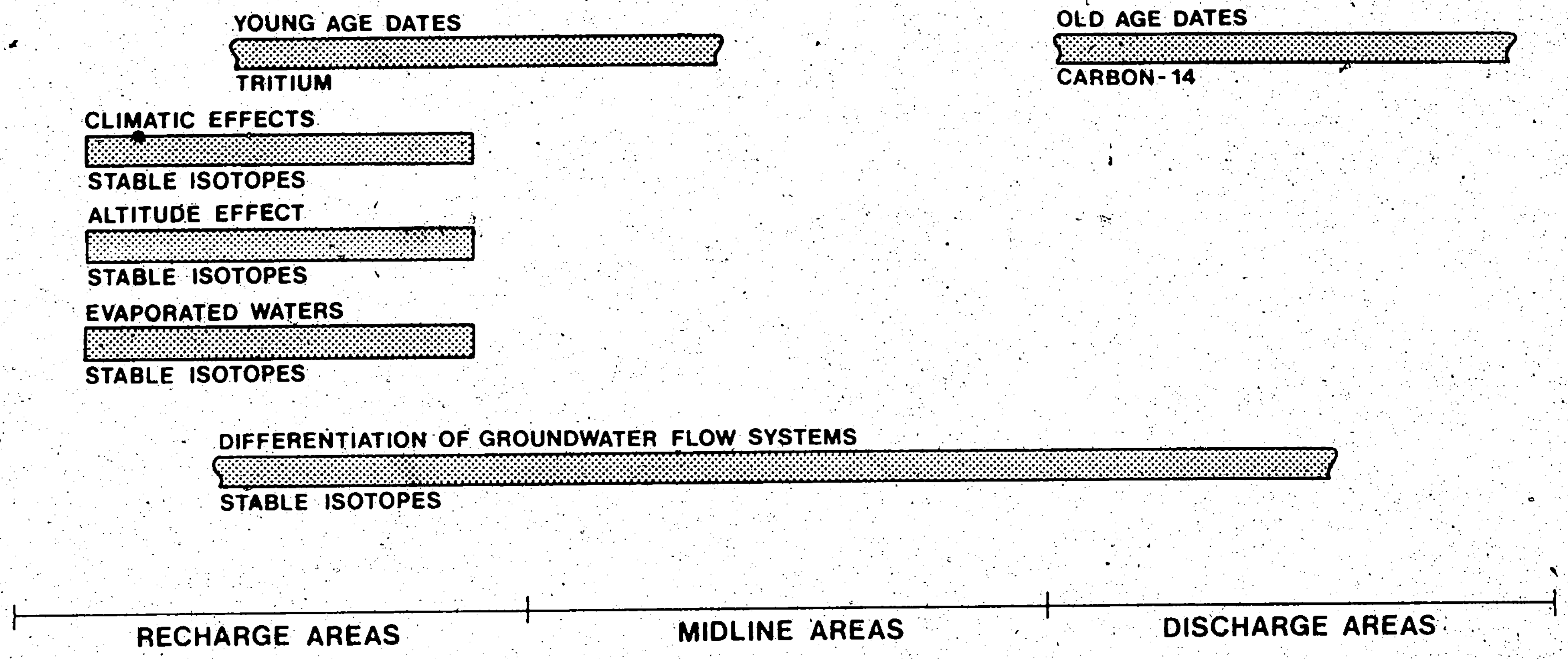


Figure 5.1. Schematic approach to isotopic tracer use in Ross Creek Basin.

groundwater flow conditions from recharge to discharge areas (Fig. 5.1).

Ideally, groundwater age dating may be applied in both recharge and discharge areas. "Young" isotopic dates imply areas of recharge; the velocity and gradient of recharge may be implied from radioisotopic measurements such as tritium. "Old" age dates can imply discharging conditions.

Not all age dating mechanisms are necessarily valid over the time range that one finds in a large, shallow basin such as Ross Creek, and therefore one must utilize different age dating tools. Information from isotopic age dating may be integrated with other knowledge of flow conditions in the area to arrive at conclusions based on the recharge/discharge relationships of Figure 5.1. In Ross Creek, several different methods of delineating groundwater ages were used and are shown on Figure 5.2 to indicate the time scale over which they are valid. Tritium and ^{14}C dates, information from stable isotopes such as paleoclimatic indicators, evaporation and fluctuating values of $\delta^{18}O$ and δD may all be used as indicators of the timing of groundwater recharge to a flow system. In addition, the delineation of flow systems that have been recharged within the past 80 years is possible by pointing out which waters contain appreciable levels of nitrate and nitrogen.

In subsequent sections each of the methods utilized to imply both groundwater flow conditions (Fig 5.1) and age (Fig 5.2) in Ross Creek Basin will be examined. The

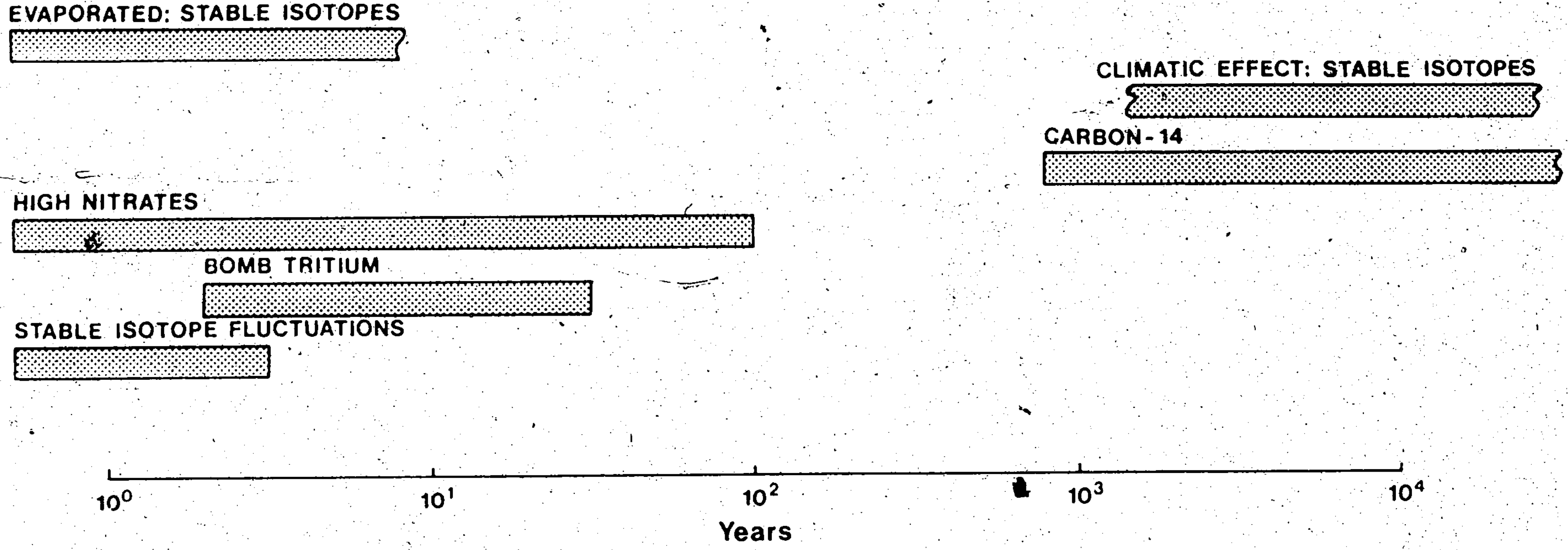


Figure 5.2. Schematic approach to isotopic age dating in Ross Creek Basin.

integrated methods used to establish a model for the basin will also be discussed.

5.2 Isotopic Tracers in Ross Creek Basin

5.2.1 Distinguishing groundwater flow systems

The most practical feature of stable isotope analyses in Ross Creek Basin has been their ability to distinguish between types of water. While this approach does not necessarily yield any information about groundwater provenance, it does allow one to delineate different types of water.

In this evaluation of the Ross Creek Bas[illegible]s have been used to: 1) isolate distinctive groundwater groupings, several of which have been interpreted as reflecting recharge conditions; and 2) confirm or reject isotopic age results. The groundwater groupings (Figures 4.9 and 4.10), help to conceptually delineate groundwater flow patterns in Ross Creek Basin, some of which are important geographically. For example, there is a distinctly ^{18}O depleted groundwater in the vicinity of Dunmore. This is demonstrated by the many occurrences of Group 1 and 2 water in that area (Fig. 4.9). In addition, much Group 2 water may be found along the western edge of Ross Creek Basin, while a small zone of Groups 1 and 2 water may be found directly in the center of the region. It is thought that net permeability contrasts in the Cretaceous bedrock between the east and west sides of the basin may lead to an older and isotopically more depleted water discharging around Dunmore. This distinctive water may be evidence for a regional groundwater flow system that is discharging in the Dunmore area. The water present in groundwater flow systems on the opposite side of the basin, around Irvine, is either diluted by local flow systems or continues out of the basin where it is discharged into the South Saskatchewan River north of Township 13.

Similarily, the discharge of isotopically depleted water in the center of the basin near the high TDS area (Figs. 3.9 and 4.9) might be due to the presence of hydraulic permeability contrasts in the bedrock, with the discharge deriving from a large scale intermediate or regional groundwater flow system. Northward trending flow might be deflected to the surface in this area because of an underlying high permeability zone such as a lens in the Bearpaw shale or underlying Oldman Formation.

The presence of other isotopically distinctive groundwaters may be due to varying recharge conditions. As shown in Figure 4.10, little geographical control on the distribution of Groups 4 to 7 waters may be seen and thus the differences that are evident reflect processes that are spatially uniform around the basin. Group 5 represent the average isotopic values of waters currently being recharged in Ross Creek Basin. For the Groups 6 and 7 waters, the distinctive values of $\delta^{18}O$ and δD are thought to have resulted from evaporation. The evaporation of recharge waters will be discussed more completely in Section 5.2.3. These distinctions are isotopically easy to make, and useful for delineating types of recharge in Ross Creek Basin.

The stable isotopes are also helpful in verifying groundwater age dating results. A comparison of isotope data from RCA-1 (Nicholls spring) and RCA-47 (Mitchell spring) demonstrate this type of application. The two springs are very similar; they both occur stratigraphically near the Cypress Hills/ Ravenscrag formational contact; they have similar groundwater chemistries (Appendix III); the springs have similar tritium contents (Table 4.2) and they have virtually the same levels of stable isotopes (Table 4.1). Therefore when laboratory results showed that RCA-1 had 69 pmc, while RCA-47 contained 98 pmc, the occurrence of fractionation of RCA-1 during the ^{14}C sample collection was indicated. While the water quality and tritium results suggested that the waters are similar, the δ^{18}O and δD provided the conclusive evidence for poor ^{14}C sampling techniques.

As demonstrated in Ross Creek, the stable isotopes provide an elegant means for comparison of waters. Distinction of water types however, does not suggest a point of origin. This will be discussed in subsequent sections.

5.2.2 Meteoric waters in Ross Creek Basin

The definition of both average meteoric water, as well as the yearly variation in $\delta^{18}O$ and δD, is of paramount importance to a study which uses isotopes to determine origin of groundwaters. The average meteoric water may be determined by long term sampling and analysis, estimation from temperature/isotope relationships, or by extrapolation from nearby results. A meteoric water line may be defined in similar ways, except that the yearly variations in the isotopic content of precipitation may be utilized to perform a regression for a region.

The expediency of defining a meteoric water line by taking samples over a short period can been seen in Figure 4.5. Although several of the evaporated rain samples are located to the right of the meteoric line, the fact that such a wide range of isotopic values are found in precipitation from Ross Creek means that a statistically significant line (r^2=.99741) may be drawn. From the results shown in Figure 4.5, it may be suggested that many years of precipitation collection and analysis would not significantly alter the equation for this line.

The slope of the meteoric water line found in Ross Creek Basin is less than that given by Craig (1961) for worldwide precipitation, but several other authors have also reported meteoric slopes less than 8. These include Bradbury (1984-Wisconsin);

$$\delta D = 7.94\delta^{18}O + 0.46$$

Desauliers et al. (1981-Ontario):

$$\delta D = 7.5\delta^{18}O + 12.6$$

Fritz et al. (1978-Chile):

$$\delta D = 7.8\delta^{18}O + 9.5$$

and Bath et al. (1978-England):

$$\delta D = 6.6\delta^{18}O + 1$$

Hage et al. (1975) noted that slopes of less than 8 invariably occurred at eight North American stations on the IAEA:WMO network if regression lines for the precipitation over the course of the year are calculated. Dansgaard (1964) noted a wide variation in the slopes of meteoric water lines at individual stations. This is not surprising, considering that the Craig (1961) line is a spatial (worldwide) effect, while annual variations at a single location are necessarily temporal. Annual slopes of less than 8 are attributed to the derivation of warm season precipitation from re-evaporated water temperature precipitation, on the other hand, more closely approximates the processes of condensation from ocean vapor (Hage et al. 1975). Why the meteoric line of a coastal station (Bath et al. 1978) should have a slope of 6.6 is not explained by the model of Hage et al. (1975), but this explanation would appear to fit very nicely conditions on the Alberta prairies. Certainly the derivation of moisture in summer air masses from re-evaporation could have resulted in a meteoric water line of less than 8 for Ross Creek Basin.

In addition to the delineation of a meteoric water line, an average meteoric water for the region must be calculated. Since little annual fluctuation of δD and $\delta^{18}O$ of groundwaters in Ross Creek Basin is noted (Fig 4.11), isotope ratios in groundwater are not expected to reflect the wide range of summer and winter precipitation values and thus must have an intermediate recharge. This is harder to measure than the annual meteoric water line, for as shown in Figure 4.7, a wide range in groundwater samples is seen. Therefore a variety of methods were utilized to estimate this value:

1. The average value of annual meteoric water could be calculated by determining the intercept of the meteoric and evaporated water lines. This would account for differences in annual precipitation amounts, as all that was available for evaporation was being enriched along the evaporation line. According to this method, the intercept of the lines is at $\delta^{18}O = -21.0°/_{oo}$ and $\delta D = -159°/_{oo}$,

2. Similarly, the interception of the two composite lines might approximate average groundwater as samples from the subsurface are included in the calculation of the regression lines. The average meteoric water line calculated by this method is very similar: $\delta^{18}O$ = -21.0°/₀₀ and δD = -164°/₀₀.

3. The averaging of 11 non-evaporated samples containing bomb tritium yields $\delta^{18}O$ values that are higher than is predicted by (1) and (2) above. By assuming that post-1952 tritium levels are indicative of recharge within a time span of similar climatic conditions, a more direct measurement of groundwater recharge can be made. The results calculated using this method are: $\delta^{18}O$ = -18.8°/₀₀; δD=-148°/₀₀.

4. The temperature vs $\delta^{18}O$ relationship of Dansgaard (1964) may be applied:

$$\delta^{18}O = 0.695\, t_a - 13.6°/_{oo} \qquad (5.1)$$

where ta is the mean annual temperature. A ten year average temperature of 5.1°C for Medicine Hat may be calculated from climatic records (Ophori and Tóth 1983); thus an isotopic mean of -10.1°/₀₀ is predicted. While Equation 5.1 was determined for coastal stations and inland northern Canadian points have been noted to seriously affect its accuracy, nevertheless at 5.1°C, this relationship is thought to be representative. Using the methods of Cerling (1984), an average $\delta^{18}O$ content of approximately -10.8°/oo is predicted.

As seen above, noted values of average meteoric waters ($\delta^{18}O$ = -18.8 to -21.0°/oo; δD = -148 to -164°/oo) in Ross Creek Basin differ considerably from those predicted from mean temperature/ isotope relationships ($\delta^{18}O$ = -10.1 to -10.8°/oo). In comparison, the average meteoric water values listed for Edmonton are $\delta^{18}O$ = -17.9°/oo and δD = -137.3°/oo (Hage et al. 1975). Schwartz and Muehlenbachs (1979) noted that meteoric water in groundwaters from shallow units overlying the Milk River aquifer was $\delta^{18}O$ = -19.7°/oo; δD = -159°/oo.

Thus the average values of recharge to southern Alberta groundwater systems appear to be isotopically depleted (i.e. represent "colder" water) than the local recharge and are even poorer in the heavy isotopes than precipitation at a station several hundred kilometers further to the north. This suggests that recharge in the region depends more heavily on the contribution from winter precipitation and spring recharge than from summer rainfall. This is not surprising because the snowmelt event is generally a time when considerable amounts of moisture are available for infiltration. High evapotranspirative potential means that little of the moisture generated during the summer months actually reaches the water table.

Attempts to distinguish an altitude effect in meteoric groundwater proved unsuccessful in Ross Creek Basin (Fig. 4.4). It is assumed that the effects of mixing and evaporation mask any altitude effect that may be present.

Waters reflecting recharge under climatic conditions colder than those found today are represented by the Group 1, and to some extent, Group 2 waters (Fig. 4.10). If Equation 5.1 is used to calculate the "apparent annual temperature"; the temperature that corresponds to the observed average meteoric water conditions; a ta = -7.5°C is concluded. The average ^{18}O content of the five Group 1 waters; $\delta^{18}O = -22.4^{\circ}/_{oo}$, results in the calculation of -12.7°C as the average apparent annual temperature of recharge for these groundwaters. Thus there may have been an actual climatic decrease of 5 degrees between current recharge conditions and those reflected in the Group 1 waters. If one uses the method of Cerling (1984) to judge the temperature change that is represented by a $3.6^{\circ}/_{oo}$ depletion in $\delta^{18}O$, the climatic shift is closer to 3-4°C. It is also possible that the climate did not change since the Group 1 waters were recharged, but that the infiltration of meltwater from the retreat of glacial icesheets contributed to the usually low values of stable isotopes in groundwater.

5.2.3 Isotopically enriched groundwaters in Ross Creek Basin

Finding levels of $\delta^{18}O$ and δD indicative of evaporation in Ross Creek Basin was unexpected (Fig 4.7). There exists little evidence for enriched groundwaters in the literature although close examination of the data of Hendry (1986) and Wallick (1984) shows the presence of these waters elsewhere in southern Alberta. High values of $\delta^{18}O$ in deer bone phosphates from southern Alberta have also been noted by A. Cormie (pers. comm.) and it is anticipated that more evidence of an evaporated signature on prairie groundwaters will be found in the future by various workers utilizing stable isotopes.

The question of how groundwater becomes evaporated must be addressed. Several possibilities may be considered:

1. It could be due to evaporating precipitation;
2. Water could be evaporated through the ground;
3. A survey bias due to sampling, storage or analysis techniques may exist;
4. Water could be lost from recharge to the groundwater system.

These possibilities will be addressed in order.

Evaporated rainfall has been noted in other parts of the world by Ehhalt et al. (1963) and Vogel et al. (1963). A light rainfall in Ross Creek Basin in May, 1984 was noted to contain isotopically enriched values of precipitation (Fig 4.5). Winter precipitation did not contain enriched levels of stable isotopes. The average values of Ross Creek Basin groundwaters are substantially depleted in the heavy isotopes relative to summer precipitation as has been discussed previously. If recharge of evaporated summer precipitation caused the isotopic enrichment of groundwaters, both the average value of recent groundwaters and the intercept of the meteoric and evaporated water lines should be closer to the values of summer rains than they are. In addition, most summer precipitation is lost as evapo-transpiration and therefore does not enter the groundwater flow system (Ophori and Tóth 1983). Isotopically enriched rainfall is not believed to cause the evaporative shifts observed.

Evaporation through the ground surface in Ross Creek Basin is a possibility for causing isotopically enriched groundwaters. Dincer et al. (1974a) described evaporation occurring through sand dunes in the Sahara Desert. While it is possible that evaporation through Alberta soils does occur, it seems unlikely that this process would result in enrichment in any but the very top layers of soil.

A third source of enriched groundwater samples may be through the mechanism of inadequate survey, storage and/or laboratory procedures. The latter two possibilities were minimized by the use of high quality containers and by quality control procedures. (see Section 3.4 and Freeman 1985). This does not eliminate the possibility that the groundwater samples collected came from poorly sealed wells that were not adequately purged before sampling. Several well volumes were not removed prior to collection thus there is no guarantee that the sampled water came directly from the aquifer. Inspection of the field notes for some of the original groundwaters separated out in Group 7 during cluster analysis revealed some questionable sampling points, such as abandoned wells or undeveloped springs and seeps where ponded water could have contaminated the sample. These points were subsequently eliminated from further study as "groundwater".

While it is still possible that the present study results were caused by faulty sampling techniques, there is no denying that a strong evaporative trend exists. As an example, RCA-23 is a flowing well where a good sample was collected, yet this groundwater is enriched in $\delta^{18}O$ by at least 5°/oo. The evaporative trend appears to be real.

A fourth mechanism for causing the groundwaters to be isotopically enriched is through the evaporation of recharge water. In this area groundwater recharge can often occur when water is ponded on the soil surface after snowmelt or heavy rains. At this time it can undergo simultaneous infiltration into the vadose zone and evaporation. This is shown diagrammatically on Figure 5.3.

The idea that groundwater recharge on the prairies occurs through the many sloughs and potholes in this region is not new (Meyboom 1966; Tóth 1966; Eisenlohr et al. 1972 and Lissey 1968). Lissey (1968) dubbed the infiltration that reached the water table in this manner "Depression-focused"

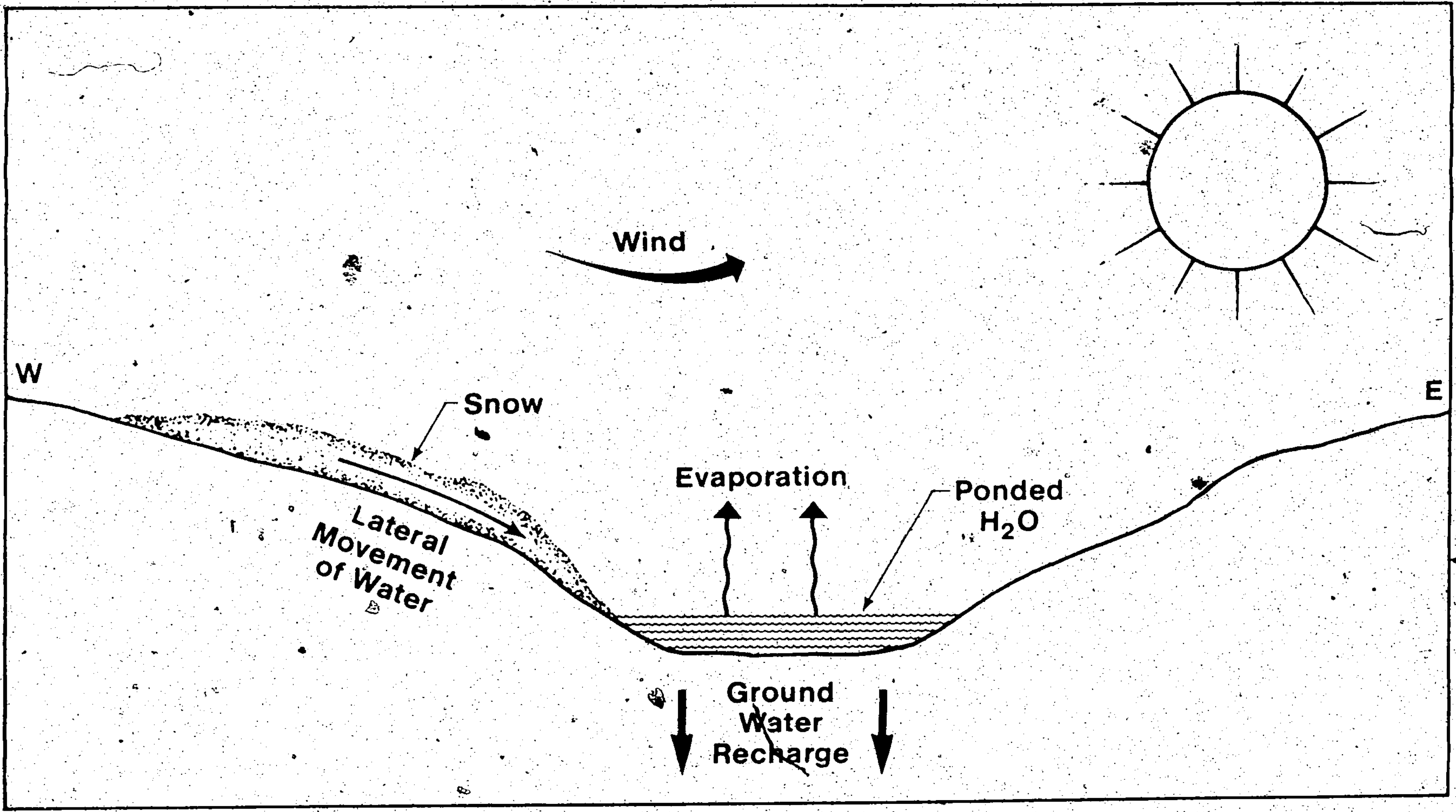


Figure 5.3. Simultaneous recharge and evaporation on the prairies. Snow is blown into depressions, where the snowmelt collects and evaporates during recharge.

recharge; a phenomenon that has been documented by electrical resistance techniques on the Suffield Weapons Range north of Ross Creek by Schwartz (1975, 1977). Schwartz observed that even in an area with few big potholes, snowmelt recharge was concentrated in small shallow depressions in upland regions. It is postulated that much of the simultaneous recharge and evaporation takes place from these depressions. The amount of snowmelt in some of the larger depressions may be enhanced by the redistribution of snowfall by chinook winds. This phenomenon, combined with the low relative humidity can cause evaporation potential to be high even in the early spring months of March, April and May. Simultaneous recharge and evaporation of ponded surface waters, particularily snowmelt, is an attractive mechanism for explaining isotopically enriched values of groundwaters.

5.2.4 Snowmelt in Ross Creek Basin

The RCE sampling trip was undertaken to examine the mechanism of recharge and possible evaporation occurring from snowmelt puddles in topographically low areas. The trip was carried out approximately one week after a major spring snowstorm struck southern Alberta in March of 1985. It was hoped that ponding would be observed and that samples of the water could be collected that demonstrated evaporation.

The trip was successful in that many samples of snow and adjacent snowmelt puddles were collected and extensive ponding was observed. In some places along the Trans-Canada

Highway, the water was up to the top wire on the fences. Ponding on the scale described by Schwartz (1975, 1977) was also observed: not only were the sloughs that are on the order of tens of meters across filled, but depressions only a few meters across had accumulations of snow and snowmelt. However, it was not clear whether or not evaporation was occurring, as temperatures were low, the sky did not clear until the middle of the second day and the winds were not blowing.

The laboratory results showed that the snow that was collected plotted on the meteoric water line and though the snowmelt had become isotopically enriched, it did not deviate from the trend. In no case was non-equilibrium evaporation noted in snowmelt that was adjacent to a melting snowbank. Possible reasons for this are: 1) either the conceptual model of simultaneous recharge and evaporation is not valid; 2) the phenomenon had not begun to occur; or 3) the snowmelt event sampled was not typical of the "average" represented in the groundwater. It is assumed that either or both of the latter two possibilities was encountered.

A substantial shift in isotope values between snow and snowmelt was noted during the RCE field trip but these shifts occurred parallel to the meteoric water line, as opposed to the expected enrichment, which would have resulted in snowmelt points plotting to the right of the meteoric water line. Figure 5.4 demonstrates that the values of ponded snowmelt (circles) are enriched in comparison to

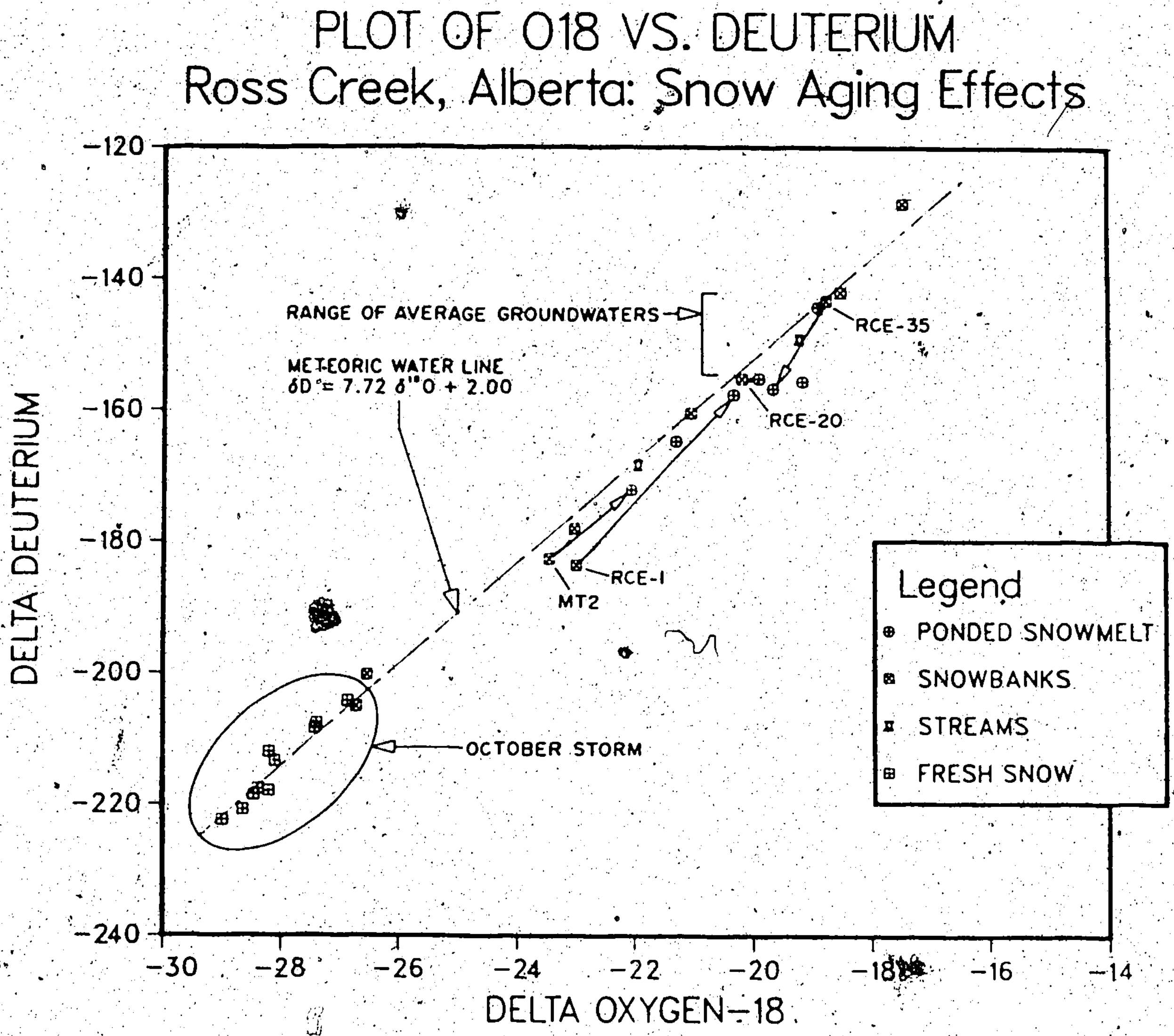


Figure 5.4. Isotope aging effects in snow. Old snow is enriched compared to the major snowfall of the winter (circled). Snow in snowbanks (labeled) appears to evolve to the values of ponded snowmelt along the lines shown.

adjacent snowbanks (squares). These snow drifts in turn are enriched in δD and $\delta^{18}O$ relative to the October snow storm (circled). This phenomenon is a typical aging process and is thought to occur due to homogenization by snowmelt infiltration (Judy et al. 1970); redistribution of snow (Moser and Stichler 1970); and through equilibrium exchange between both a solid-liquid and solid-vapor phase (Arnason 1970).

Isotope exchange during snow aging causes firn to be enriched with respect to fresh precipitation. The enriched snow undergoes a rapid kinetic liquid-vapor exchange as it melts and is collected in shallow depressions, where it undergoes simultaneous recharge and non-equilibrium evaporation. The result is an evaporated signature on the groundwater.

The implications of evaporation of snowmelt for groundwater management in Ross Creek Basin are not clear at this point. Further work is needed to quantify recharge, evaporation and soil moisture in the region over the long term. The fact that a significant portion of recharge in Ross Creek derives from infiltration of snowmelt agrees qualitatively with the results of Sophocleous and Perry (1985) in Kansas, as well as the soil moisture budgets given by Ophori and Tóth (1983) and Ophori (1986). However, neither of these models takes into account evaporation of recharge waters; in particular Ophori and Tóth (1983) used monthly averaged precipitation in their model, implicitly assuming a simultaneous recharge to either the soil/groundwater system or evapotranspiration. Recharge appears to derive from an accumulation of snow from several winter months and if additional evaporation occurs during the early spring, the amount of potential recharge that actually reaches the water table may be reduced, possibly resulting in isotopically enriched groundwaters.

5.3 Groundwater Age Dating

Figure 5.2 diagrams the age dating tools that have been applied in delineating groundwater flow systems in the Ross Creek Basin. The time span over which each method utilized is valid is also shown. While none of the techniques employed in the current study can be expected to yield strictly quantitative information, they may be divided into qualitative, semi-quantitative and quantitative techniques. Methods such as the use of hydrochemical facies relationships may be considered as qualitative, while the modeling of radioisotope values may be considered to approximate quantitative techniques. Because of the special interpretation applied to all three levels of age dating information, they will be discussed separately in subsequent sections.

5.3.1 Qualitative dating methods

Hydrochemical facies merely imply age relationships in groundwater systems in that it is possible to distinguish between discharge and recharge areas. Generally, the concentrations of ions increase along the direction of flow, however in some cases, even these results are obscured. Schwartz (1974) found that concentrations of most dissolved constituents decreased in the direction of groundwater flow in a region of southern Ontario. As suggested by Schwartz (pers. comm.) the ability of groundwater to dissolve the porous medium; the degree of chemical "aggressiveness" inherent in water is fixed at the time of recharge. In a basin like Ross Creek, where recharge conditions have undoubtably changed markedly over the time span of ^{14}C ages found, mixed hydrochemical relationships may be expected.

Nevertheless, reasonable results can be obtained by the mapping of hydrochemical facies (Fig. 3.9) and dissolved solids (Fig. 3.10). These methods help to set the stage for an interpretation of groundwater flow, and in the process, imply where the youngest and oldest waters should be sought. In the Cypress Hills, hydrochemical facies indicate that recharge occurs along the Plateau, in the dissected areas north of Elkwater and in other topographically high places; while discharge occurs along the major water courses in the basin.

The use of paleoclimatic indicators is qualitative in this type of setting. If recharge conditions different from those found currently exist in part of the basin (Section 5.2.2), the obvious explanation is a paleoclimatic change. This is difficult to infer in the current study as few of the ^{14}C dates are reliable. Only the modern average groundwater values ($\delta^{18}O$ = -18.80°/oo); two values around 6000 years (RCE-31 and RCD-15; $\delta^{18}O$ = -18.78°/oo and -18.15°/oo respectively); and one 9000 year old value (RCE-33; $\delta^{18}O$ = -22.04°/oo) are thought to accurately indicate different recharge eras. While the change in $\delta^{18}O$ values from modern values to 6000 ybp is barely greater than one standard deviation of the average modern value, the $\delta^{18}O$ shift from modern (and 6000 years) to 9000 years is substantial.

However, while the depleted groundwaters are probably old, just when this water was recharged probably cannot be ascertained from a single ^{14}C measurement. A colder water recharging 9000 years ago would not agree with the thinking of Hendry et al. (1986) who place the Altithermal Period, a warmer and drier period, at 3000-11,000 ybp. Since three of the drift sheets found in the area were deposited between 10,000 and 15,000 ybp (Westgate 1968), it is possible that the $\delta^{18}O$ and δD depleted waters may be associated with deglaciation in southern Alberta. This may have taken place around 9000 ybp in Ross Creek Basin. Clearly, further data are needed in order to render the paleoclimatic information yielded by the stable isotope values of any more than qualitative use in the Ross Creek Basin.

5.3.2 Semi-quantitative age dating

Fluctuations in the stable isotope content of groundwaters have been interpreted as indicative of incompletely dispersed and thus extremely young waters. The four groundwater sources that demonstrate seasonal variations in isotopic inputs are shown in Figure 4.11. That the waters are young is supported by post bomb tritium levels in the Krauss flowing well.

In addition, the hydrogeological setting of the CHPP seepage also suggests that the variations in isotope levels are due to fluctuating content of stable isotopes in recharge that occurs over the course of a year. This seep feeds a small dugout on top of the Cypress Hills Plateau at approximately 4710 feet (1435m). Indicative of the extremely high water table found in the Hills, the seep can only derive input in the very immediate area and it is clear that the water emerging from the seep must have recharged only a short time before.

Tritium data are useful when applied in a semi-quantitative manner because post-1952 recharge can be delineated. Exceptions to this occur: 1) when the tritium value is more than 2 TU, but less than 30 TU. Such a case would result from mixing between pre-bomb and recent waters; and, 2) when values of less than 30 TU have been considered to contain no tritium due to the detection limits of the laboratory (Table 3.4), even though tritium levels in post-1980 recharge may be expected to fall into this range.

When viewed spatially the tritium distribution was not significant (Fig. 4.12), but it did demonstrate that shallow local groundwater systems occur throughout Ross Creek Basin. Recharging conditions were indicated by tritium levels in the Cypress Hills wells: the deep Ophori/Alberta Environment well (70m) had no tritium, while the 15m well in the same group indicated recharge that was an average of 15-20 years old. Seasonal variations in the stable isotope content of the Krauss flowing well confirmed recent recharge.

With tritium data it was also possible to determine that the discharge along Ross Creek in Township 12 at the Ophori/Alberta Environment wells have both a shallow, local flow component and a deeper, older aspect of groundwater. The intermediate (36m) and deep (74m) wells at the site contained no detectable tritium, while a sample taken from the buried channel well (15m deep) contained 103 TU. This latter level is interpreted to represent water with an average age of 15 to 25 years.

The Township 12 site was not modeled using the methods outlined in Section 3.3, but it is thought that the volumes of water moving through the Oldman and Foremost Formations are sufficiently low so that little dilution or leakage into the buried channel aquifer occurs. The channel aquifer probably exhibits strong horizontal movement, as slightly older water is noted at the Schneider spring only a few hundred meters north of the well site (124 TU). Pumping of the shallow Ophori/Alberta Environment well indicated a constant head boundary at distance, which results from hydraulic connection with Ross Creek (Ophori and Tóth 1985). The Schneider spring is located at Ross Creek.

The difference between shallow, local groundwater flow systems and more deeply occurring flow patterns can be revealed by examination of both tritium and stable isotope data, and semi-quantitative deduction. The Pfaff spring (RCA-45) and the Friemark spring (RCA-46) are approximately 3 km apart and at first glance it was thought that the two were under similar flow regimes as both occur on the sharp enbankment on the south side of the Trans-Canada Highway in the Ross Creek Valley. However, the two springs exhibit drastically different levels of stable isotopes: RCA-45 is a Group 2 water (Fig 4.9); while RCA-46 is a Group 5 water. Negligible tritium levels occur in RCA-45 (17 TU), contrasting with post-1952 values in RCA-46 (67 TU) suggesting that different flow conditions are present. It is thought the RCA-45 has a deeper source, perhaps from an intermediate or regional level, while much of the water coming into the Friemark Spring is of shallow, local origin. These effects are also supported by the stable isotope groupings (Section 5.2).

Nitrate-nitrogen levels from water quality analyses can be used for semi-quantitative age dating purposes, but the method has serious limitations. As noted by Freeze and Cherry (1979), Grisak (1975) and Kaplan and Magaritz (1986), high nitrate-nitrogen levels in groundwater are almost always associated with anthropomorphic activities, although the exact nature of higher-than-background levels may be attributable to either fertilizer use, contamination from manure, or the cultivation of native grasslands. High nitrate-nitrogen levels in Ross Creek Basin groundwaters then might be a product of recharge that has occurred after 1900-1920, when the region was first settled. Background levels for the area are approximately less than 1 ppm (Appendix III; Table A3.2). One must be careful however, when drawing conclusions about groundwater based on nitrate-nitrogen levels because wooden cribbing in old wells appears to be a suspect in allowing contamination of the well water from surface sources. Without representative sampling of pure aquifer water, it is difficult to assess the degree of contamination imparted to the well water through the cribbing.

Two sampling points that contain post-bomb tritium, RCA-20 and RCA-23 (Table 4.2) also contain substantial levels of nitrates (Appendix III; Table A3.2). Similarly, the well from which sample RCB-12 was collected was not sampled for tritium, but it does have a high level of NO_3-N which may indicate recharge within the past 80 years, since it is a flowing well and the seepage through cribbing probably does not contaminate the sample to any great degree.

^{14}C analyses may also have a semi-quantitative application in distinguishing "young" (i.e. less than 1000 ybp) waters from older waters (1000-50,000 ypb). The only possible sign of regional groundwater flow was the Hoffman flowing well (RCB-41), however this age is believed to have been severely affected by inadequate sampling techniques and not truly representative of the groundwater age. Unfortunately, the loss of the RCA-45 sample negated any chances of proving that very old water, possibly originating in a deep-seated flow system, discharges in the Dunmore area.

The Meier well (RCE-33) was postulated to be located in the midst of a large-scale discharge area (Ophori and Tóth 1983). While the isotope age date of 9000 ybp indicates an old water, it is felt that more time would be needed for groundwater to move from the Cypress Hills to this area. However, mixture of a shallow component of flow with a deeper seated system could result in this ^{14}C age.

The simultaneous sampling of ^{14}C and tritium revealed the relative insensitivity of ^{14}C analyses at ages below 3000 ybp. ^{14}C ages of less than 1400 ybp (RCA-6) appear to reflect modern recharge as indicated by post-1952 levels of tritium, even though levels greater than 100 pmc are expected.

5.3.3 Quantitative age dating

Numerical modeling analysis was carried out for two of the sites sampled for radioisotopes utilizing the methods outlined in Section 3.3. The sites modeled were the Cypress

Hills/Ravenscrag formational contact springs and the springs which occur along the Eastend/Bearpaw formational contact. It was felt that if flow through these zones could be modeled then a significant portion of the flow in Ross Creek would be accounted for. Quantitative age dates at these sites would help to calibrate the basin model. The rationale behind each of the models was to correlate isotopic dating with the known hydrological parameters of the region.

In each of the scenarios, the age dates were felt to be accurate. Two similar tritium results were obtained from the Nicholls and Mitchell springs (RCA-1 and RCA-47), on the north side of the Cypress Hills. These springs were judged to ~~obtain~~ similar recharge and are located at approximately equal positions in the stratigraphic profile. Similarly, ^{14}C ages at two of the Eastend springs agreed and are believed to have been collected without CO_2 fractionation.

Values of hydraulic conductivity for each formation were kept as close as possible to those determined by Freeze (1969a). These values are compared to those utilized by Ophori (1986) and the ranges of permeability coefficients used in the current work in Table 5.1. The reason why the K values used in the present study (Table 5.1) are multiples of 3.4 is that Freeze (1969a) utilized units of igal/day/ft^2 and the current study calculated the area of a streamtube in terms of m^2. In all cases, values of K were adjusted from those given by Freeze (1969a) as part of the calibration process. A K_x/K_y ratio of 100:1 was maintained in the model.

FORMATION	RANGE Kx FREEZE(1969a)	RANGE Kx OPHORI(1986)	THIS STUDY RANGE Kx MS RUNS	THIS STUDY RANGE Kx EAST RUNS
CYPRESS HILLS	$4 \times 10^{-7} - 4 \times 10^{-4}$	8.4×10^{-5}	$4 \times 10^{-5} - 8 \times 10$	$4 \times 10^{-4} - 4 \times 10^{-6}$
RAVENSCRAG	$4 \times 10^{-8} - 4 \times 10^{-10}$	4.4×10^{-5}	$2 \times 10^{-8} - 4 \times 10^{-6}$	$2 \times 10^{-6} -$ 2×10^{-8}
FRENCHMAN BUTTE	$4 \times 10^{-6} - 4 \times 10^{-8}$	4.5×10^{-6}	---	
BATTLE	-- --	---	---	$4 \times 10^{-7} -$ 4×10^{-9}
WHITEMUD	$4 \times 10^{-5} - 4 \times 10^{-8}$	---	---	
EASTEND	$4 \times 10^{-5} - 4 \times 10^{-7}$	4.5×10^{-5}	---	$4 \times 10^{-6} - 4 \times 10^{-8}$
BEARPAW	4×10^{-10} 4×10^{-12}	4.2×10^{-8}	---	$2 \times 10^{-8} - 4 \times 10^{-10}$

Table 5.1. Values of permeability for Ross Creek Basin formations. All values given in units of m/s.

This was adjusted utilizing the results of Freeze (1969a) and by comparison with the values assumed by Ophori (1986)[4].

The hydrological setting of Mitchell spring (RCA-47) was modeled in the first set of simulations. This spring is situated in the lodgepole pine forest on the north slope of the Cypress Hills. Because of its topographical position, post-1952 levels of tritium and modern values of stable isotopes, Mitchell spring is thought to derive its recharge from the Hills. It has a discharge of around $0.2m^3$/min and at one time was used as the water supply for the Town of Elkwater. For the model, a two-layer system was developed, with a highly permeable layer overlying a less permeable unit in order to simulate the relationship between the Cypress Hills gravels and the Ravenscrag Formation. Impermeable boundaries were set on the south and bottom sides of the system, while a subdued water table formed a sloping boundary on the top. The area modeled thus tapered into a wedge. Permeability contrasts between the upper and lower layers were maintained at no less than 10:1. Figure 5.5 shows a typical system configuration of the type ultimately used in the simulations. The streamtube area assumed to contribute to the Mitchell spring is shaded and the streamtubes are numbered.

The value of K_x for the Cypress Hills gravels (Layer 1) was originally set at 340m/d (Freeze 1969a). However,

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[4] K_x and K_y are defined as the horizontal and vertical components of hydraulic conductivity, respectively.

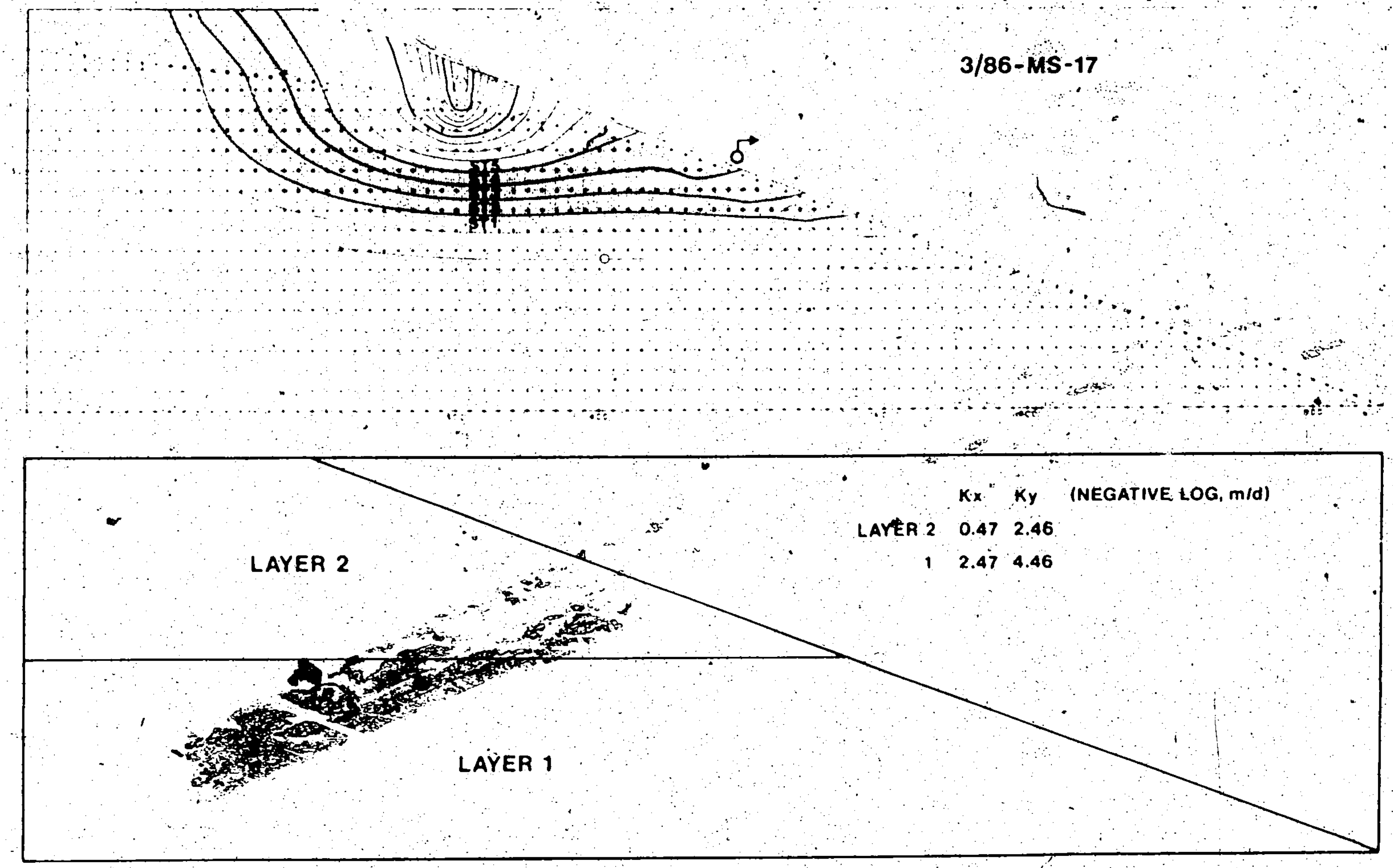

Figure 5.5. Results of numerical simulation analysis of the Mitchell spring. The bottom profile shows the configuration of geologic units in the system. The top profile shows the calculated distribution of stream functions in the cross section. The shaded region within the numbered streamtubes were assumed to contribute to the age of a sample from the spring.

because the tritium value of the spring (152 TU) represents an age of 20±5 ybp water (Table 3.4), the value of K_x for the top layer was subsequently scaled down. Results of the four simulations that best fit the tritium data are given in Table 5.2. As may be seen, the K_x for the Cypress Hills gravels that best fit the tritium data is approximately 10^{-4}m/s.

Thus, useful information about groundwater flow near the top of the Cypress Hills has been obtained. It appears that most of the recharge to the system is discharged along the north slope of the Plateau, resulting in little downward migration through the Ravenscrag and underlying formations.

It does appear however, that the values of K_x calculated for the Cypress Hills gravels are too low. 10^{-4}m/s is the same value as that used by Ophori (1986) for simulating the Ravenscrag/Cypress Hills Formation as a single unit, but Freeze and Cherry (1979) indicate that the permeability of unconsolidated gravels ranges between 1 to 10^{-3}m/s, while the lowest K_x value of the Cypress Hills Formation that Freeze (1969a) noted was 10^{-5} m/s (Table 5.1).

The reasons for this discrepancy are unclear. Possibly the gravels are poorly sorted and thus less permeable than originally thought. Perhaps dispersion plays a more significant role than was previously considered. If a dispersivity of 100m is assumed for the gravels (after Anderson 1979); at an average travel distance of 400m to the

RUN NUMBER	AREA OF STREAM TUBE (m²)	DELTA PSI (m)	NUMBER OF CONTRIBUTING STREAM TUBES	T(YEARS)	KH CYPRESS HILLS FM (m/s)	KH CYPRESS HILLS FM ([illegible]tive log m/a)	KH RAVENSCRAG FORMATION (m/s)
T 86-MS-[illegible]	3500	1 5	2 5	0 9	4 × 10[illegible]	-0 53	4 × 10[illegible]
[illegible]	35[illegible]	0 025	3 [illegible]	45	8 × 10	1 17	8 × 10[illegible]
[illegible] 86-MS-[illegible]	3500	0 1	3 75	9 0	4 × 10[illegible]	0 47	[illegible] × 10[illegible]
T 86-MS-18	3500	0 5	3 75	1 9	2 × 10[illegible]	-0 23	2 × 10[illegible]

Table 5.2. Summary of numerical modeling: Mitchell spring. Values of porosity were assumed to be constant (0.35), as were anistropy (K_x/K_y = 100:1).

Mitchell spring, the dispersion parameter, D/vx becomes 100m/400m = 0.25. Therefore, dispersion is not negligible (Fig. 3.12), and a value of 152 TU may represent water that still contains a considerable component of mid-1960's tritium that is only slowly being diluted and discharged. In addition, the location of the springs on the hills and the travel distance is not known exactly, and therefore since the gravels have been deposited on top of an erosional surface, it is possible that the simulations do not fit the real life situation with absolute precision.

It is felt that overall a K_x equal to 10^{-4}m/s is a reasonable result. Certainly much more information has been yielded from the stream function simulation of Mitchell spring than would have been obtained from an application of the models shown in Figure 3.11.

Computer techniques were also applied to model flow relationships that occur at the Eastend/Bearpaw contact springs. ^{14}C ages of 6 springs in this area ranged from 300 to 10000 ybp (Fig. 4.13) but as mentioned, the 300 ybp value has been shown to contain recent recharge, while the three values of 8500 to 10000 ybp are believed to have undergone fractionation during sampling. The two remaining values, RCA-31 (6500 ybp) and RCD-15 (6000 ybp), are believed to represent valid ages for groundwater discharge along this geological contact. However, it was unknown whether the flow systems represented by the ^{14}C dates are intermediate flow systems originating in the Cypress Hills (Ophori 1986), or whether a significant portion of the flow is derived from recharge on the broad sloping area north of Elkwater Lake.

The J. Mack spring (RCD-15) was chosen for simulation. This spring is situated in the midst of a cluster of 12 major springs that occur within 5 km of each other. Thus the Mack spring should be representative of a large portion of the groundwater that discharges in this area. The spring has a discharge of approximately 0.08m^3/min and is used for household and barnyard purposes. Excess water from the spring flows into a tributary of Ross Creek. The profile that was simulated was a 5-layer system (Fig. 5.6). Layer 5 represents the Cypress Hills Formation and was assumed to be 50-100 times more permeable than the underlying Ravenscrag/Frenchman Butte Formation which forms Layer 4. Layer 4 was 10-20 times more permeable than Layer 3 (the Battle and Whitemud Formations). The Eastend Formation (Layer 2), the largest section in the profile, was assumed to be 100 times more permeable than Layer 3 and 1000 times more permeable than the Bearpaw Shale (Layer 1). K_x/K_y was kept equal to 100:1 in all of the layers. A typical configuration of permeabilities throughout the cross section is shown in Figure 5.6.

The K_x's were chosen to agree with the values given by Freeze (1969b) and were adjusted in the model's calibration. ^{14}C age was assumed to be between 6000 and 7000 years.

The bottom, left and right boundaries of the model were assumed to be no flow boundaries. It was felt that while

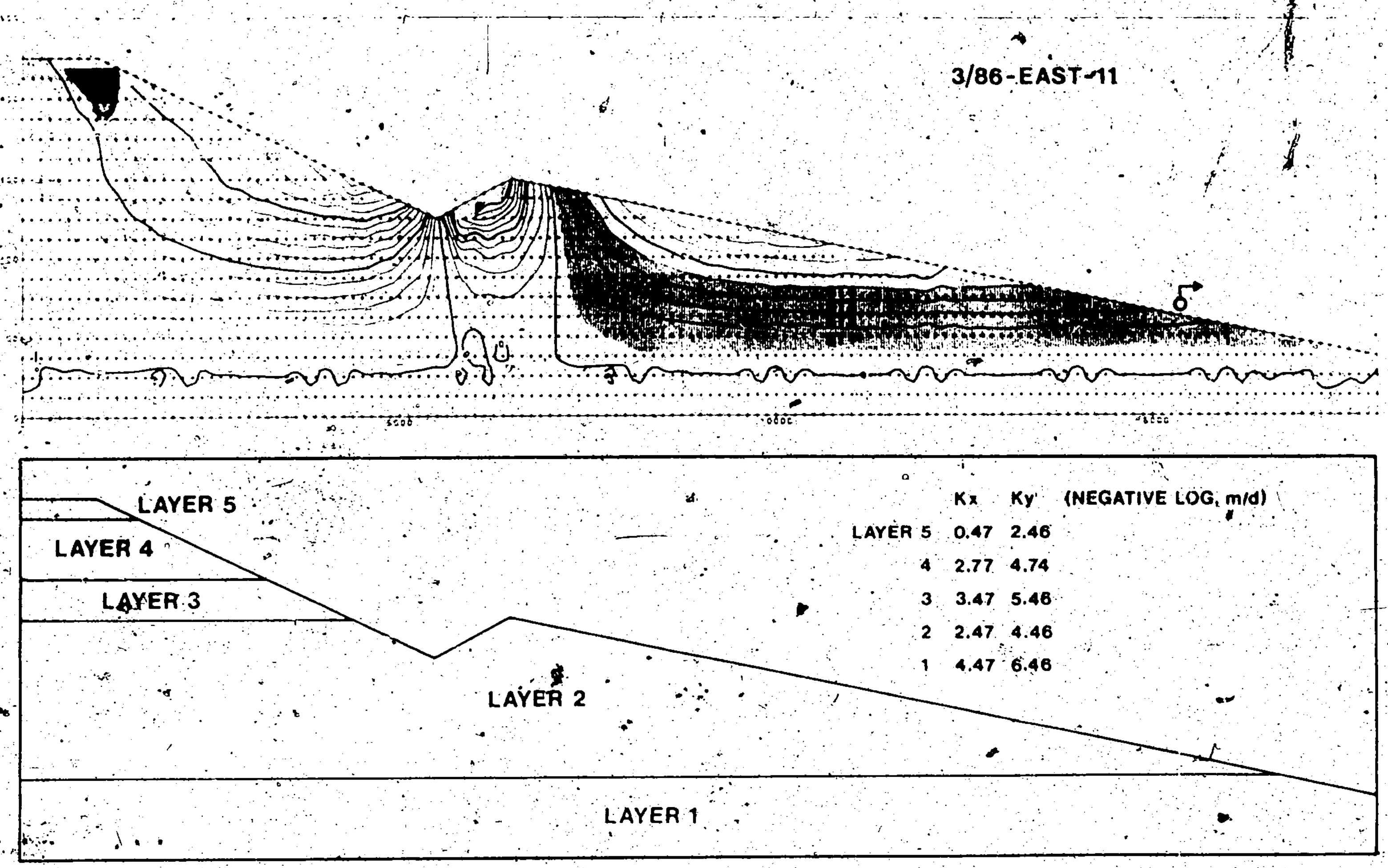

Figure 5.6. Results of numerical simulation analysis of the J. Mack spring. The bottom profile shows the configuration of geologic units in the system. The top profile shows the calculated distribution of stream functions in the cross section. The shaded region within the numbered streamtubes were assumed to contribute to the age of a sample from the spring.

this assumption imposed some unrealistic constraints on flow to the right in the system as well as downward through the Bearpaw Formation, quantitatively this problem was not substantial. A comparison of the number of stream functions that go through the Cypress Hill Formation into the Ravenscrag Formation in Figures 5.5 and 5.6 helps to justify this approach: in Figure 5.5, no flow is calculated to pass between the layers, while in Figure 5.6, when the larger scale system is modeled, very few stream functions pass into the Ravenscrag Formation. A similar configuration exists at the Eastend springs: the Bearpaw Formation is about two orders of magnitude less permeable than the Eastend Formation. The fact that the Oldman Formation has a K_x postulated to be intermediate between those of the overlying strata will affect the flow in those units very little, much in the manner that Layer 3 in Figure 5.6 does not seriously alter flow conditions near the top of the Plateau. The better resolution of the numerical solution of the steady state finite element equation due to greater node density in a small profile was felt to be of higher priority than was the mapping of the inconsequential amount of groundwater flow through the Bearpaw Formation in a large cross section.

Figure 5.6 shows that two groundwater divides are calculated on either side of the hill north of Elkwater Lake. This would appear to decrease the possibility that substantial amounts of groundwater flow from the Cypress Hills discharge along the Eastend/Bearpaw contact. The flow to these springs derives solely from the hummocky slope north of the lake. Most of the groundwater that is recharged in the Cypress Hills discharges at the Cypress Hills springs (Figs. 5.5 and 5.6), while the remainder seeps out along the north slope of the Plateau and into Elkwater Lake.

Table 5.3 summarizes the results of three of the calibrated Mack spring modeling runs. As may be seen by comparing #EAST-8 with #EAST-9, differences in the K_x of Layer 5 had no effect on groundwater patterns in the Eastend Formation and thus age dates at the Mack spring. The average K_x for the Eastend Formation that is predicted by the simulations is approximately 10^{-}[illegible]m/s. This agrees well with the value of 4 x 10^{-}[illegible]m/s determined for the Eastend Formation by Freeze (1969a).

The values of hydraulic conductivity predicted by the simulations compare favorably with known values. This provides evidence that the water emerging from springs at the Eastend/Bearpaw geologic contact are not fed by infiltration in the Cypress Hills, but instead result from recharge in the hummocky grasslands north of Elkwater Lake. Actual precipitation in this area is felt to be similar to that predicted by Ophori and Tóth (1983) for the whole basin, and on an average year, one would predict that some of the surplus springtime water budget is available for recharge to the groundwater system. This recharge provides a source of groundwater for springs along the Eastend/Bearpaw contact.

RUN NUMBER	AREA OF STREAM TUBE (m²)	DELTA PSI (m)	NUMBER OF CONTRIBUTING STREAM TUBES	T (YEARS)	KH EASTEND FORMATION (m/s)	KH EASTEND FORMATION (negative log m/d)	KH BEARPAW FORMATION (m/s)	KH CYPRESS HILLS FM (m/s)
J.86-EAST-8	68 × 10[illegible]	0.0750	3.5	2500	4 × 10[illegible]	0.47	2 × 10[illegible]	4 × 10[illegible]
J.86-EAST-9	68 × 10[illegible]	0.0750	3.5	2500	4 × 10[illegible]	0.47	4 × 10[illegible]	4 × 10[illegible]
J.86-EAST-10	68 × 10[illegible]	0.0050	7.0	18800	4 × 10[illegible]	1.47	4 × 10[illegible]	4 × 10[illegible]

Table 5.3. Summary of numerical modeling: J. Mack spring. Values of porosity were assumed to be constant (0.35), as were anistropy (K_x/K_y = 100:1).

The simulation shown in Figure 5.6 also demonstrates several other features of the groundwater flow patterns around the Cypress Hills:

1. The Sailer and Brown springs (RCB-1 and RCB-3, respectively) may derive from recharge in the Cypress Hills. The model of the Mack spring does not extend to the western portion of the basin, where the Eastend Formation pinches out much closer to the Plateau than in the eastern segment of the Basin (Fig. 3.3). Therefore, it is felt that intermediate groundwater flow systems may contribute to groundwater discharge along the Eastend/ Bearpaw contact on this side of the basin. Unfortunately, trustworthy ^{14}C samples were not obtained in this area.

2. The Mack spring models support the Mitchell spring models in showing that most of the recharge that occurs on top of the Cypress Hills is discharged at the Cypress Hills/Ravenscrag formational boundary. Water that is not discharged in the springs probably feeds the large streams that begin on the north slope of the Plateau.

3. Discharge occurring along the base of the north incline of the Hills (i.e. the Kajewski Spring; RCA-26 and the Elkwater Town Well; RCA-6) is partially derived from recharge along the top of the Cypress Hills. Most of this flow is locally derived, however.

5.4 Integrated Groundwater Model

The use of isotopes as part of an integrated hydrogeologic investigation in Ross Creek Basin has helped to delineate groundwater flow patterns. The work of Ophori and others (Ophori 1986; Ophori and Tóth 1983, 1985) mapped patterns of discharge and recharge in the region, but provided only a qualitative evaluation of Ross Creek Basin. Many of the hydrological manifestations of groundwater flow that are attributed by those authors to regional effects are the result of localized systems.

On the basis of results obtained, the following may be stated with regards to groundwater flow conditions in Ross Creek Basin:

1. The water that recharges in the Cypress Hills is discharged via large springs, seeps and influent streams on the incline and at the base of the Plateau. Precipitation in this area is significant, and is probably much greater than the 500mm assumed by Ophori and Tóth (1983)~~. In addition~~, cooler climatic conditions are found in the Hills than exist in the rest of the basin. A large volume of recharge to the groundwater in this area is postulated.

2. The Eastend Forma[illegible]eceives a significant component of recharge from the region immediately north of the Cypress Hills. This groundwater is deflected laterally along the Eastend/ Bearpaw contact and discharges i[illegible]

series of large springs in Township 9. These springs do not reflect any climatic differences from present day conditions, although the water appears to have been recharged around 6000 ybp.

3. Permeability contrasts in the Bearpaw, Oldman and Foremost Formations result in the discharge of deep seated flow systems in a small area in the center of Ross Creek Basin and near the town of Dunmore. The volumetric contribution of these large-scale flow systems is difficult to ascertain, but local effects are largely masked in the center of this discharge. A climatic change of -3 to 4°C different than present day conditions is suggested by low values of $\delta^{18}O$ and δD. A single ^{14}C datum suggests that the average recharge age was 9000 years ago.

4. The western edge of Ross Creek Basin appears to contain an older and more deeply seated flow than the rest of the basin and may represent a less marked (or more dilute) example of the processes discussed in (3) above. Waters in this area are depleted in $\delta^{18}O$ and δD with respect to waters from the rest of the basin. No reliable ^{14}C age dates were collected in this area to substantiate a hypothesis of paleo-recharge conditions.

5. Present day recharge in Ross Creek Basin appears to be subject to evaporation during infiltration. This is a phenomenon that makes this area unique. The degree of

water lost to simultaneous evaporation and recharge would be difficult to quantify, but it may have significant negative implications for a groundwater management model of the area (e.g. Ophori 1986).

6. Many of the springs in Ross Creek Basin depend on very shallow sources of recharge. The long term quality and quantity of discharge from these features will depend on environmental factors such as simultaneous evaporation-recharge and sources of nitrate-nitrogen.

7. Discharge quantities at the Schneider ranch (Township 12, Range 4W4) may be significantly affected by the presence of a buried channel gravel deposit. Treatment of this feature as a long-term, regional source of discharge may result in premature depletion of the area's groundwater resources.

6. CONCLUSIONS AND SUMMARY

The current study has demonstrated that regional groundwater flow systems are extremely complex and often elude the application of traditional models in the absence of detailed data. This complexity holds especially true in the glaciated Plains regions of North America because of the constant interrelationships between flow systems that has developed.

In a study such as the current work, an overview must be maintained that includes principles of hydrochemistry, isotope geochemistry, climatology, and hydrology, as well as conceptual hydrogeology. This has been termed an integrated approach.

The current study has enhanced the conceptual model of groundwater flow in Ross Creek Basin through the use of stable isotopes, radioisotopes, and numerical simulations. Positive and negative results have been found which should be of use not only in Ross Creek, but in similar studies elsewhere.

Stable isotopes can distinguish between types of groundwater flow systems and help to elucidate mechanisms of recharge on the Plains. Temporal meteoric water lines are easy to define in the region because of the wide annual variations in the isotope content of precipitation. Little quantitative information is yielded by these analyses, however. No altitude effect could be delineated to assist in isolating sources of recharge. Evaporation is virtually impossible to estimate over such a wide area and paleoclimatic indicators must be combined with reliable age dates to be of use.

Tritium analyses were proven to be excellent indicators of recent recharge components in groundwater flow systems. Definition of a tritium input function for the region should assist in future uses of this hydrologic tool. However, unless additional tritium is input to the atmosphere within the next few years, conventional counting techniques will be no longer able to reliably detect tritium in precipitation. Already it is difficult to distinguish some configurations of pre-1952 and post-1952 waters.

^{14}C sampling proved to be of limited value in Ross Creek Basin, mainly due to a faulty sample collection process. Fractionation of CO_2 because of exsolution from the sample containers rendered many of the analyses useless. This is unfortunate, because reliable age dating in several areas of distinctively depleted levels of $\delta^{18}O$ and δD would have been an asset.

Numerical simulations of groundwater age dates by the stream function method proved to be a useful way of verifying isotope age measurements. This has been shown to be a significant improvement over past techniques of isotope age date modeling in groundwater. Simulation of ^{14}C dates in large scale systems proved to be more successful than for tritium in smaller profiles.

In addition to providing answers about the patterns of groundwater flow in Ross Creek Basin, the current study has pointed out several issues that should be researched in greater detail in the future. These include:

1. Methods of ^{14}C sampling. Valuable information was lost in this study due to poor ^{14}C sampling methodology. Refinements of these techniques might include the construction of instrumentation for small volume ^{14}C counting or the formulation of a sampling program that includes a convenient method for collecting large amounts of water without exsolving CO_2.
2. The formulation of detailed tritium input functions for Alberta. With the recent availability of tritium analysis facilities in the province, more Alberta scientists are likely to utilize this isotope in their work. Detailed data as to the projected levels of tritium in Alberta rainfall since 1952 will have to be worked out before these techniques can become meaningful, however.
3. The modeling of isotope data. Further theoretical development of the stream function techniques of modeling isotopic age dates is needed. This method shows great promise for future application, especially in situations where unconfined aquifers exist.
4. Isotopic tracing of groundwater recharge. There is much that remains to be learned about the movement of water through the unsaturated zone. This study has suggested

that evaporation occurs during recharge on the prairies, but the actual mechanics of this process are not understood, nor are the dynamics of other physical or chemical processes that take place during soil moisture infiltration.

5. Isotopic aging processes of snow. This study found that snow in Ross Creek Basin underwent an isotopic enrichment process during aging. In addition, snowmelt rapidly equilibriated to remarkably uniform levels of δ^{18}O and δD throughout the region. Any study of snowmelt infiltration utilizing stable isotopes will have to be able to model the isotopic shifts of both snow and snowmelt prior to recharge.

6. Paleoclimatic information yielded from groundwater studies. An improved methodology for taking ^{14}C samples in Ross Creek Basin might reveal some interesting clues as to past conditions of groundwater recharge in southern Alberta. During the course of further endeavors in this area, it is likely that the temperature data obtained from δ^{18}O levels could have been attached to a specific time period. In addition, the hydrochemistry of individual water samples may also contribute to a future understanding of the province's paleoenvironmental conditions.

Overall, the application of an integrated approach in Ross Creek Basin has helped to delineate groundwater flow patterns and has aided in quantifying the resource. Water is scarce on the Great Plains and it is only through careful definition, development and management of this valuable commodity that long term supplies in this region will be ensured. Future integrated approaches in hydrogeology will utilize work done in Ross Creek Basin and ultimately, benefit to future generations will result.

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APPENDIX I: IMPLEMENTATION OF THE STREAM FUNCTION THEORY

A steady state, finite element, two-dimensional, cross sectional profile FORTRAN code written by E.O. Frind (1971) is in popular use at the University of Alberta, Department of Geology. The program is poorly documented, but well understood by graduate students in the Hydrogeology program. It is easily altered to calculate stream functions as outlined by Frind and Matanga (1985).

The actual changes to the code are straight forward. To simulate a cross sectional profile where the upper bounds of the system are assumed to be represented by a constant head boundary (water table condition) the following revisions were instituted:

1. Alter K_x to $1/K_y$ and K_y to $1/K_x$.

2. The boundary conditions are changed. First-type boundary conditions (constant head) in the potential solution become second-type boundaries (constant flux) in the stream function calculation and vice-versa. This means that no-flow boundaries (sides and bottom of the profile) are specified as constant values of stream functions and are commonly equal to zero.

   Values of flux along the water table must be read into the F matrix, after the place in the code where it is initialized to zeros. These water table fluxes are calculated for a node along the water table by averaging the head differences on either side:

Flux(Node 2) =½ {Head(Node 3)-Head(Node 1)} (A.1.T)

These fluxes are not left as constants.

3. I/O should be adjusted to read in the water table and no-flux nodal values.

A listing of the altered code is included as Figure A.1.1.

In order to facilitate changes between simulations , a code for generating a finite element grid was written in FORTRAN-77. By using the grid generating programs, a regular mesh of nodes and element may be created for each modeling situation which requires geologic or topographic adjustments.

All computing was done on the University of Alberta Amdahl 360 mainframe computer. FORTG and FORTRANVS level compilers were utilized to convert the FORTRAN codes into machine code.

Contouring of stream functions was performed through the use of a program owned by the UA Computing Services. This code, called SURFACE II (Sampson 1978) produces files that can be plotted on a Calcomp graphics system. The calibration and adjustments associated with the use of SURFACE II made this part of the exercise very frustrating.

```
C     STEADY-STATE POTENTIAL DISTRIBUTION IN 2-D CROSS-SECTION
C     LINEAR TRIANGULAR FINITE ELEMENTS: EXPLICIT CONSTANT HEAD NODES
C
      COMMON S(1401,30),U(1570),F(1570)
      DIMENSION TITLE(20),X(1570),Y(1570),IN(2825,3),TYPE(1570),
     1AL(2825),LC(1570),SC(1401,166),XI(3),YI(3),B(3),C(3),SE(3,3),
     2FB(1570),CY(2825),YF(1570),CX(2825)
      DATA CON/1HC/,START/2HFE/,EXIT/2HXX/
C
C     PROBLEM PARAMETERS
  800 READ (5,10) CARD
      IF (CARD.EQ.EXIT) STOP
      IF (CARD.NE.START) GO TO 800
      READ (5,10) TITLE
   10 FORMAT (20A4)
      WRITE (6,12) TITLE
   12 FORMAT (/1H1,10X,20A4)
      READ (5,13) NN,NE,NB
   13 FORMAT (10I5)
      WRITE (6,14) NN,NE,NB
   14 FORMAT (//10X,'NUMBER OF NODES',8X,I4/10X,'NUMBER OF ELEMENTS',
     15X,I4/10X,'ESTIMATED BANDWIDTH',4X,I4)
C
C     NODE COORDINATES
      READ (5,21) (I,X(I),Y(I),TYPE(I),FB(I),K=1,NN)
   21 FORMAT (I5,2F10.2,4X,A1,F10.5)
      WRITE (6,22)
   22 FORMAT (//10X,'NODE COORDINATES'/11X,'NODE',12X,'X',15X,'Y',13X,
     1'TYPE',8X,'FB VALUE'/ )
      WRITE (6,23) (I,X(I),Y(I),TYPE(I),FB(I),I=1,NN)
   23 FORMAT (10X,I4,2F16.2,12X,A1,F16.2)
C
C     ELEMENT INCIDENCES AND PERMEABILITY
      READ (5,31) (I,(IN(I,J),J=1,3),K=1,NE)
   31 FORMAT (4I5)
   35 READ (5,33) J1,J2,CKX,CKY,ANGLE
   33 FORMAT (2I5,3F10.0)
      DO 32 J=J1,J2
      CX(J) = CKX
      CY(J) = CKY
   32 AL(J) = ANGLE
      IF (J2.LT.NE) GO TO 35
      WRITE (6,36)
   36 FORMAT (//10X,'ELEMENT DATA'/10X,'ELEMENT',10X,'INCIDENCE',17X,
     1'PERMEABILITY',6X,'INCLINATION'/23X,'1',7X,'2',7X,'3',13X,'X',
     210X,'Y'/ )
      WRITE (6,37) (I,(IN(I,J),J=1,3),CX(I),CY(I),AL(I),I=1,NE)
   37 FORMAT (10X,I4,2X,3I8,4X,2F11.0,F12.1)
C
C     CONDENSATION CODE
      LC(1) = 0
      IF (TYPE(1).EQ.CON) LC(1)=1
      DO 41 I=2,NN
      K = 0
      IF (TYPE(I).EQ.CON) K=1
   41 LC(I) = LC(I-1)+K
      NC = LC(NN)
      N = NN-NC
      WRITE (6,42) NC,N
   42 FORMAT (//10X,'NUMBER OF CONSTANT-HEAD NODES',I5/10X,
```

Figure A.1.1. Listing of finite element stream function program.

```
     1'NUMBER OF DEGREES OF FREEDOM',I6)
C
C CONDENSATION OF FB MATRIX
C
      KI = 0
      DO 2 I=1,NN
        IF(TYPE(I).EQ.CON) GO TO 2
        KI = KI + 1
        FB(KI) = FB(I)
    2 CONTINUE
C
C     CLEAR ARRAYS
      DO 45 I=1,N
      DO 46 J=1,NB
   46 S(I,J) = 0.
      DO 45 J=1,NC
   45 SC(I,J) = 0.
C
C     LOOP OVER ELEMENTS
      NB1 = 0
      DO 100 L=1,NE
C
C     ELEMENT CONDUCTIVITY MATRIX
      ALPHA = AL(L)*3.141593/180.
      COSA = COS(ALPHA)
      SINA = SIN(ALPHA)
      DO 51 I=1,3
      J = [illegible]I)
      XI(I) [illegible]COSA*X(J)+SINA*Y(J)
   51 YI(I) [illegible]COSA*Y(J)-SINA*X(J)
      B(1) = YI(2)-YI(3)
      B(2) = YI(3)-YI(1)
      B(3) = YI(1)-YI(2)
      C(1) = XI(3)-XI(2)
      C(2) = XI(1)-XI(3)
      C(3) = XI(2)-XI(1)
      DEL = XI(2)*YI(3)-XI(3)*YI(2)-XI(1)*YI(3)+XI(3)*YI(1)+XI(1)*YI(2)
     1-XI(2)*YI(1)
C     WRITE(4,987) L,DEL
C 987 FORMAT(I10,F20.0)
      BY = (.5/CX(L))/DEL
      BX = (.5/CY(L))/DEL
      DO 52 I=1,3
      DO 52 J=1,3
   52 SE(I,J) = BX*B(I)*B(J)+BY*C(I)*C(J)
C
C     GLOBAL CONDUCTIVITY MATRIX
      DO 61 I=1,3
      KI = IN(L,I)
      IF (TYPE(KI).EQ.CON) GO TO 61
      II = KI-LC(KI)
      DO 62 J=1,3
      KJ = IN(L,J)
      IF (TYPE(KJ).EQ.CON) GO TO 65
      JJ = KJ-LC(KJ)-II+1
      IF (JJ.LT.1) GO TO 62
      IF (JJ.GT.NB1) NB1=JJ
      IF (JJ.LE.NB) GO TO 63
      WRITE (6,64) L,JJ
   64 FORMAT (//10X,'ELEMENT',I4,2X,'REQUIRES BANDWIDTH OF',I4)
```

Figure A.1.1. (con.)

```
      GO TO 62
   63 S(II,JJ) = S(II,JJ)+SE(I,J)
      GO TO 62
   65 CONTINUE
      JJ = LC(KJ)
      SC(II,JJ) = SC(II,JJ)+SE(I,J)
   62 CONTINUE
   61 CONTINUE
C
C     END OF ELEMENT LOOP
  100 CONTINUE
      WRITE (6,81) NB1
   81 FORMAT (  10X,'FINAL BANDWIDTH',15X,I4)
      IF (NB1.LE.NB) GO TO 82
      WRITE (6,83)
   83 FORMAT (//10X,'EXECUTION TERMINATED')
      GO TO 800
   82 CONTINUE
      NB = NB1
C
C     DECOMPOSE
      CALL DBAND (N,NB,IEX)
      IF (IEX.EQ.0) GO TO 91
      WRITE (6,92)
   92 FORMAT (//10X,'DECOMPOSITION FAILED - EXECUTION TERMINATED' )
      GO TO 800
   91 CONTINUE
C
C     FLUX VECTOR
      K = 0
      DO 111 I=1,NN
      IF (TYPE(I).NE.CON) GO TO 111
      K = K+1
      YF(K) = 0.0
  111 CONTINUE
      DO 112 I=1,N
      F(I) = 0.
      F(I) = F(I)+FB(I)
      DO 113 J=1,NC
  113 F(I) = F(I)-SC(I,J)*YF(J)
  112 CONTINUE
C
C     SOLVE
      CALL SBAND (N,NB)
C
C     EXPAND HEAD VECTOR
      DO 121 II=1,NN
      I = NN-II+1
      IF (TYPE(I).EQ.CON) GO TO 122
      K = I-LC(I)
      U(I) = U(K)
      GO TO 121
  122 U(I) = 0.0
  121 CONTINUE
C
C     OUTPUT
      WRITE (6,131)
  131 FORMAT (1H1,10X,'STEADY-STATE STREAM FUNCTION DISTRIBUTION'/11X,
     1'NODE',8X,'TOTAL HEAD'/ )
      WRITE (6,132) (I,U(I),I=1,NN)
```

Figure A.1.1. (con.)

```
  132 FORMAT (10X,I4,F16.4)
C
C CALL SUBROUTINE TO OUTPUT FOR SURFACE II PLOTTING PACKAGE
C
      CALL SURFII(NN,X,Y)
      GO TO 800
      END
      SUBROUTINE DBAND (N,NB,IEX)
      COMMON S(1401,30),U(1570),F(1570)
      IEX = 0
      DO 22 I=1,N
      IP = N-I+1
      IF (NB.LT.IP) IP=NB
      DO 22 J=1,IP
      IQ = NB-J
      IF ((I-1).LT.IQ) IQ=I-1
      SUM = S(I,J)
      IF (IQ.LT.1) GO TO 45
      DO 44 K=1,IQ
      II = I-K
      JZ = J+K
   44 SUM = SUM - S(II,K+1)*S(II,JZ)
   45 IF (J.NE.1) GO TO 23
      IF (SUM.LE.0.) GO TO 26
      TEMP = 1./SQRT(SUM)
      S(I,J) = TEMP
      GO TO 22
   26 WRITE (6,31) I
   31 FORMAT (1H1,10X,19HDBAND FAILS AT ROW'  ,I4 )
      IEX = 1
      RETURN
   23 S(I,J) = SUM*TEMP
   22 CONTINUE
      RETURN
      END
      SUBROUTINE SBAND (N,NB)
      COMMON S(1401,30),U(1570),F(1570)
      DO 22 I=1,N
      J = I-NB+1
      IF ((I+1).LE.NB) J=1
      SUM = F(I)
      K1 = I-1
      IF (J.GT.K1) GO TO 34
      DO 33 K=J,K1
      II = I-K+1
   33 SUM = SUM - S(K,II)*U(K)
   34 U(I) = SUM*S(I,1)
   22 CONTINUE
      DO 44 I1=1,N
      I = N-I1+1
      J = I+NB-1
      IF (J.GT.N) J=N
      SUM = U(I)
      K2 = I+1
      IF (K2.GT.J) GO TO 25
      DO 55 K=K2,J
      KK = K-I+1
   55 SUM = SUM - S(I,KK)*U(K)
   25 U(I) = SUM*S(I,1)
   44 CONTINUE
```

Figure A.1.1. (con.)

```
      RETURN
      END
C
C SUBROUTINE [illegible] OUTPUT FOR SURFACE II PLOTTING PACKAGE
C
      SUBROUTINE SURFII(NN,X,Y)
      COMMON S(1401,30),U(1570),F(1570)
      DIMENSION X(1570),Y(1570)
      DO 100,I=1,NN
        WRITE(4 1000) X(I),Y(I),U(I)
  100 CONTINUE
 1000 FORMAT(3F16.4)
      RETURN
      END
End of file
```

Figure A.1.1. (con.)

APPENDIX II: TABLES OF WELL DATA

Table A.2.1. All sampling points sorted by location. Listed in order of: Township, range, section and lsd.

SAMPLE	LOCATION				OWNER DESCRIPTION	TYPE OF WATER	ALTITUDE OF SAMPLING POINT	DEPTH OF WELL	DEPTH TO WATER
RCA-49	4	7	8	2W4	CHPP	PUDDLE	4735.0	---	---
RCA-51	7	7	8	2W4	CHPP	DUGOUT	4710.0	---	---
RCB-45	7	7	8	2W4	CHPP	DUGOUT	4710.0	---	---
RCD-2	7	7	8	2W4	CHPP	DUGOUT	4710.0	---	---
MT-6	7	7	8	2W4	CHPP	DUGOUT	4710.0	---	---
RCA-50	7	7	8	2W4	CHPP	SEEP	4712.0	---	---
RCB-46	7	7	8	2W4	CHPP	SEEP	4712.0	0	0
RCC-6	7	7	8	2W4	CHPP	SEEP	4712.0	---	---
RCD-3	7	7	8	2W4	CHPP	SEEP	4712.0	---	---
RCD-27	[illegible]	7	8	2W4	WINTER	PPT	4700.0	---	---
RCE-9	12	8	8	2W4	WINTER(N)	PPT	4710.0	---	---
RCE-10	12	8	8	2W4	WINTER(O)	PPT	4710.0	---	---
RCE-7	12	8	8	2W4	DUKE AE#2093E	WELL	4710.0	---	---
RCE-8	12	8	8	2W4	DUKE AE#2084E	WELL	4710.0	46	42
RCC-23	14	8	8	2W4	SUMMER	PPT	4710.0	312	292
RCD-26	2	18	8	2W4	WINTER	PPT	4725.0	---	---
RCC-9	2	18	8	2W4	CHPP-MOOSE PAST	SEEP	4375.0	---	---
RCC-10	6	18	8	2W4	CHPP-SKI RUN	SPRING	4300.0	0	0
RCB-48	15	18	8	2W4	CHPP-SKI HILL	STREAM	4550.0	0	0
RCE-5	5	19	8	2W4	WINTER(N)	PPT	4125.0	---	---
RCB-47	10	19	8	2W4	CHPP-GROUP CAMP	WELL	4060.0	---	---
RCA-52	2	21	8	2W4	CHPP-PINES	SPRING	4025.0	115	38
RCC-5	2	21	8	2W4	CHPP-PINES	SPRING	4630.0	0	0
RCC-2	13	23	8	2W4	CHPP-SPRUCE	CREEK	4630.0	---	---
RCC-3	3	26	8	2W4	CHPP-MUSKEG	SEEP	4380.0	---	---
RCC-24	9	27	8	2W4	SUMMER	PPT	4425.0	---	---
RCD-1	9	27	8	2W4	WINTER	PPT	4300.0	---	---
RCC-4	10	27	8	2W4	CHPP-S. COULEE	SPRING	4275.0	---	---
RCC-13	2	28	8	2W4	CHPP-BENCHES	SPRING	4400.0	0	0
RCA-54	14	30	8	2W4	SUMMER	PPT	4600.0	0	0
RCA-53	14	30	8	2W4	FELESKY	WELL	4000.0	---	---
RCC-25	14	30	8	2W4	FELESKY	WELL	4000.0	120	18
RCA-1	13	11	8	3W4	CHPP-NICHOLLS	SPRING	4000.0	---	---
RCC-8	13	11	8	3W4	CHPP-NICHOLLS	SPRING	4700.0	0	0
RCD-[illegible]	13	11	8	3W4	CHPP-NICHOLLS	SPRING	4700.0	---	---
RCA[illegible]	12	12	8	3W4	SUMMER	PPT	4700.0	---	---
RCC[illegible]	12	12	8	3W4	SUMMER	PPT	4750.0	---	---
RCD-4	[illegible]	12	8	3W4	WINTER	PPT	4760.0	---	---
RCA-47	[illegible]	13	8	3W4	CHPP-MITCHELL	SPRING	4740.0	---	---
RCC-7	[illegible]	13	8	3W4	CHPP-MITCHELL	SPRING	4660.0	0	0
RCD-8	3	13	8	3W4	CHPP-MITCHELL	SPRING	4660.0	---	---
RCA-2	4	14	8	3W4	CHPP-MITCHELL	SPRING	4660.0	---	---
RCC-26	10	16	8	3W4	KAJEWSKY	SPRING	4660.0	---	---
RCD-10	10	16	8	3W4	KAJEWSKY	SPRING	4100.0	0	0
RCD-7	7	23	8	3W4	WINTER	PPT	4100.0	---	---
RCA-3	7	23	8	3W4	CHPP-FIREROCK	WELL	~~4175.0~~	---	---
RCC-1[illegible]	7	23	8	3W4	CHPP-FIREROCK	WELL	4050.0	250	74
RCD-6	7	23	8	3W4	CHPP-FIREROCK	WELL	4175.0	---	---
RCA-5	12	23	8	3W4	CHPP	SEEP	4190.0	---	---
RCE-6	6	24	8	3W4	CHPP AE#2094E	WELL	4100.0	0	0
R[illegible]A-6	7	24	8	3W4	ELKWATER TOWN	WELL	4060.0	112	99
RCB-23	7	24	8	3W4	ELKWATER TOWN	WELL	4050.0	130	119
RCC-12	7	24	8	3W4	ELKWATER TOWN	WELL	4050.0	---	---
RCD-9	7	24	8	3W4	ELKWATER TOWN	WELL	4025.0	---	---
MT-5	7	24	8	3W4	ELKWATER TOWN	WELL	4020.0	---	---
RCE-36	7	24	8	3W4	ELKWATER TOWN	WELL	4050.0	---	---
RCD-25	8	24	8	3W4	WINTER	PPT	4050.0	---	---
RCA-4	11	[illegible]	8	3W4	CHPP-ELKWATER	LAKE	4010.0	---	---
RCB-49	11	24	8	3W4	CHPP-ELKWATER	LAKE	3990.0	---	---
RCC-11	11	24	8	3W4	CHPP-ELKWATER	LAKE	3990.0	---	---
RCD-28	11	24	8	3W4	CHPP-ELKWATER	LAKE	3990.0	---	---
RCA-7	11	25	8	3W4	A.PETER	WELL	3990.0	---	---
RCE-4	16	26	8	3W4	WINTER(O)	PPT	4000.0	112	40
RCB-22	4	27	8	3W4	RUSSIL	SPRING	4010.0	---	---
RCD-11	4	27	8	3W4	RUSSIL	SPRING	3875.0	0	0
RCB-4	6	29	8	3W4	BROWN EST.-F	SPRING	4000.0	---	---
RCB-3	11	30	8	3W4	BROWN EST.-H	SPRING	3900.0	0	0
RCD-19	11	30	8	3W4	BROWN EST.-H	SPRING	3750.0	0	0
RCA-9	11	35	8	3W4	B.SCHORR	SLOUGH	3750.0	---	---
RCA-8	4	36	8	3W4	A.PETER	SLOUGH	3975.0	---	---
RCC-31	1	4	9	2W4	ROAD ALLOWANCE	F.WELL	3975.0	---	---
RCD-[illegible]	1	4	9	2W4	ROAD ALLOWANCE	F.WELL	4010.0	15	0
RCC-32	8	5	9	2W4	E.NEUBAUER	SPRING	4000.0	---	---
RCA-18	13	8	9	2W4	E.MACK-FIELD	DUGOUT	3942.0	0	0
RCA-71	14	8	9	2W4	E.MACK-FIELD	SEEP	3775.0	---	---
RCD-15	5	18	9	2W4	J.MACK	SPRING	3740.0	0	0
RCA-19	1	19	9	2W4	E.MACK-HOMESTE	SPRING	3725.0	0	0
							3625.0	0	0

Table A.2.1. (con.)

SAMPLE	LOCATION				OWNER DESCRIPTION	TYPE OF WATER	ALTITUDE OF SAMPLING POINT	DEPTH OF WELL	DEPTH TO WATER
RCA-20	9	19	9	2W4	D.NEUBAUER	SPRING	3525.0	0	0
RCC-30	9	19	9	2W4	D.NEUBAUER	SPRING	3550.0	---	---
RCD-21	9	19	9	2W4	D.NEUBAUER	SPRING	3475.0	---	---
RCA-17	4	30	9	2W4	E.MACK-CORRAL	SPRING	3476.0	0	0
RCA-55	14	2	9	3W4	D.LYALL	WELL	3875.0	187	90
RCB-2	13	5	9	3W4	[illegible]	WELL	3675.0	36	25
RCA-12	15	9	9	3W4	J.IGNATIUS	SPRING	3740.0	0	0
RCC-27	15	9	9	3W4	J.IGNATIUS	SPRING	3740.0	---	---
RCE-36	12	11	9	3W4	WINTER(O)	PPT.	3825.0	---	---
RCE-37	12	11	9	3W4	H.SEITZ	SLOUGH	3825.0	---	---
RCA-16	9	13	9	3W4	J.ENGLER	SPRING	3675.0	0	0
RCA-10	13	14	9	3W4	B.WEISS-FIELD	SPRING	3675.0	0	0
RCA-56	15	15	9	3W4	H.SEITZ	SPRING	3650.0	0	0
RCC-28	15	15	9	3W4	H.SEITZ	SPRING	3650.0	---	---
RCD-13	15	16	9	3W4	WINTER	PPT.	3675.0	---	---
RCD-12	15	16	9	3W4	H.SEITZ	SPRING	3675.0	---	---
RCA-13	1	22	9	3W4	B.WEISS-CORRAL	SPRING	3625.0	0	0
RCC-29	1	22	9	3W4	B.WEISS-CORRAL	SPRING	3625.0	---	---
RCD-14	1	22	9	3W4	B.WEISS-CORRAL	SPRING	3625.0	---	---
RCA-11	4	24	9	3W4	B.WEISS-HOMEST	SPRING	3640.0	4	0
RCD-29	4	25	9	3W4	ROSS	CREEK	3490.0	---	---
RCA-15	4	25	9	3W4	C.HERMANN	S.SEEP	3490.0	0	0
RCA-14	7	26	9	3W4	W.SWADLING	F.WELL	3510.0	10	0
RCA-59	1	30	9	3W4	D.SCHORR	SEEP	3625.0	---	---
MT-4	16	33	9	3W4	VOSSLER	S.SEEP	3520.0	0	0
RCB-6	16	2	9	4W4	A.RATH	WELL	3625.0	20	16
RCB-7	10	4	9	4W4	DRAUDSON#1	WELL	3650.0	48	30
RCB-5	14	12	9	4W4	FLAIG	F WELL	3400.0	2	0
RCB-8	1	16	9	4W4	DRAUDSON#2	WELL	3600.0	12	7
RCB-9	1	20	9	4W4	BURGEVITZ	DUGWELL	3575.0	10	6
RCB-11	8	23	9	4W4	GEIGLE	WELL	3450.0	8	2
RCB-10	13	23	9	4W4	BOSCHEE	F.WELL	3375.0	80	0
RCB-1	2	24	9	4W4	K.SAILER	SPRING	3540.0	0	0
RCD-20	2	24	9	4W4	K.SAILER	SPRING	3550.0	---	---
RCB-15	8	28	9	4W4	R.REIGER	DUGOUT	3325.0	---	---
RCB-14	11	28	9	4W4	R.REIGER	WELL	3360.0	43	15
RCC-34	13	36	9	4W4	M.RATH-GARDEN	WELL	3535.0	15	11
RCB-16	5	36	9	5W4	G.SEITZ	WELL	3525.0	28	14
RCA-21	13	7	10	2W4	A.SCHORR	WELL	3190.0	5	0
RCC-37	13	7	10	2W4	A.SCHORR	WELL	3190.0	---	---
RCD-17	13	7	10	2W4	A.SCHORR	WELL	3190.0	---	---
RCA-27	12	18	10	2W4	ROSS	CREEK	3180.0	---	---
RCA-28	16	30	10	2W4	B.SCHORR	DUGWELL	3115.0	26	16
RCC-38	16	30	10	2W4	B.SCHORR	DUGWELL	3115.0	---	---
RCA-58	6	4	10	3W4	R.JANS-STOCK	WELL	3400.0	14	10
RCA-57	7	4	10	3W4	R.JANS-HOUSE	F.WELL	3375.0	218	0
RCC-35	7	4	10	3W4	R.JANS-HOUSE	F.WELL	3375.0	---	---
RCA-22	1	14	10	3W4	F.BOLLINGER	WELL	3200.0	20	1
RCA-62	13	18	10	3W4	J.LENTZ	DUGOUT	3175.0	---	---
RCA-63	13	18	10	3W4	SUMMER	PPT.	3175.0	---	---
RCB-24	3	22	10	3W4	J.GILL	SPRING	3125.0	0	0
RCA-23	6	24	10	3W4	KRAUSS	F.WELL	3075.0	10	0
RCD-18	6	24	10	3W4	KRAUSS	F.WELL	3075.0	---	---
RCA-24	9	26	10	3W4	C.JANS	DUGOUT	2950.0	---	---
MT-2	13	27	10	3W4	SNOWBANK	PPT.	2700.0	---	---
RCA-64	10	30	10	3W4	C.GILL	WELL	3070.0	15	13
RCC-36	10	30	10	3W4	C.GILL	WELL	3075.0	---	---
RCC-16	16	32	10	3W4	SUMMER-CLOUDE	RUNOFF	2950.0	---	---
RCE-31	8	33	10	3W4	DUKE AE#2089E	WELL	2970.0	69	27
RCE-32	8	33	10	3W4	DUKE AE#2079E	WELL	2970.0	778	383
RCC-15	9	33	10	3W4	SUMMER-CLOUDB	PPT.	2975.0	---	---
RCA-67	9	33	10	3W4	L.ZIEGLER	WELL	2960.0	110	-99
RCA-25	12	35	10	3W4	B.OTTO	DUGWELL	3025.0	7	1
RCC-39	12	35	10	3W4	B.OTTO	DUGWELL	3025.0	---	---
RCA-26	16	36	10	3W4	G.V.M.RANCH	WELL	3100.0	30	12
RCA-60	1	1	10	4W4	M.RATH-OLD HOU	WELL	3500.0	-99	-99
RCC-33	4	1	10	4W4	M.RATH-STOCK	WELL	3525.0	18	6
RCB-12	5	3	10	4W4	FALCON RANCH	F.WELL	3175.0	80	0
RCB-18	4	6	10	4W4	CLARK	WELL	3310.0	32	1
RCB-13	16	9	10	4W4	SCHEFFELMEIR	WELL	3090.0	11	3
RCA-61	1	14	10	4W4	M.REIGER	SPRING	3360.0	0	0
RCB-49	7	18	10	4W4	LANGE	WELL	3105.0	70	30
RCE-33	12	25	10	4W4	D.MEIER	WELL	3000.0	30	24
RCB-26	16	27	10	4W4	WILDE	WELL	3000.0	55	-99
RCB-20	[illegible]	28	10	4W4	I.NEITZ	WELL	2925.0	70	28
RCB-21	[illegible]	31	10	4W4	A.WUTZKE	WELL	2850.0	18	10
RCE-27	13	35	10	4W4	C.ZEIGLER	WELL	3000.0	22	12
RCB-17	16	12	10	5W4	D.SCHORR	DUGOUT	3140.0	---	---
RCA-29	11	31	11	2W4	IRVINE P-CAN	WELL	2500.0	340	295
RCC-22	16	31	11	2W4	IRVINE P-CAN	WELL	2500.0	---	---
RCE-12	16	31	11	2W4	IRVINE P-CAN	WELL	2500.0	---	---
RCA-31	16	32	11	2W4	A.BROST	DUGOUT	2575.0	---	---
RCD-24	1	4	11	3W4	WINTER	PPT.	3375.0	---	---
RCE-34	[illegible]	4	11	3W4	SNOW	MELT	2960.0	---	---
RCE-35	2	4	11	3W4	WINTER(N)	PPT.	2960.0	---	---
RCA-66	15	5	11	3W4	W.STUBER	DUGOUT	2920.0	---	---
RCA-65	1	6	11	3W4	G.RETELBACK	DUGOUT	2940.0	---	---
RCE-3	9	9	11	3W4	WINTER(N)	PPT.	2825.0	---	---

Table A.2.1. (con.)

SAMPLE	LOCATION	OWNER DESCRIPTION	TYPE OF WATER	ALTITUDE OF SAMPLING POINT	DEPTH OF WELL	DEPTH TO WATER
MT-3	13 10 11 3W4	SNOWMELT	PUDDLE	2975.0	---	---
RCA-68	3 15 11 3W4	SUMMER	PPT	2620.0	---	---
RCB-50	3 15 11 3W4	ACREAGE	WELL	2615.0	---	---
RCA-69	13 17 11 3W4	R.DEERING	WELL	2700.0	16	12
RCA-70	5 23 11 3W4	R.RESCH	WELL	2575.0	10	5
RCC-40	13 23 11 3W4	R.RESCH	WELL	2575.0	80	65
RCE-23	1 25 11 3W4	SNOW	MELT	2625.0	---	---
RCB-51	15 28 11 3W4	COUILLARD	WELL	2650.0	400	260
RCE-11	11 34 11 3W4	ROSS	CREEK	2465.0	---	---
RCD-23	12 34 11 3W4	WINTER	PPT	2585.0	---	---
RCA-46	3 35 11 3W4	K.FRIEMARK	SPRING	2460.0	---	---
RCC-41	3 35 11 3W4	K.FRIEMARK	SPRING	2460.0	0	0
RCE-13	4 35 11 3W4	K.FRIEMARK	SPRING	2460.0	---	---
RCB-25	11 2 11 4W4	E.YANKE	WELL	2910.0	---	---
RCB-27	5 5 11 4W4	RENKE	WELL	2825.0	35	25
RCB-28	1 8 11 4W4	A.RIEGER	WELL	2800.0	14	7
RCE-25	8 9 11 4W4	DUKE AE#2092E	WELL	2790.0	22	10
RCE-26	8 9 11 4W4	DUKE AE#2091E	WELL	2790.0	79	13
RCE-28	7 20 11 4W4	C.SCHMIDEK	SPRING	2675.0	207	58
RCB-30	8 21 11 4W4	W.LENTZ	SPRING	2450.0	0	0
RCC-17	1 24 11 4W4	E.PINDER	WELL	2700.0	0	0
RCB-32	13 24 11 4W4	WUTCH	SLOUGH	2640.0	50	17
RCE-24	13 24 11 4W4	WUTCH	SLOUGH	2640.0	---	---
RCE-21	16 25 11 4W4	DUKE AE#2080E	WELL	2650.0	---	---
RCE-22	16 25 11 4W4	DUKE AE#2081E	WELL	2650.0	226	162
RCB-29	13 30 11 4W4	E.JANS	WELL	2560.0	66	55
RCB-31	5 34 11 4W4	G.LENTZ	WELL	2580.0	-99	7
RCB-44	15 36 11 4W4	A.ELHART	WELL	2600.0	30	15
RCA-32	16 7 12 2W4	M.BROST	WELL	2600.0	52	46
RCC-21	16 7 12 2W4	M.BROST	WELL	2600.0	110	60
RCA-37	1 30 12 2W4	C.ZIEGLER	WELL	2660.0	---	---
RCA-30	1 1 12 3W4	H.AMAN	WELL	2500.0	60	40
RCA-45	1 5 12 3W4	R.PFAFF	SPRING	2450.0	76	30
RCE-14	1 5 12 3W4	R.PFAFF	SPRING	2450.0	0	0
RCA-33	5 15 12 3W4	R.FRANZ	WELL	2520.0	---	---
RCC-20	5 15 12 3W4	R.FRANZ	WELL	2520.0	---	---
RCA-44	1 18 12 3W4	G.ZIEGENHAGEL	SEEP	2420.0	---	---
RCA-40	8 20 12 3W4	R.ROTH	WELL	2475.0	0	0
RCA-36	8 24 12 3W4	J.ZELLER	SPRING	2550.0	30	9
RCA-35	11 24 12 3W4	A.ZELLER	DUGOUT	2565.0	0	0
RCA-34	11 24 12 3W4	A.ZELLER	WELL	2575.0	---	---
RCA-39	9 27 12 3W4	H.BROST	WELL	2625.0	36	25
RCC-19	9 27 12 3W4	H.BROST	WELL	2625.0	304	200
RCA-42	15 31 12 3W4	W.DRISCOLL	WELL	2480.0	---	---
RCC-18	15 31 12 3W4	W.DRISCOLL	WELL	2480.0	15	5
RCA-41	12 33 12 3W4	E.MILLER	WELL	2550.0	---	---
RCA-38	4 36 12 3W4	R.HAUSAUER	WELL	2700.0	65	24
RCB-33	5 7 12 4W4	DIETELBACH	WELL	2415.0	25	15
RCB-52	4 8 12 4W4	VEHICLE INSP ST	WELL	2440.0	-99	21
RCB-37	3 9 12 4W4	DUNMORE CAMPGND	WELL	2400.0	40	20
RCB-36	4 10 12 4W4	DAVIES	WELL	2440.0	30	25
RCE-16	16 10 12 4W4	DUKE AE#2088E	WELL	2380.0	30	25
RCE-17	16 10 12 4W4	DUKE AE#2087E	WELL	2380.0	118	16
RCE-18	16 10 12 4W4	DUKE AE#2086E	WELL	2380.0	49	19
RCB-34	1 11 12 4W4	PASHLEY	WELL	2425.0	243	16
RCE-2	10 12 12 4W4	SNOW	MELT	2380.0	12	9
RCE-1	10 12 12 4W4	WINTER(N)	PPT	2380.0	---	---
RCA-43	16 13 12 4W4	B.ZIEGENHAGEL	WELL	2430.0	---	---
RCB-35	3 14 12 4W4	B.SCHNEIDER	SPRING	2420.0	46	14
RCE-19	8 15 12 4W4	SNOW	MELT	2420.0	0	0
RCE-20	8 15 12 4W4	WINTER(N)	PPT	2420.0	---	---
RCE-15	8 15 12 4W4	B.SCHNEIDER	SPRING	2370.0	---	---
RCB-39	1 19 12 4W4	LA POULET FARM	WELL	2300.0	---	---
RCB-40	11 32 12 4W4	SCHMIPF	WELL	2350.0	60	12
RCB-53	11 2 12 5W4	DUNMORE TOWN	WELL	2425.0	341	80
RCB-38	6 12 12 5W4	CAVAN	WELL	2375.0	165	87
RCB-43	7 23 12 5W4	J.STOCK	WELL	2275.0	12	8
RCB-42	11 24 12 5W4	HOFFMAN	F.WELL	2350.0	95	-99
RCE-30	11 24 12 5W4	HOFFMAN	F.WELL	2350.0	0	0
RCB-41	14 24 12 5W4	HOFFMAN	SEEP	2340.0	---	---
RCD-22	1 30 12 5W4	WINTER	PPT	2335.0	5	0
RCE-29	8 35 12 6W4	SOUTH SASK-MH	RIVER	2200.0	---	---
MT-1	10 35 12 6W4	SOUTH SASK-MH	RIVER	2175.0	---	---

Table A.2.2. Available physical well and spring data. The zone of completion is calculated from the elevation of the sampling point, assuming 100 feet of glacial drift everywhere north of Elkwater Lake. Source: Groundwater Information files and Ophori and Tóth (1983).

SAMPLE	LOCATION	OWNER DESCRIPTION	TYPE OF WATER	ALTITUDE (IN FEET)	DEPTH OF WELL	ELEVATION OF WELL	ZONE OF COMPLETION	DEPTH TO WATER	ELEVATION OF WATER
RCA-1	13 11 8 3W4	CHPP-NICHOLLS	SPRING	4700.0	0.0	4700.0	CYPRESS HILLS	0.0	4700.0
RCA-3	7 23 8 3W4	CHPP-[illegible]REROCK	WELL	4050.0	250.0	3800.0	EASTEND FM	74.0	3976.0
RCA-5	12 23 8 3W4	CHPP	SEEP	4100.0	0.0	4100.0	GLACIAL TILL	0.0	4100.0
RCA-6	7 24 8 3W4	EL[illegible]TER TOWN	WELL	4050.0	130.0	3920.0	EASTEND FM	119.0	3931.0
RCA-7	11 25 8 3W4	[illegible]	WELL	4000.0	112.0	3888.0	EASTEND FM	40.0	3960.0
RCA-10	13 14 9 3W4	[illegible]-FIELD	SPRING	3675.0	0.0	3675.0	GLACIAL TILL	0.0	3675.0
RCA-11	4 24 9 3W4	B.WEISS-HOMEST	SPRING	3640.0	4.0	3636.0	GLACIAL TILL	0.0	3640.0
RCA-12	15 8 9 3W4	V.IGNATIUS	SPRING	3740.0	0.0	3740.0	GLACIAL TILL	0.0	3740.0
RCA-13	1 22 9 3W4	B.WEISS-CORRAL	SPRING	3625.0	0.0	3625.0	GLACIAL TILL	0.0	3625.0
RCA-14	7 26 9 3W4	V.SVADLING	F.WELL	3510.0	10.0	3500.0	GLACIAL TILL	0.0	3510.0
RCA-15	4 25 9 3W4	C.HERMANN	S.SEEP	3490.0	0.0	3490.0	GLACIAL TILL	0.0	3490.0
RCA-16	8 13 9 3W4	J.ENGLER	SPRING	3675.0	0.0	3675.0	GLACIAL TILL	0.0	3675.0
RCA-17	4 30 9 2W4	E.MACK-CORRAL	SPRING	3476.0	0.0	3476.0	GLACIAL TILL	0.0	3476.0
RCA-18	1 19 9 2W4	E.MACK-HOMESTE	SPRING	3625.0	0.0	3625.0	GLACIAL TILL	0.0	3625.0
RCA-20	8 19 9 2W4	D.NEUBAUER	SPRING	3525.0	0.0	3525.0	GLACIAL TILL	0.0	3525.0
RCA-21	13 7 10 2W4	A.SCHORR	WELL	3190.0	5.0	3185.0	GLACIAL TILL	0.0	3190.0
RCA-22	1 14 10 3W4	F.BOLLINGER	WELL	3200.0	20.0	3180.0	GLACIAL TILL	1.0	3199.0
RCA-23	6 24 10 3W4	KRAUSS	F.WELL	3075.0	10.0	3065.0	GLACIAL TILL	0.0	3075.0
RCA-25	12 35 10 3W4	B.OTTO	DUGWELL	3025.0	7.0	3018.0	GLACIAL TILL	1.0	3024.0
RCA-26	16 36 10 3W4	G.V.M.RANCH	WELL	3100.0	30.0	3070.0	GLACIAL TILL	12.0	3088.0
RCA-28	16 30 10 2W4	B.SCHORR	DUGWELL	3115.0	26.0	3089.0	GLACIAL TILL	16.0	3099.0
RCA-29	11 31 11 2W4	IRVINE P-CAN	WELL	2500.0	340.0	2160.0	OLDMAN FM	295.0	2205.0
RCA-30	1 1 12 3W4	H.AMAN	WELL	2500.0	76.0	2424.0	GLACIAL TILL	30.0	2470.0
RCA-32	16 7 12 2W4	M.BROST	WELL	2600.0	110.0	2490.0	OLDMAN FM	60.0	2540.0
RCA-34	11 24 12 3W4	A.ZELLER	WELL	2575.0	36.0	2539.0	GLACIAL TILL	25.0	2550.0
RCA-36	8 24 12 3W4	J.ZELLER	SPRING	2550.0	0.0	2550.0	GLACIAL TILL	0.0	2550.0
RCA-37	1 30 12 2W4	C.ZIEGLER	WELL	2660.0	60.0	2600.0	GLACIAL TILL	40.0	2620.0
RCA-38	4 36 12 3W4	R.HAUSAUER	WELL	2700.0	25.0	2675.0	GLACIAL TILL	15.0	2685.0
RCA-39	8 27 12 3W4	H.BROST	WELL	2625.0	304.0	2321.0	OLDMAN FM	200.0	2425.0
RCA-40	8 20 12 3W4	R.ROTH	WELL	2475.0	30.0	2445.0	GLACIAL TILL	9.0	2466.0
RCA-41	12 33 12 3W4	E.MILLER	WELL	2550.0	65.0	2485.0	GLACIAL TILL	24.0	2526.0
RCA-42	15 31 12 3W4	V.DRISCOLL	WELL	2480.0	15.0	2465.0	GLACIAL TILL	5.0	2475.0
RCA-43	16 13 12 4W4	B.ZIEGENHAGEL	WELL	2430.0	46.0	2384.0	GLACIAL TILL	14.0	2416.0
RCA-44	1 18 12 3W4	G.ZIEGENHAGEL	SEEP	2420.0	0.0	2420.0	GLACIAL TILL	0.0	2420.0
RCA-45	1 8 12 3W4	R.PFAFF	SPRING	2450.0	0.0	2450.0	GLACIAL TILL	0.0	2450.0
RCA-46	3 35 11 3W4	K.FRIEMARK	SPRING	2460.0	0.0	2460.0	GLACIAL TILL	0.0	2460.0
RCA-47	3 13 8 3W4	CHPP-MITCHELL	SPRING	4660.0	0.0	4660.0	CYPRESS HILLS	0.0	4660.0
RCA-50	7 7 8 2W4	CHPP	SEEP	4712.0	0.0	4712.0	CYPRESS HILLS	0.0	4712.0
RCA-52	2 21 8 2W4	CHPP-PINES	SPRING	4630.0	0.0	4630.0	RAVENSCRAG FM	0.0	4630.0
RCA-53	14 30 8 2W4	FELESKY	WELL	4000.0	120.0	3880.0	EASTEND FM	18.0	3982.0
RCA-55	14 2 9 3W4	D.LYALL	WELL	3875.0	187.0	3688.0	EASTEND FM	90.0	3785.0
RCA-56	15 15 9 3W4	H.SEITZ	SPRING	3650.0	0.0	3650.0	GLACIAL TILL	0.0	3650.0
RCA-57	7 4 10 3W4	R.JANS-HOUSE	F.WELL	3375.0	218.0	3157.0	BEARPAW SHALE	0.0	3375.0
RCA-58	6 4 10 3W4	R.JANS-STOCK	WELL	3400.0	14.0	3386.0	GLACIAL TILL	10.0	3390.0
RCA-61	1 1[illegible] 10 4W4	M.REIGER	SPRING	3360.0	0.0	3360.0	GLACIAL TILL	0.0	3360.0
RCA-64	10 30 10 3W4	C.GILL	WELL	3070.0	15.0	3055.0	GLACIAL TILL	13.0	3057.0
RCA-67	9 33 10 3W4	L.ZIEGLER	WELL	2960.0	110.0	2850.0	BEARPAW SHALE	--	---
RCA-68	13 17 11 3W4	R.DEERING	WELL	2700.0	10.0	[illegible]	GLACIAL TILL	5.0	2695.0
RCA-70	5 23 11 3W4	R.RESCH	WELL	2575.0	80.0	2495.0	GLACIAL TILL	65.0	2510.0
RCA-71	14 8 9 2W4	E.MACK-FIELD	SEEP	3740.0	0.0	3740.0	GLACIAL TILL	0.0	3740.0
RCB-1	2 24 9 4W4	K.SAILER	SPRING	3540.0	0.0	3540.0	GLACIAL TILL	0.0	3540.0
RCB-2	13 5 8 3W4	L.PFIEFFER	WELL	3675.0	36.0	3639.0	GLACIAL TILL	25.0	3650.0
RCB-3	11 30 8 3W4	BROWN EST.-H	SPRING	3750.0	0.0	3750.0	GLACIAL TILL	0.0	3750.0
RCB-4	6 29 8 3W4	BROWN EST.-F	SPRING	3900.0	0.0	3900.0	GLACIAL TILL	0.0	3900.0
RCB-5	14 12 9 4W4	FLATG	F.WELL	3400.0	2.0	3398.0	GLACIAL TILL	0.0	3400.0
RCB-6	16 2 9 4W4	A.RATH	WELL	3625.0	20.0	3605.0	GLACIAL TILL	16.0	3609.0
RCB-7	10 4 9 4W4	DRAUDSON#1	WELL	3650.0	48.0	3602.0	GLACIAL TILL	30.0	3620.0
RCB-8	1 16 9 4W4	DRAUDSON#2	WELL	3600.0	12.0	[illegible]	GLACIAL TILL	7.0	3593.0
RCB-9	1 20 9 4W4	BURGEVITZ	DUGWELL	3575.0	10.0	[illegible]	GLACIAL TILL	6.0	3569.0
RCB-10	13 23 9 4W4	BOSCHEE	F.WELL	3375.0	80.0	3295.0	GLACIAL TILL	0.0	3375.0
RCB-11	8 23 9 4W4	GEIGLE	WELL	3450.0	8.0	3442.0	GLACIAL TILL	2.0	3448.0
RCB-12	5 3 10 4W4	FALCON RANCH	F.WELL	3175.0	80.0	3095.0	GLACIAL TILL	0.0	3175.0
RCB-13	16 9 10 4W4	SCHEFFELMEIR	WELL	3090.0	11.0	3079.0	GLACIAL TILL	3.0	3087.0
RCB-14	11 28 9 4W4	R.REIGER	WELL	3360.0	43.0	3317.0	GLACIAL TILL	15.0	3345.0
RCB-16	5 36 9 5W4	G.SEITZ	WELL	3525.0	28.0	3497.0	GLACIAL TILL	14.0	3511.0
RCB-18	4 6 10 4W4	CLARK	WELL	3310.0	32.0	3278.0	GLACIAL TILL	1.0	3309.0
RCB-19	7 18 10 4W4	LANGE	WELL	3105.0	70.0	3035.0	GLACIAL TILL	30.0	3075.0
RCB-20	5 28 10 4W4	I.MEITZ	WELL	2925.0	70.0	2855.0	GLACIAL TILL	28.0	2897.0
RCB-21	8 31 10 4W4	A.MUTZKE	WELL	2850.0	18.0	2832.0	GLACIAL TILL	10.0	2840.0
RCB-22	4 27 8 3W4	RUSSIL	SPRING	3875.0	0.0	3875.0	GLACIAL TILL	0.0	3875.0
RCB-24	3 22 10 3W4	J.GILL	SPRING	3125.0	0.0	3125.0	GLACIAL TILL	0.0	3125.0
RCB-25	11 2 11 4W4	E.YANKE	WELL	2910.0	35.0	2875.0	GLACIAL TILL	25.0	2885.0
RCB-26	16 27 10 4W4	WILDE	WELL	3000.0	55.0	2945.0	GLACIAL TILL	--	---
RCB-27	5 5 11 4W4	RENKE	WELL	2825.0	14.0	2811.0	GLACIAL TILL	7.0	2818.0
RCB-28	1 8 11 4W4	A.RIEGER	WELL	2800.0	22.0	2778.0	GLACIAL TILL	10.0	2790.0
RCB-29	13 30 11 4W4	E.JANS	WELL	2560.0	--	----	---	7.0	2553.0
RCB-30	8 21 11 4W4	W.LENTZ	SPRING	2450.0	0.0	2450.0	GLACIAL TILL	0.0	2450.0
RCB-31	5 34 11 4W4	G.LENTZ	WELL	2580.0	30.0	2550.0	GLACIAL TILL	15.0	2565.0
RCB-33	5 7 12 4W4	DIETELBACH	WELL	2415.0	--	---	---	21.0	2394.0
RCB-34	1 11 12 4W4	PASHLEY	WELL	2425.0	12.0	2413.0	GLACIAL TILL	9.0	2416.0
RCB-35	3 14 12 4W4	B.SCHNEIDER	SPRING	2420.0	0.0	2420.0	GLACIAL TILL	0.0	2420.0
RCB-36	4 10 12 4W4	DAVIES	WELL	2440.0	30.0	2410.0	GLACIAL TILL	25.0	2415.0
RCB-37	3 9 12 4W4	DUNMORE CAMPGND	WELL	2400.0	30.0	2370.0	GLACIAL TILL	25.0	2375.0
RCB-38	6 12 12 5W4	CAVAN	WELL	2375.0	12.0	2363.0	GLACIAL TILL	8.0	2367.0
RCB-39	1 19 12 4W4	LA POULET FARM	WELL	2300.0	60.0	2240.0	GLACIAL TILL	12.0	2288.0
RCB-40	11 32 12 4W4	SCHNIPF	WELL	2350.0	341.0	2009.0	OLDMAN FM	80.0	2270.0
RCB-41	14 24 12 5W4	HOFFMAN	SEEP	2340.0	5.0	2335.0	GLACIAL TILL	0.0	2340.0
RCB-42	11 24 12 5W4	HOFFMAN	F.WELL	2350.0	0.0	2350.0	GLACIAL TILL	0.0	2350.0
RCB-43	7 23 12 5W4	J.STOCK	WELL	2275.0	95.0	2180.0	GLACIAL TILL	---	---
RCB-44	15 36 11 4W4	A.ELHART	WELL	2600.0	52.0	2548.0	GLACIAL TILL	46.0	2554.0
RCB-47	10 19 8 2W4	CHPP-GROUP CAMP	WELL	4025.0	115.0	3910.0	EASTEND FM	38.0	3987.0
RCB-50	3 15 11 3W4	ACREAGE	WELL	2615.0	16.0	2599.0	GLACIAL TILL	12.0	2603.0
RCB-51	15 28 11 3W4	COUILLARD	WELL	2650.0	400.0	2250.0	OLDMAN FM	260.0	2390.0
RCB-52	4 8 12 4W4	VEHICLE INSP ST	WELL	2440.0	40.0	[illegible]	GLACIAL TILL	20.0	2420.0
RCB-53	11 2 12 5W4	DUNMORE TOWN	WELL	2425.0	165.0	2260.0	OLDMAN FM	87.0	2338.0
RCC-4	10 27 8 2W4	CHPP-S. COULEE	SPRING	4400.0	0.0	4400.0	FRENCHMAN BUTTE	0.0	4400.0
RCC-8	2 16 8 2W4	CHPP-MOOSE PAST.	SEEP	4300.0	0.0	4300.0	WHITEMUD FM	0.0	4300.0
RCC-10	6 18 8 2W4	CHPP-SKI RUN	SPRING	4550.0	0.0	4550.0	RAVENSCRAG FM	0.0	4550.0
RCC-13	2 28 8 2W4	CHPP-BENCHES	SPRING	4600.0	0.0	4600.0	RAVENSCRAG FM	0.0	4600.0
RCC-17	1 24 11 4W4	E.PINDER	WELL	2700.0	50.0	2650.0	GLACIAL TILL	17.0	2683.0
RCC-26	10 16 9 3W4	KAJEWSKY	SPRING	4100.0	0.0	4100.0	GLACIAL TILL	0.0	4100.0
RCC-31	1 4 9 2W4	ROAD ALLOWANCE	F.WELL	4010.0	15.0	3995.0	GLACIAL TILL	0.0	4010.0
RCC-32	8 5 9 2W4	E.NEUBAUER	SPRING	3942.0	0.0	3942.0	GLACIAL TILL	0.0	3942.0
RCC-33	4 1 10 4W4	M.RATH-STOCK	WELL	3525.0	18.0	3507.0	GLACIAL TILL	6.0	3519.0
RCC-34	13 36 9 4W4	M.RATH-GARDEN	WELL	3535.0	15.0	3520.0	GLACIAL TILL	11.0	3524.0
RCD-15	8 18 9 2W4	J.MACK	SPRING	3725.0	0.0	3725.0	GLACIAL TILL	0.0	3725.0
WF-4	16 33 9 3W4	VOSSLER	S.SEEP	3520.0	0.0	3520.0	GLACIAL TILL	0.0	3520.0
RCE-6	6 24 8 3W4	CHPP AE#2084E	WELL	4060.0	112.0	3948.0	EASTEND FM	99.0	3961.0
RCE-7	12 8 8 2W4	DUKE AE#2093E	WELL	4710.0	46.0	4664.0	CYPRESS HILLS	42.0	4668.0
RCE-8	12 8 8 2W4	DUKE AE#2084E	WELL	4710.0	312.0	4398.0	FRENCHMAN BUTTE	292.0	4418.0

Table A.2.2. (con'.)

SAMPLE	LOCATION	OWNER DESCRIPTION	TYPE OF WATER	ALTITUDE (IN FEET)	DEPTH OF WELL	ELEVATION OF WELL	ZONE OF COMPLETION	DEPTH TO WATER	ELEVATION OF WATER
RCE-16	16 10 12 4W4	DUKE AE#2088E	WELL	2380.0	118.0	2262.0	OLDMAN FM	16.0	2364.0
RCE-17	16 10 12 4W4	DUKE AE#2087E	WELL	2380.0	49.0	2331.0	GLACIAL TILL	19.0	2361.0
RCE-18	16 10 12 4W4	DUKE AE#2086E	WELL	2380.0	243.0	2137.0	OLDMAN FM	16.0	2364.0
RCE-21	16 25 11 4W4	DUKE AE#2080E	WELL	2650.0	226.0	2424.0	OLDMAN FM	162.0	2488.0
RCE-22	16 25 11 4W4	DUKE AE#2081E	WELL	2650.0	66.0	2584.0	GLACIAL TILL	55.0	2595.0
RCE-25	8 9 11 4W4	DUKE AE#2092E	WELL	2790.0	79.0	2711.0	GLACIAL TILL	13.0	2777.0
RCE-26	8 9 11 4W4	DUKE AE#2091E	WELL	2790.0	207.0	2583.0	OLDMAN FM	58.0	2732.0
RCE-27	13 35 10 4W4	C.ZEIGLER	WELL	3000.0	22.0	2978.0	GLACIAL TILL	12.0	2988.0
RCE-28	7 20 11 4W4	C.SCHMIDEK	SPRING	2675.0	0.0	2675.0	GLACIAL TILL	0.0	2675.0
RCE-31	8 33 10 3W4	DUKE AE#2089E	WELL	2970.0	69.0	2901.0	GLACIAL TILL	27.0	2943.0
RCE-32	8 33 10 3W4	DUKE AE#2079E	WELL	2970.0	778.0	2192.0	OLDMAN FM	383.0	2587.0
RCE-33	12 25 10 4W4	D MEIER	WELL	3000.0	30.0	2970.0	GLACIAL TILL	24.0	2976.0

APPENDIX III: GROUNDWATER HYDROCHEMISTRY

Groundwater quality, is in general, poor in Ross Creek Basin, as it is in most till-covered areas of the Great Plains. Potable water exists only near recharge points in the Cypress Hills, and the quality is doubtless enhanced by the lack of till in this region. Groundwater quality degrades rapidly as one travels north from the Plateau.

In the present study, groundwater chemistry data were principally utilized to examine relationships between ionic consituents and isotope content. In particular, it was thought that relationships between hydrochemical facies such as potassium and sodium versus ^{14}C age might demonstrate a strongly positive correlation. In addition, possible links between the stable isotopic content of the groundwater and the chemistry were also sought.

Few positive results were noted in Pearson correlation analyses. These analyses were fraught with two major difficulties: 1)there were too few tritium and ^{14}C analyses for significant trends to be pointed up in the calculations; and 2)very low correlations between the stable isotopes and chemistry data were often significant because of the high number of samples involved. No correlation between hydrochemical facies factors (such as percentage chloride) and ^{14}C were noted. In addition, weak positive correlations were found between the stable isotopes and most ionic constituents. Closer examination of the data and possible future visits, with simultaneous isotopic and groundwater quality sampling are needed to draw conclusions about the groundwater chemistry in the area.

Table A.3.1. Groundwater quality results: Part 1. All values given in mg/L. Source: Groundwater Information Centre files and Ophori and Tóth (1983).

SAMPLE	LOCATION	OWNER DESCRIPTION	TYPE OF WATER	CA	MG	K	NA	CL	SO4	CO3	HCO3
RCA-1	13 11 8 3W4	CHPP-NICHOLLS	SPRING	64.00	4.25	0.39	2.30	4.80	1.77	0.0	175.50
RCA-4	11 24 8 3W4	CHPP-ELKWATER	LAKE	29.00	35.00	3.70	14.00	20.00	5.00	0.0	251.00
RCA-6	7 24 8 3W4	ELKWATER TOWN	WELL	51.00	26.00	0.0	96.00	78.00	4.00	0.0	436.00
RCA-7	11 25 8 3W4	A.PETER	WELL	26.00	6.10	6.26	2.30	7.20	3.55	0.0	112.85
RCA-9	11 35 8 3W4	B.SCHORR	SLOUGH	27.00	13.98	23.46	2.30	2.40	7.09	0.0	186.05
RCA-10	13 14 9 3W4	B.WEISS-FIELD	SPRING	86.00	29.77	13.69	286.70	420.00	14.18	10.80	642.94
RCA-12	15 9 9 3W4	J.IGNATIUS	SPRING	81.00	30.38	9.38	195.50	324.00	5.32	0.0	531.92
RCA-14	7 26 9 3W4	W.SWADLING	F.WELL	220.00	131.00	8.70	269.00	1266.00	37.00	0.0	472.00
RCA-16	9 13 9 3W4	J.ENGLER	SPRING	67.00	21.87	7.43	142.60	141.60	3.55	0.0	539.24
RCA-17	4 30 9 2W4	E.MACK-CORRAL	SPRING	92.00	40.00	6.20	106.00	239.00	8.00	10.00	431.00
RCA-20	9 19 9 2W4	D.NEUBAUER	SPRING	200.00	150.00	0.0	167.70	176.40	0.0	0.0	0.0
RCA-21	13 7 10 2W4	A.SCHORR	WELL	160.00	99.63	34.41	94.30	453.60	33.68	0.0	395.89
RCA-23	6 24 10 3W4	KRAUSS	F.WELL	138.00	127.58	13.69	264.50	720.00	88.63	0.0	589.26
RCA-25	12 35 10 3W4	B.OTTO	DUGWELL	130.00	43.74	8.60	34.50	237.60	7.09	0.0	395.89
RCA-26	16 36 10 3W4	G.V.M.RANCH	WELL	0.0	0.0	0.0	0.0	2200.00	41.00	0.0	432.00
RCA-28	16 30 10 2W4	B.SCHORR	DUGWELL	264.00	144.00	0.0	0.0	910.00	35.00	0.0	419.00
RCA-29	11 31 11 2W4	IRVINE P-CAN	WELL	331.00	82.00	7.40	198.00	750.00	72.00	0.0	677.00
RCA-31	16 32 11 2W4	A.BROST	DUGOUT	20.00	1.22	18.77	18.40	31.20	12.41	0.0	50.02
RCA-32	16 7 12 2W4	M.BROST	WELL	72.00	40.00	4.50	182.00	394.00	8.00	5.00	402.00
RCA-33	5 15 12 3W4	R.FRANZ	WELL	100.00	84.44	6.26	234.60	614.40	19.50	0.0	605.12
RCA-34	11 24 12 3W4	A.ZELLER	WELL	0.0	0.0	0.0	0.0	2311.00	46.00	0.0	0.0
RCA-36	8 24 12 3W4	J.ZELLER	SPRING	60.00	120.00	0.0	0.0	184.00	25.00	0.0	0.0
RCA-37	1 30 12 2W4	C.ZIEGLER	WELL	0.0	0.0	0.0	0.0	853.00	166.00	0.0	868.00
RCA-38	4 36 12 3W4	R.HAUSAUER	WELL	60.00	34.00	12.00	8.00	26.00	5.00	0.0	351.00
RCA-39	9 27 12 3W4	H.BROST	WELL	66.00	71.00	8.50	583.00	982.00	22.00	0.0	924.00
RCA-40	8 20 12 3W4	R.ROTH	WELL	170.00	158.00	0.0	278.30	1105.00	21.00	0.0	490.00
RCA-42	15 31 12 3W4	W.DRISCOLL	WELL	84.00	77.00	0.0	0.0	414.00	27.00	0.0	280.00
RCA-43	16 13 12 4W4	B.ZIEGENHAGEL	WELL	45.00	27.30	4.30	455.40	427.20	15.95	0.0	919.88
RCA-46	3 35 11 3W4	K.FRIEMARK	SPRING	101.00	43.50	0.0	0.0	457.00	7.00	0.0	324.00
RCA-47	3 13 8 3W4	CHPP-MITCHELL	SPRING	100.00	50.00	0.0	0.0	10.00	2.00	0.0	0.0
RCA-52	2 21 8 2W4	CHPP-PINES	SPRING	89.00	12.76	0.39	4.60	7.20	3.55	0.0	321.47
RCA-53	14 30 8 2W4	FELESKY	WELL	64.00	48.00	0.0	0.0	25.00	5.00	0.0	0.0
RCA-56	16 15 9 3W4	H.SEITZ	SPRING	146.00	57.11	7.04	115.00	376.80	8.86	0.0	551.44
RCA-57	7 4 10 3W4	R.JANS-HOUSE	F.WELL	162.00	63.00	0.0	0.0	1000.00	21.00	0.0	796.00
RCA-62	13 18 10 3W4	J.LENTZ	DUGOUT	420.00	375.44	15.64	303.30	2740.80	23.04	0.0	585.60
RCA-64	10 30 10 3W4	C.GILL	WELL	430.00	573.48	16.03	609.50	3811.20	120.54	0.0	562.42
RCA-65	1 6 11 3W4	G.RETELBACK	DUGOUT	0.0	0.0	85.00	1700.00	5820.00	135.00	0.0	220.00
RCA-66	15 5 11 3W4	W.STUBER	DUGOUT	2.00	2.00	2.90	464.00	28.00	268.00	29.00	725.00
RCA-69	13 17 11 3W4	R.DEERING	WELL	160.00	84.00	0.0	0.0	180.00	20.00	0.0	0.0
RCA-70	5 23 11 3W4	R.RESCH	WELL	156.00	63.00	17.10	148.00	548.00	18.00	14.00	453.00
RCB-1	2 24 9 4W4	K.SAILER	SPRING	144.00	75.00	5.40	190.00	430.00	4.00	0.0	788.00
RCB-2	13 5 9 3W4	L.PFIEFFER	WELL	75.00	24.91	0.78	4.60	16.80	1.77	6.60	343.43
RCB-3	11 30 8 3W4	BROWN EST.-H	SPRING	133.00	60.14	11.73	128.80	432.00	5.32	0.0	516.06
RCB-5	14 12 9 4W4	FLAIG	F.WELL	112.00	41.31	10.95	292.10	489.60	7.09	0.0	702.11
RCB-10	13 23 9 4W4	BOSCHEE	F.WELL	215.00	96.00	0.0	470.50	1169.00	18.00	0.0	658.00
RCB-12	5 3 10 4W4	FALCON RANCH	F.WELL	0.0	0.0	0.0	0.0	49.30	10.70	0.0	520.00
RCB-13	16 9 10 4W4	SCHEFFELMEIR	WELL	210.00	116.00	0.0	0.0	674.00	106.00	0.0	544.00
RCB-14	11 28 9 4W4	R.REIGER	WELL	334.00	315.90	9.38	144.90	1848.00	70.90	0.0	503.25
RCB-16	5 36 9 5W4	G.SEITZ	WELL	46.00	170.00	0.0	60.50	180.00	136.00	0.0	302.00
RCB-18	4 6 10 4W4	CLARK	WELL	230.00	370.58	3.77	285.20	1118.40	207.38	0.0	823.50
RCB-20	5 28 10 4W4	I.NEITZ	WELL	142.00	54.68	6.65	135.70	441.60	15.95	0.0	484.95
RCB-21	8 31 10 4W4	A.WUTZKE	WELL	201.00	69.86	4.69	117.30	643.20	12.41	0.0	414.00
RCB-22	4 27 8 3W4	RUSSIL	SPRING	71.00	30.00	1.30	3.00	29.00	1.00	0.0	332.00
RCB-24	3 22 10 3W4	J.GILL	SPRING	137.00	82.00	0.0	145.60	510.00	11.00	0.0	420.00
RCB-25	11 2 11 4W4	E.YANKE	WELL	144.00	68.04	3.52	27.60	160.80	10.64	0.0	606.95
RCB-27	5 5 11 4W4	RENKE	WELL	424.00	52.26	14.86	101.20	312.00	23.04	0.0	496.54
RCB-28	1 8 11 4W4	A.RIEGER	WELL	189.00	65.00	5.90	128.00	402.00	35.00	0.0	432.00
RCB-29	13 30 11 4W4	E.JANS	WELL	30.00	12.15	3.13	374.00	69.60	90.40	45.50	882.90
RCB-30	8 21 11 4W4	W.LENTZ	SPRING	83.00	52.00	3.70	132.00	293.00	3.00	0.0	486.00
RCB-31	5 34 11 4W4	G.LENTZ	WELL	114.00	49.00	25.00	19.00	124.00	33.00	0.0	463.00
RCB-33	5 7 12 4W4	DIETELE CH	WELL	297.00	130.00	12.40	600.00	2377.00	48.00	0.0	528.00
RCB-36	4 10 12 4W4	DAVIES	WELL	99.00	43.70	1.56	13.80	112.80	3.55	0.0	417.24
RCB-37	3 9 12 4W4	DUNMORE CAMPGND	WELL	14.00	9.72	8.21	52.10	14.40	8.86	68.40	94.55
RCB-38	6 12 12 5W4	CAVAN	WELL	107.00	54.00	15.20	63.00	319.00	26.00	0.0	419.00
RCB-39	1 19 12 4W4	LA POULET FARM	WELL	45.00	40.70	3.91	395.60	410.40	44.31	0.0	829.60
RCB-40	11 32 12 4W4	SCHMIPF	WELL	42.00	33.00	3.60	650.00	462.00	98.00	0.0	1304.00
RCB-41	14 24 12 5W4	HOFFMAN	SEEP	217.00	94.00	0.90	59.00	289.00	2.00	0.0	823.00
RCB-43	7 23 12 5W4	J.STOCK	WELL	28.00	30.00	5.90	244.00	30.00	50.00	4.00	741.00
RCB-44	15 36 11 4W4	A.ELHART	WELL	160.00	160.00	0.0	51.20	28.00	12.00	0.0	0.0
RCB-47	10 19 8 2W4	CHPP-GROUP CAMP	WELL	57.00	12.00	0.60	4.00	8.00	1.00	0.0	247.00
RCB-50	3 15 11 3W4	ACREAGE	WELL	357.00	60.00	13.80	195.00	750.00	36.00	0.0	781.00
RCB-51	15 28 11 3W4	COUILLARD	WELL	0.0	0.0	0.0	42.70	97.00	222.00	0.0	582.00
RCB-53	11 2 12 5W4	DUNMORE TOWN	WELL	37.00	36.00	0.0	422.20	379.00	8.00	0.0	682.00
RCC-4	10 27 8 2W4	CHPP-S. COULEE	SPRING	200.00	115.00	0.0	0.0	25.00	4.00	0.0	0.0
RCC-10	6 18 8 2W4	CHPP-SKI RUN	SPRING	[illegible]	20.00	1.30	5.00	14.00	1.00	0.0	320.00
RCC-17	1 24 11 4W4	E.PINDER	WELL	[illegible]	1.00	1.90	183.00	59.00	2.00	0.0	424.00
RCC-31	1 4 9 2W4	ROAD ALLOWANCE	F.WELL	180.00	97.20	8.21	57.50	420.00	[illegible]	0.0	259.86
RCC-33	4 1 10 4W4	M.RATH-STOCK	WELL	270.00	191.00	0.0	182.10	1470.00	30.00	0.0	289.00
RCC-34	13 36 9 4W4	M.RATH-GARDEN	WELL	93.00	38.88	5.47	29.90	100.80	3.55	13.20	356.24
RCD-15	5 18 9 2W4	J.MACK	SPRING	60.00	24.00	6.90	139.00	160.00	2.00	0.0	525.00
RCE-7	12 8 8 2W4	DUKE AE#2093E	WELL	37.00	16.00	7.00	449.00	710.00	19.00	0.0	461.00
RCE-8	12 8 8 2W4	DUKE AE#2084E	WELL	130.00	58.00	11.00	150.00	514.00	13.00	0.0	476.00
RCE-15	8 15 12 4W4	B.SCHNEIDER	SPRING	146.00	54.68	6.65	180.90	580.80	14.18	0.0	485.56
RCE-21	16 25 11 4W4	DUKE AE#2080E	WELL	11.00	3.00	5.00	504.00	461.00	11.00	[illegible]	742.00
RCE-22	16 25 11 4W4	DUKE AE#2081E	WELL	143.00	75.00	14.00	170.00	720.00	19.00	0.0	302.00
RCE-28	7 20 11 4W4	C.SCHMIDEK	SPRING	98.00	66.00	5.00	100.00	426.00	12.00	0.0	377.00
RCE-31	8 33 10 3W4	DUKE AE#2089E	WELL	176.00	109.00	13.00	214.00	806.00	21.00	0.0	545.00
RCE-32	8 33 10 3W4	DUKE AE#2079E	WELL	1.00	2.00	23.00	690.00	12.00	560.00	209.00	491.00

Table A.3.2. Groundwater quality results: Part 2. Values of pH and EC(μs/cm) excluded, all levels given in mg/L. Source: Groundwater Information Centre files and Ophori and Tóth (1983).

SAMPLE	LOCATION	OWNER DESCRIPTION	TYPE OF WATER	PH	EC	HARDNESS	NH4 N	NO3 N	F	ALK	FE	TDS
RCA-1	13 11 8 3W4	CHPP-NICHOLLS	SPRING	7.90	270.00	177.50	0.05	0.30	0.10	176.00	0.01	184.45
RCA-4	11 24 8 3W4	CHPP-ELKWATER	LAKE	8.20	438.00	217.00	0.0	0.05	0.28	206.00	0.03	230.55
RCA-6	7 24 8 3W4	ELKWATER TOWN	WELL	7.70	0.0	234.00	0.0	0.0	0.15	358.00	0.13	469.93
RCA-7	11 25 8 3W4	A.PETER	WELL	0.0	0.0	260.00	0.0	0.0	0.0	0.0	0.53	51.94
RCA-9	11 35 8 3W4	B.SCHORR	SLOUGH	0.0	2520.00	120.00	0.0	0.0	0.0	145.00	0.13	163.36
RCA-10	13 14 9 3W4	B.WEISS-FIELD	SPRING	8.20	3060.00	1091.00	0.0	0.62	0.16	387.00	0.70	1095.99
RCA-12	15 9 9 3W4	J.IGNATIUS	SPRING	8.20	1390.00	600.00	0.05	2.45	0.21	452.00	0.02	927.65
RCA-14	7 26 9 3W4	W.SWADLING	F.WELL	8.40	1087.00	296.00	0.0	0.28	0.14	5.00	0.19	1836.13
RCA-16	9 13 9 3W4	J.ENGLER	SPRING	8.40	1700.00	337.50	0.20	0.05	0.24	545.00	0.03	711.30
RCA-17	4 30 9 2W4	E.MACK-CORRAL	SPRING	8.40	1103.00	395.00	0.0	0.45	0.25	370.00	0.28	715.45
RCA-20	9 19 9 2W4	D.NEUBAUER	SPRING	0.0	0.0	350.00	0.0	38.25	0.0	250.00	0.01	1013.56
RCA-21	13 7 10 2W4	A.SCHORR	WELL	8.20	380.00	225.00	0.10	0.75	0.26	228.00	0.01	1015.75
RCA-23	6 24 10 3W4	KRAUSS	F.WELL	8.20	1700.00	810.00	0.05	52.90	0.34	325.00	0.03	1781.78
RCA-25	12 35 10 3W4	B.OTTO	DUGWELL	8.70	2100.00	15.00	0.0	1.45	2.27	643.00	2.70	856.45
RCA-26	16 36 10 3W4	G.V.M.RANCH	WELL	8.20	1640.00	710.00	0.05	0.05	0.28	482.00	0.57	2530.99
RCA-28	16 30 10 2W4	B.SCHORR	DUGWELL	8.10	2920.00	885.00	0.20	0.05	0.48	637.00	1.13	1736.55
RCA-29	11 31 11 2W4	IRVINE P-CAN	WELL	7.90	2200.00	916.00	0.45	0.0	0.60	656.00	0.20	1834.20
RCA-31	16 32 11 2W4	A.BROST	DUGOUT	8.60	9940.00	4080.00	0.15	0.10	0.26	208.00	0.14	227.38
RCA-32	16 7 12 2W4	M.BROST	WELL	8.00	2150.00	598.00	0.80	1.55	0.60	523.00	0.92	1022.09
RCA-33	5 15 12 3W4	R.FRANZ	WELL	8.00	0.0	485.00	0.0	0.44	0.20	392.00	0.20	1298.95
RCA-34	11 24 12 3W4	A.ZELLER	WELL	8.00	3230.00	459.00	0.0	0.04	0.23	758.00	0.55	2812.53
RCA-36	8 24 12 3W4	J.ZELLER	SPRING	8.80	2000.00	180.00	0.0	0.0	0.0	357.00	0.10	603.30
RCA-37	1 30 12 2W4	C.ZIEGLER	WELL	0.0	0.0	0.0	0.0	26.00	0.0	525.00	0.0	1449.18
RCA-38	4 36 12 3W4	R.HAUSAUER	WELL	0.0	650.00	288.00	0.0	0.45	0.31	288.00	0.40	320.19
RCA-39	9 27 12 3W4	H.BROST	WELL	8.40	1385.00	343.00	0.0	10.80	0.32	333.00	0.06	1980.20
RCA-40	8 20 12 3W4	R.ROTH	WELL	0.0	0.0	1074.00	0.0	8.00	0.22	490.00	0.05	2061.79
RCA-42	15 31 12 3W4	W.DRISCOLL	WELL	8.50	1130.00	487.00	0.0	0.45	0.46	658.00	0.10	1001.89
RCA-43	16 13 12 4W4	B.ZIEGENHAGEL	WELL	7.90	750.00	427.50	0.05	2.00	0.16	343.00	0.03	1189.84
RCA-46	3 35 11 3W4	K.FRIEMARK	SPRING	7.80	5160.00	2172.00	0.15	0.10	0.40	482.00	0.32	898.46
RCA-47	3 13 8 3W4	CHPP-MITCHELL	SPRING	0.0	0.0	150.00	0.0	0.0	0.0	170.00	0.0	264.00
RCA-52	2 21 8 2W4	CHPP-PINES	SPRING	8.10	1300.00	392.50	1.10	0.10	0.25	427.00	0.32	374.46
RCA-53	14 30 8 2W4	FELESKY	WELL	8.00	480.00	112.00	0.0	0.0	0.0	136.00	0.16	223.76
RCA-56	15 15 9 3W4	H.SEITZ	SPRING	8.30	1340.00	570.00	0.05	1.05	0.28	488.00	0.04	1008.30
RCA-57	7 4 10 3W4	R.JANS-HOUSE	F.WELL	8.50	730.00	392.50	0.05	7.05	0.33	314.00	0.01	1465.64
RCA-62	13 18 10 3W4	J.LENTZ	DUGOUT	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3882.22
RCA-64	10 30 10 3W4	C.GILL	WELL	8.30	1090.00	467.00	0.05	0.55	0.26	270.00	0.15	5725.33
RCA-65	1 6 11 3W4	G.RETELBACK	DUGOUT	8.10	1040.00	640.00	0.05	2.30	0.29	498.00	0.47	8049.45
RCA-66	15 5 11 3W4	W.STUBER	DUGOUT	8.00	0.0	2680.00	0.0	23.80	1.70	180.00	0.10	980.43
RCA-69	13 17 11 3W4	R.DEERING	WELL	7.20	2000.00	244.00	0.0	0.0	0.0	306.00	0.09	627.69
RCA-70	5 23 11 3W4	R.RESCH	WELL	7.50	0.0	496.00	0.0	4.60	0.22	[illegible]	0.11	1211.79
RCB-1	2 24 9 4W4	K.SAILER	SPRING	7.70	1830.00	667.00	0.0	0.22	0.24	[illegible]	0.16	1287.13
RCB-2	13 5 9 3W4	L.PFIEFFER	WELL	8.50	1500.00	705.00	1.30	0.10	0.41	780.00	0.12	580.42
RCB-3	11 30 8 3W4	BROWN EST.-H	SPRING	7.70	1830.00	667.00	0.0	0.22	0.24	646.00	0.16	1159.72
RCB-5	14 12 9 4W4	FLAIG	F.WELL	8.40	930.00	495.00	0.10	0.05	0.33	459.00	0.08	1228.75
RCB-10	13 23 9 4W4	BOSCHEE	F.WELL	0.0	0.0	931.00	0.0	19.00	0.21	539.00	0.19	2376.26
RCB-12	5 3 10 4W4	FALCON RANCH	F.WELL	0.0	0.0	1001.00	0.0	175.00	0.19	544.00	0.11	1161.76
RCB-13	16 9 10 4W4	SCHEFFELMEIR	WELL	0.0	0.0	2249.00	0.0	130.00	0.96	226.00	0.41	1817.91
RCB-14	11 28 9 4W4	R.REIGER	WELL	8.20	940.00	555.00	0.10	0.10	0.30	542.00	1.43	3050.15
RCB-16	5 36 9 5W4	G.SEITZ	WELL	0.0	0.0	812.00	0.0	290.00	0.15	248.00	0.11	2026.11
RCB-18	4 6 10 4W4	CLARK	WELL	8.10	1400.00	580.00	0.10	1.00	0.28	398.00	0.04	2458.60
RCB-20	5 28 10 4W4	I.NEITZ	WELL	8.20	1700.00	790.00	0.10	0.10	0.24	340.00	0.08	1001.10
RCB-21	8 31 10 4W4	A.WUTZKE	WELL	8.20	685.00	5.00	0.0	0.22	0.50	348.00	0.04	1258.27
RCB-22	4 27 8 3W4	RUSSIL	SPRING	7.80	525.00	300.00	0.0	0.45	0.23	264.00	0.50	296.19
RCB-24	3 22 10 3W4	J.GILL	SPRING	7.80	1500.00	679.00	0.0	7.70	0.25	420.00	0.25	1171.96
RCB-25	11 2 11 4W4	E.YANKE	WELL	0.0	0.0	0.0	0.0	0.0	0.0	65.00	5.00	458.60
RCB-27	5 5 11 4W4	RENKE	WELL	9.10	2470.00	660.00	0.35	0.10	0.17	156.00	0.07	721.47
RCB-28	1 8 11 4W4	A.RIEGER	WELL	9.10	1200.00	525.00	0.05	1.10	0.24	407.00	0.03	1114.00
RCB-29	13 30 11 4W4	E.JANS	WELL	7.70	3270.00	417.00	0.0	0.45	1.12	894.00	9.06	1126.73
RCB-30	8 21 11 4W4	W.LENTZ	SPRING	8.30	1440.00	427.50	0.60	0.05	0.26	424.00	0.35	821.67
RCB-31	5 34 11 4W4	G.LENTZ	WELL	7.60	1741.00	740.00	0.0	172.00	0.16	354.00	0.02	1338.38
RCB-33	5 7 12 4W4	DIETELBACH	WELL	8.20	1670.00	590.00	0.05	0.85	0.31	398.00	0.57	3707.53
RCB-36	4 10 12 4W4	DAVIES	WELL	10.00	340.00	75.00	0.10	0.10	0.24	192.00	0.16	390.21
RCB-37	3 9 12 4W4	DUNMORE CAMPGND	WELL	7.90	240.00	125.00	2.40	0.10	0.10	153.00	0.08	199.61
RCB-38	6 12 12 5W4	CAVAN	WELL	8.10	1651.00	409.00	0.0	0.22	0.82	589.00	0.62	939.19
RCB-39	1 19 12 4W4	LA POULET FARM	WELL	8.60	3210.00	72.50	0.10	0.10	0.85	1332.00	0.50	1743.06
RCB-40	11 32 12 4W4	SCHMIPF	WELL	8.30	3100.00	241.00	0.0	2.04	0.42	1070.00	1.94	1941.58
RCB-41	14 24 12 5W4	HOFFMAN	SEEP	7.40	1597.00	930.00	0.0	0.45	0.46	675.00	0.09	1068.98
RCB-43	7 23 12 5W4	J.STOCK	WELL	8.40	1300.00	191.00	0.0	0.45	0.37	608.00	6.34	761.03
RCB-44	15 36 11 4W4	A.ELHART	WELL	0.0	0.0	320.00	0.0	0.0	0.0	310.00	0.0	597.20
RCB-47	10 19 8 2W4	CHPP-GROUP CAMP	WELL	8.10	395.00	191.00	0.0	0.22	0.18	202.00	0.04	204.81
RCB-50	3 15 11 3W4	ACREAGE	WELL	0.0	0.0	320.00	0.0	8.40	0.20	260.00	0.0	1605.01
RCB-51	15 28 11 3W4	COUILLARD	WELL	8.50	1657.00	648.00	0.0	29.30	0.37	396.00	0.03	729.13
RCB-53	13 2 12 5W4	DUNMORE TOWN	WELL	0.0	0.0	240.00	0.0	4.10	0.60	559.00	0.05	1235.81
RCC-4	10 27 8 2W4	CHPP-S. COULEE	SPRING	0.0	0.0	315.00	0.0	0.0	0.0	330.00	1.00	543.00
RCC-10	6 18 8 2W4	CHPP-SKI RUN	SPRING	7.60	509.00	246.00	0.0	0.22	0.16	262.00	0.02	265.49
RCC-17	1 24 11 4W4	E.PINDER	WELL	8.20	685.00	5.00	0.0	0.22	0.50	348.00	0.04	457.71
RCC-31	1 4 9 2W4	ROAD ALLOWANCE	F.WELL	8.30	410.00	275.00	0.05	0.45	0.21	264.00	0.04	926.89
RCC-33	4 1 10 4W4	M.RATH-STOCK	WELL	0.0	0.0	1458.00	0.0	4.70	1.10	289.00	0.32	2337.64
RCC-34	13 36 9 4W4	M.RATH-GARDEN	WELL	8.10	720.00	327.50	1.55	0.20	0.20	284.00	0.35	443.24
RCD-15	5 18 9 2W4	J.MACK	SPRING	8.90	3600.00	1295.00	0.20	0.05	0.18	454.00	0.18	664.70
RCE-7	12 8 8 2W4	DUKE AE#2093E	WELL	7.60	2150.00	163.00	0.07	0.07	1.00	378.00	0.70	1465.31
RCE-8	12 8 8 2W4	DUKE AE#2084E	WELL	8.00	1540.00	565.00	0.65	0.05	0.20	390.00	7.20	1117.42
RCE-15	8 15 12 4W4	B.SCHNEIDER	SPRING	8.30	3080.00	818.00	0.0	0.95	0.41	548.00	0.26	1326.48
RCE-21	16 25 11 4W4	DUKE AE#2080E	WELL	8.60	2090.00	40.00	0.84	0.07	0.87	654.00	1.66	1389.37
RCE-22	16 25 11 4W4	DUKE AE#2081E	WELL	6.80	1750.00	665.00	0.21	0.07	0.42	248.00	0.18	1290.79
RCE-28	7 20 11 4W4	C.SCHMIDEK	SPRING	0.0	0.0	520.00	0.0	0.0	0.0	390.00	1.50	942.58
RCE-31	8 33 10 3W4	DUKE AE#2089E	WELL	7.20	2150.00	890.00	0.49	0.63	0.48	447.00	0.15	1610.14
RCE-32	8 33 10 3W4	DUKE AE#2079E	WELL	9.80	3090.00	10.00	6.23	0.14	1.40	751.00	1.39	1740.61

Table A.3.3. Results of hydrochemical facies calculations. Ca/Mg given as a ratio; all other values given as the milliequivalent percentage of the total anions or cations. Source: Groundwater Information Centre files and Óphori and Tóth (1983).

SAMPLE	LOCATION	OWNER DESCRIPTION	TYPE OF WATER	%CA	%MG	%NA+K	%CA+MG	%CL	%SO4	%CARB	%SO4+CL	CA/MG
RCA-1	13 11 8 3W4	CHPP-NICHOLLS	SPRING	90.22	5.99	3.79	96.21	0.97	2.64	96.39	3.61	15.06
RCA-4	11 24 8 3W4	CHPP-ELKWATER	LAKE	35.50	42.84	21.66	78.34	1.81	7.25	90.94	9.06	0.83
RCA-6	7 24 8 3W4	ELKWATER TOWN	WELL	29.48	15.03	55.49	44.51	0.77	15.06	84.17	15.83	1.96
RCA-7	11 25 8 3W4	A.PETER	WELL	63.94	15.00	21.05	78.95	2.87	5.83	91.30	8.70	4.26
RCA-9	11 35 8 3W4	B.SCHORR	SLOUGH	40.46	20.95	38.60	61.40	3.63	1.23	95.15	4.85	1.93
RCA-10	13 14 9 3W4	B.WEISS-FIELD	SPRING	20.18	6.99	72.83	27.17	1.30	38.61	60.09	39.91	2.89
RCA-12	15 9 9 3W4	J.IGNATIUS	SPRING	25.61	9.61	64.78	35.22	0.62	37.62	61.76	38.24	2.67
RCA-14	7 26 9 3W4	W.SWADLING	F.WELL	34.99	20.84	44.17	55.83	2.08	71.32	26.59	73.41	1.68
RCA-16	9 13 9 3W4	J.ENGLER	SPRING	28.05	9.15	62.80	37.20	0.52	20.69	78.79	21.21	3.06
RCA-17	4 30 9 2W4	E.MACK-CORRAL	SPRING	37.67	16.38	45.95	54.05	1.16	34.74	64.10	35.90	2.30
RCA-20	9 19 9 2W4	D.NEUBAUER	SPRING	38.63	28.97	32.39	67.61	0.0	100.00	0.0	100.00	1.33
RCA-21	13 7 10 2W4	A.SCHORR	WELL	41.20	25.66	33.14	66.86	3.81	51.36	44.83	55.17	1.61
RCA-23	6 24 10 3W4	KRAUSS	F.WELL	25.38	23.46	51.16	48.84	6.34	51.51	42.15	57.85	1.08
RCA-25	12 35 10 3W4	B.OTTO	DUGWELL	59.95	20.17	19.88	80.12	1.11	37.09	61.80	38.20	2.97
RCA-26	16 36 10 3W4	G.V.M.RANCH	WELL	0.0	0.0	0.0	0.0	1.53	82.30	16.16	83.84	0.0
RCA-28	16 30 10 2W4	B.SCHORR	DUGWELL	64.71	35.29	0.0	100.00	2.57	66.72	30.72	69.28	1.83
RCA-29	11 31 11 2W4	IRVINE P-CAN	WELL	53.53	13.26	33.21	66.79	4.80	50.03	45.16	54.84	4.04
RCA-31	16 32 11 2W4	A.BROST	DUGOUT	34.25	2.09	63.66	36.34	13.25	33.32	53.42	46.58	16.39
RCA-32	16 7 12 2W4	M.BROST	WELL	24.12	13.40	62.48	37.52	0.99	48.70	50.31	49.69	1.80
RCA-33	5 15 12 3W4	R.FRANZ	WELL	23.51	19.85	56.63	43.37	1.57	49.59	48.84	51.16	1.18
RCA-34	11 24 12 3W4	A.ZELLER	WELL	0.0	0.0	0.0	0.0	1.95	98.05	0.0	100.00	0.0
RCA-36	8 24 12 3W4	J.ZELLER	SPRING	33.33	66.67	0.0	100.00	11.96	88.04	0.0	100.00	0.50
RCA-37	1 30 12 2W4	C.ZIEGLER	WELL	0.0	0.0	0.0	0.0	8.80	45.20	46.00	54.00	0.0
RCA-38	4 36 12 3W4	R.HAUSAUER	WELL	52.63	29.82	17.54	82.46	1.31	6.81	91.88	8.12	1.76
RCA-39	9 27 12 3W4	H.BROST	WELL	9.06	9.75	81.19	18.81	1.14	50.93	47.93	52.07	0.93
RCA-40	8 20 12 3W4	R.ROTH	WELL	28.04	26.06	45.90	54.10	1.30	68.38	30.32	69.68	1.08
RCA-42	15 31 12 3W4	W.DRISCOLL	WELL	53.05	46.95	0.0	100.00	3.74	57.42	38.83	61.17	1.13
RCA-43	16 13 12 4W4	B.ZIEGENHAGEL	WELL	8.46	5.13	86.41	13.59	1.17	31.34	67.49	32.51	1.65
RCA-46	3 35 11 3W4	K.FRIEMARK	SPRING	69.90	30.10	0.0	100.00	0.89	57.99	41.12	58.88	2.32
RCA-47	3 13 8 3W4	CHPP-MITCHELL	SPRING	66.67	33.33	0.0	100.00	16.67	83.33	0.0	100.00	2.00
RCA-52	2 21 8 2W4	CHPP-PINES	SPRING	83.37	11.95	4.67	95.33	1.07	2.17	96.76	3.24	6.97
RCA-53	14 30 8 2W4	FELESKY	WELL	57.14	42.86	0.0	100.00	16.67	83.33	0.0	100.00	1.33
RCA-56	15 15 9 3W4	H.SEITZ	SPRING	44.90	17.56	37.53	62.47	0.95	40.21	58.85	41.15	2.56
RCA-57	7 4 10 3W4	R.JANS-HOUSE	F.WELL	72.00	28.00	0.0	100.00	1.16	55.04	43.81	56.19	2.57
RCA-62	13 18 10 3W4	J.LENTZ	DUGOUT	37.55	33.57	28.88	71.12	0.69	81.83	17.48	82.52	1.12
RCA-64	10 30 10 3W4	C.GILL	WELL	26.40	35.20	38.40	61.60	2.68	84.80	12.51	87.49	0.75
RCA-65	1 6 11 3W4	G.RETELBACK	DUGOUT	0.0	0.0	100.00	0.0	2.19	94.25	3.56	96.44	0.0
RCA-66	15 5 11 3W4	W.STUBER	DUGOUT	0.42	0.42	99.15	0.85	25.52	2.67	71.81	28.19	1.00
RCA-69	13 17 11 3W4	R.DEERING	WELL	65.57	34.43	0.0	100.00	10.00	90.00	0.0	100.00	1.90
RCA-70	5 23 11 3W4	R.RESCH	WELL	40.61	16.40	42.98	57.02	1.74	53.05	45.21	54.79	2.48
RCB-1	2 24 9 4W4	K.SAILER	SPRING	34.75	18.10	47.15	52.85	0.33	35.19	64.48	35.52	1.92
RCB-2	13 5 9 3W4	L.PFIEFFER	WELL	71.23	23.66	5.11	94.89	0.48	4.56	94.96	5.04	3.01
RCB-3	11 30 8 3W4	BROWN EST.-H	SPRING	39.86	18.02	42.12	57.88	0.56	45.31	54.13	45.87	2.21
RCB-5	14 12 9 4W4	FLAIG	F.WELL	24.54	9.05	66.41	33.59	0.59	40.84	58.57	41.43	2.71
RCB-10	13 23 9 4W4	BOSCHEE	F.WELL	27.51	12.28	60.20	39.80	0.98	63.36	35.66	64.34	2.24
RCB-12	5 3 10 4W4	FALCON RANCH	F.WELL	0.0	0.0	0.0	0.0	1.84	8.50	89.66	10.34	0.0
RCB-13	16 9 10 4W4	SCHEFFELMEIR	WELL	64.42	35.58	0.0	100.00	8.01	50.91	41.09	58.91	1.81
RCB-14	11 28 9 4W4	R.REIGER	WELL	41.53	39.28	19.18	80.82	2.93	76.30	20.78	79.22	1.06
RCB-16	5 36 9 5W4	G.SEITZ	WELL	16.64	61.48	21.88	78.12	22.01	29.13	48.87	51.13	0.27
RCB-18	4 6 10 4W4	CLARK	WELL	25.86	41.66	32.48	67.52	9.65	52.04	38.32	61.68	0.62
RCB-20	5 28 10 4W4	I.NEITZ	WELL	41.88	16.13	41.99	58.01	1.69	46.85	51.45	48.55	2.60
RCB-21	8 31 10 4W4	A.WUTZKE	WELL	51.16	17.78	31.05	68.95	1.16	60.13	38.71	61.29	2.88
RCB-22	4 27 8 3W4	RUSSIL	SPRING	67.43	28.49	4.08	95.92	0.28	8.01	91.71	8.29	2.37
RCB-24	3 22 10 3W4	J.GILL	SPRING	37.58	22.49	39.93	60.07	1.17	54.20	44.63	55.37	1.67
RCB-25	11 2 11 4W4	E.YANKE	WELL	59.22	27.98	12.80	87.20	1.37	20.66	77.98	22.02	2.12
RCB-27	5 5 11 4W4	RENKE	WELL	42.42	17.88	39.70	60.30	2.77	37.52	59.71	40.29	2.37
RCB-28	1 8 11 4W4	A.RIEGER	WELL	48.72	16.76	34.52	65.48	8.25	44.22	47.52	52.48	2.91
RCB-29	13 30 11 4W4	E.JANS	WELL	7.16	2.90	89.95	10.05	8.31	6.39	85.30	14.70	2.47
RCB-30	8 21 11 4W4	W.LENTZ	SPRING	30.66	19.21	50.13	49.87	0.38	37.47	62.15	37.85	1.60
RCB-31	5 34 11 4W4	G.LENTZ	WELL	55.07	23.67	21.26	78.74	5.32	20.00	74.68	25.32	2.33
RCB-33	5 7 12 4W4	DIETELBACH	WELL	28.57	12.51	58.92	41.08	1.63	80.49	17.88	82.12	2.28
RCB-36	4 10 12 4W4	DAVIES	WELL	62.63	27.65	9.72	90.28	0.67	21.14	78.19	21.81	2.27
RCB-37	3 9 12 4W4	DUNMORE CAMPGND	WELL	16.66	11.57	71.77	28.23	4.76	7.73	87.51	12.49	1.44
RCB-38	6 12 12 5W4	CAVAN	WELL	44.73	22.58	32.69	67.31	3.40	41.75	54.84	45.16	1.98
RCB-39	1 19 12 4W4	LA POULET FARM	WELL	9.27	8.39	82.34	17.66	3.45	31.95	64.60	35.40	1.11
RCB-40	11 32 12 4W4	SCHMIPF	WELL	5.76	4.53	89.71	10.29	5.26	24.79	69.96	30.04	1.27
RCB-41	14 24 12 5W4	HOFFMAN	SEEP	58.51	25.34	16.15	83.85	0.18	25.94	73.88	26.12	2.31
RCB-43	7 23 12 5W4	J.STOCK	WELL	9.09	9.74	81.16	18.84	6.06	3.64	90.30	9.70	0.93
RCB-44	15 36 11 4W4	A.ELHART	WELL	43.10	43.10	13.79	86.21	30.00	70.00	0.0	100.00	1.00
RCB-47	10 19 8 2W4	CHPP-GROUP CAMP	WELL	77.45	16.30	6.25	93.75	0.39	3.13	96.48	3.52	4.75
RCB-50	3 15 11 3W4	ACREAGE	WELL	57.05	9.59	33.37	66.63	2.30	47.86	49.84	~~50.16~~	5.95
RCB-51	15 28 11 3W4	COUILLARD	WELL	0.0	0.0	100.00	0.0	24.64	10.77	64.59	35.41	0.0
RCB-53	11 2 12 5W4	DUNMORE TOWN	WELL	7.47	7.27	85.26	14.74	0.75	35.45	63.80	36.20	1.03
RCC-4	10 27 8 2W4	CHPP-S. COULEE	SPRING	63.49	36.51	0.0	100.00	13.79	86.21	0.0	100.00	1.74
RCC-10	6 18 8 2W4	CHPP-SKI RUN	SPRING	71.51	21.67	6.83	93.17	0.30	4.18	95.52	4.48	3.30
RCC-17	1 24 11 4W4	E.PINDER	WELL	0.54	0.54	98.93	1.07	0.41	12.16	87.42	12.58	1.00
RCC-31	1 4 9 2W4	ROAD ALLOWANCE	F.WELL	52.49	28.35	19.16	80.84	0.52	61.46	38.02	61.98	1.85
RCC-33	4 1 10 4W4	M.RATH-STOCK	WELL	41.98	29.70	28.32	71.68	1.68	82.17	16.15	83.85	1.41
RCC-34	13 36 9 4W4	M.RATH-GARDEN	WELL	55.61	23.25	21.15	78.85	0.75	21.28	77.98	22.02	2.39
RCD-15	5 18 9 2W4	J.MACK	SPRING	26.10	10.44	63.46	36.54	0.29	23.29	76.42	23.58	2.50
RCE-7	12 8 8 2W4	DUKE AE#2093E	WELL	7.27	3.14	89.59	10.41	1.60	59.66	38.74	61.26	2.31
RCE-8	12 8 8 2W4	DUKE AE#2084E	WELL	37.25	16.62	46.13	53.87	1.30	51.25	47.46	52.54	2.24
RCE-15	8 15 12 4W4	B.SCHNEIDER	SPRING	36.66	13.73	49.61	50.39	1.31	53.75	44.94	55.06	2.67
RCE-21	16 25 11 4W4	DUKE AE#2080E	WELL	2.10	0.57	97.32	2.68	0.89	37.21	61.90	38.10	3.67
RCE-22	16 25 11 4W4	DUKE AE#2081E	WELL	35.57	18.66	45.77	54.23	1.83	69.16	29.01	70.99	1.91
RCE-28	7 20 11 4W4	C.SCHMIDEK	SPRING	36.43	24.54	39.03	60.97	1.47	52.27	46.26	53.74	1.48
RCE-31	8 33 10 3W4	DUKE AE#2089E	WELL	34.38	21.29	44.34	55.66	1.53	58.75	39.72	60.28	1.61
RCE-32	8 33 10 3W4	DUKE AE#2079E	WELL	0.14	0.28	99.58	0.42	44.03	0.94	55.03	44.97	0.50