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**GROUNDWATER FLOW PATTERNS IN THE
MANOTICK AREA: A GIS PERSPECTIVE**

by

E. Anne Sager-Kinsman. Hon. B.A., Hon. B.Sc.

A thesis submitted to
the Faculty of Graduate Studies and Research
in partial fulfillment of
the requirements for the degree of
Master of Science

Ottawa-Carleton Geoscience Centre

and

Department of Earth Sciences

Carleton University

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The undersigned recommend to the Faculty of Graduate Studies
and Research acceptance of the thesis

**GROUNDWATER FLOW PATTERNS IN THE
MANOTICK AREA: A GIS PERSPECTIVE**

submitted by E. Anne Sager-Kinsman, Hon. B.A., Hon. B.Sc.
in partial fulfillment of the requirements for
the degree of Master of Science

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Thesis Supervisor

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Chairman, Department of
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ABSTRACT

Development within and around Manotick, Ontario is increasing demand on water resources in the area and affecting both water quality and quantity. This study was conducted in order to define the bedrock aquifer serving the area, to characterize the bedrock groundwater flow pattern and its controls and to assess the usefulness of a GIS in this context.

A computerized data base comprised of 2,987 records and covering a 250-km² local watershed was developed using Ontario Ministry of the Environment (MOE) well records. These records provide data on geographic location, bedrock surface, lithologies encountered and water level data for each well. Such a spatial data base lends itself well to analysis through geographic information system (GIS) technology. Point data were processed by a controlled interpolation method to produce a number of surfaces, including bedrock topography, elevation of Nepean sandstone and average potentiometric surfaces for all bedrock wells, and for carbonate and sandstone wells separately. These surfaces were then processed to analyze horizontal and vertical groundwater movement in the study area.

In addition, a limited groundwater sampling program was conducted to obtain geochemical and isotopic data with a view to verifying the general pattern of bedrock groundwater flow produced by computer modelling.

It was found that the area is underlain by what is effectively one fracture-dominated bedrock aquifer made up of Oxford and March carbonate and Nepean sandstone units. The overall groundwater gradient is controlled by bedrock topography and the aquifer is locally drained in the vicinity of the Rideau River. The geochemistry and isotopic data indicate relatively recent recharge over much of the study area, except possibly in the deepest part of the Nepean Formation.

MOE well record data suggested the presence of faulting in one part of the study area. Follow-up geophysical data confirmed that this is a possibility.

This study demonstrates a potentially significant application of MOE well records and indicates the usefulness of applying GIS integration and analysis techniques to the characterization of groundwater flow within a local watershed.

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Figure 2 - Faults and outcrops in study area (After Williams *et al.*, 1982)

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Chapter 1 INTRODUCTION

1.1 BACKGROUND

This thesis arose out of concerns expressed by residents of the Manotick area about the quality and quantity of their well water supply in the context of a rapidly expanding population base and an accompanying increase in the number of primarily domestic wells.

Manotick, Ojibway for "Island in the River", is a small community (population 3,000) located 12 kilometres south of the Ottawa-Macdonald-Cartier International Airport astride the Rideau River on Long Island (Figure 1). Originally settled as a small service center for the surrounding farming community, it is now increasingly a bedroom community for the city of Ottawa. Of the approximately 1,500 buildings in the village, only 200 homes in a development at the north end of Long Island are served by a communal well, while the remainder of the residences and commercial establishments are served by individual wells (Robinson, A.J. and Associates Inc., 1991) and on-site sewage disposal systems. This means that Manotick is one of the largest communities in Ontario to rely so extensively on private services. Yet growth continues. Accordingly, residents are concerned about the ability of the natural system to support further development, in terms of both the quality and quantity of water available. Groundwater is perceived to be threatened by pollution from such sources as domestic sewage effluent, agricultural, domestic and commercial chemicals, effluent from the regional garbage disposal located in the Kars esker, and the Rideau River itself. With regard to quantity, the perception exists among some residents that lowering of the water table is already in progress.

Figure 1 - Location map of study area.

A number of previous groundwater-related studies exist for the Manotick area. However, in most cases these have been commercially prepared for land developers. They are difficult to obtain, most are very restricted in scope and of limited applicability to the present work.

This study depicts the bedrock groundwater flow regime surrounding the village of Manotick in as much detail as possible through a computer-based analysis of provincial Ministry of the Environment well records and a limited groundwater sampling program. In so doing, it creates a useful resource base for future work.

1.2 PURPOSE AND OBJECTIVES

The purpose of this thesis is to characterize the regional bedrock groundwater flow regime in the Manotick area. Only the bedrock aquifer was considered in this study because the limited number of wells finishing in the surficial sediment aquifer makes it impracticable to model the latter by the present techniques.

The primary objectives of the study are as follows:

- (i) to characterize bedrock groundwater flow patterns in the study area and their controls;
- (ii) to ascertain whether the carbonate and sandstone units underlying the study area function together as a single aquifer;
- (iv) to assess the usefulness of a GIS-based approach to the spatial analysis of well record data sets; and

- (iii) to obtain geochemical and isotopic data to enhance the understanding of regional flow (recharge to discharge) as characterized by the GIS modelling.

1.3 SCOPE OF WORK

Work on this thesis initially began with the manual plotting and contouring of data from approximately 1,350 Ontario Ministry of the Environment well records, dating from 1947 to 1984, to obtain a bedrock surface and an average regional potentiometric surface. It was then decided to develop a computer data base using these initial records for eventual processing with GIS software. Another approximately 1,637 records were subsequently added to the data base in order to make it as up-to-date and complete as possible and to expand the study area. Although the concept of a potentiometric surface is only rigorously valid for confined horizontal flow in a horizontal aquifer, it is adopted here as a first-order approach, and an average regional potentiometric surface was prepared for the Manotick area, with a view to delineating recharge and discharge zones, or zones of potentiometric highs and lows. The potential extent of recharge from precipitation or leakage to the aquifer was assessed by examining surficial materials. Subsurface features were analysed in order to further characterize the groundwater flow pattern and its controls.

A groundwater sampling program of 47 wells was undertaken and samples analysed for major ion chemistry and for tritium, deuterium and oxygen-18 isotopes. These data were used to enhance the understanding of regional flow and to assess groundwater behavior and the nature of recharge.

Chapter 2 GEOLOGICAL SETTING

2.1 GEOLOGICAL HISTORY

The Ottawa-St. Lawrence Lowland is described by Wilson (1946) as a structurally-controlled basin within the St. Lawrence Lowlands physiographic province. It is bounded on the north by Precambrian crystalline rocks of the Canadian Shield and on the south by the Adirondack Mountains. Its western margin is formed by the Frontenac Axis of the Canadian Shield, while the eastern border is defined by the Beauharnois Anticline, another axis of the Canadian Shield which crosses the central part of the St. Lawrence Lowlands at the confluence of the Ottawa and St. Lawrence Rivers.

The basin is floored by largely flat-lying Paleozoic sedimentary rocks resting unconformably on the Precambrian crystalline basement rocks. In most places, a thick cover of Quaternary surficial materials overlies the Paleozoic sediments, which outcrop only in stream beds and banks and in a few structural highs (Occhietti, 1989). The Paleozoic formations are generally undisturbed by faulting except in the vicinity of the northern boundary of the lowland. Manotick is located near the northern and western margins of the lowland in the Ottawa area, which is characterized by a relatively high fault density (Williams and Telford, 1986). Faulting is reported in the study area itself (Figure 2) and is described in greater detail in Section 2.2.

Brandon (1960) divides the geologic history of the area into three phases corresponding to the three basic geologic units referred to above: (i) the time of formation of the crystalline basement rocks, (ii) the time of deposition of the flat-lying sediments when the land was submerged beneath a succession of shallow, warm seas, and (iii) the period "during and

Figure 2 - Faults and outcrops in study area (After Williams *et al.*, 1982)

after the last ice age, when glacial deposits, clays, and sands were deposited". Between the second and third of these phases there is a gap in the geologic record, which corresponds to a long period of erosion or non-deposition.

The oldest rocks in the area belong to the ca. 1.0 Ga Grenville Orogen (Wynne-Edwards, 1972), which consists of a polyorogenic belt of earlier tectonic, sedimentary and plutonic elements ranging in age from Archean to mid-Proterozoic and imprinted by Grenvillian metamorphism. The Grenville Orogen was peneplained by approximately 650 Ma ago (Cosca *et al.*, 1991). Perhaps all that remains of it in the study area are the sands and gravels of the Covey Hill Formation, which were deposited in a terrestrial environment in the Upper Cambrian and/or earlier (Williams, 1991) as the Iapetus Ocean began to open approximately 540 to 570 million years ago. During the upper Cambrian and the Ordovician, as the seas transgressed and withdrew, the strata overlying the Covey Hill Formation were laid down in an intracontinental shelf environment (Williams, 1991), beginning with the sandstone of the Nepean Formation and followed by the deeper-water carbonate facies of the March and Oxford Formations.

The Iapetus Ocean closed during the Appalachian Orogeny, which ended approximately 250 million years ago and which reworked Ordovician sedimentary rocks east of the Appalachian Front, but left their counterparts in the the Ottawa-St. Lawrence Lowlands relatively undeformed. When the Appalachian Orogeny ended, the Atlantic Ocean began to open, with the creation of the Ottawa Valley rift zone as part of the St. Lawrence valley system (Kumarapeli and Saull, 1966), and with structural implications for the area which will be referred to in a subsequent section (section 2.2). The preserved geological record then jumps from the youngest Ordovician sediments (Queenston Formation) to the recent sediments of the Quaternary Period, during which the eroded, uneven surface of Ordovician and Precambrian rock was covered by Pleistocene and recent sediments.

Although this area was probably covered by at least four separate ice advances (Bélanger and Harrison, 1980), evidence remains from only the final event. This ice sheet advanced in a generally north-to-south direction. In addition to a blanket of till, the retreating ice left behind sand and gravel ridges. The weight of the ice had depressed the earth's crust, but before it could rebound, freshwater glacial lakes were inundated by an arm of the Champlain Sea which extended up the St. Lawrence and Ottawa River valleys leaving behind thick deposits of marine clays, silty clays and sand (Fulton, 1987). As the land rebounded, the rivers re-emerged. Finally, modern fluvial sediments were added to the complex glacial deposits overlying the bedrock in this area.

2.2 STRUCTURE AND TECTONICS

Structural patterns in the Ottawa-St. Lawrence Lowlands may have originated in early Cambrian times or before. Kumarapeli (1985) suggests that the continental rifting which initiated the formation of the Iapetus Ocean, in Pre-Cambrian-Cambrian times, caused structural damage in the continent of Laurentia, which contained the ancient North American landmass. This damage would have included two aulacogens — the Ottawa and Saguenay grabens — as well as a zone of step faulting parallel to the ancient continental margin and possible fractures transverse to this margin. Thus, a major portion of the later St. Lawrence rift system (Kumarapeli and Saull, 1966), itself a failed arm of the Mesozoic rift system which opened the Atlantic Ocean, may have formed by reactivation of Iapetan fault zones and aulacogens. Kumarapeli (1985) cites various lines of evidence — including the localization of Archean mineral deposits (Kutina and Fabri, 1972), results of the 1982 COCRUST long-range seismic experiment across the Ottawa graben showing that it has expression at Moho depth (Mereu *et al.*, 1984), and evidence that the faults in the St. Lawrence and Champlain Valleys were already in existence when the platformal

sedimentation began in the Late Precambrian and/or early Cambrian (Lewis, 1971) — in support of this account of the origin of the oldest structural features in the area.

Williams (1991) also implies that Paleozoic structure may reflect earlier lines of weakness, pointing out that the orientations of faults and joint sets of the Ottawa-St. Lawrence Lowland correspond to the trend of the Ottawa Valley rift zone, as well as to the trends of other adjacent rift zones — the Timiskaming Valley, the Champlain Valley and the Southern Great Lakes. He considers that faulting which occurred after deposition of the Cambro-Ordovician sedimentary sequence resulted from the reactivation of pre-existing faults. Reactivation has been documented in the case of the Rideau Lake Fault, with most movement having occurred before deposition of the Paleozoic rocks rather than after (Wynne-Edwards, 1967).

During the Mesozoic, before the opening of the Atlantic Ocean, the Ottawa Valley rift zone was probably connected to the global rift system through the St. Lawrence Valley rift zone (Kumarapeli and Saull, 1966). As recently as the Cretaceous, this area was still affected by extensional tectonics, as evidenced by carbonatite dykes which are probably Cretaceous in age (Williams, 1991). However, as a result of the failure of the St. Lawrence rift system and the continued widening of the Atlantic Ocean, the tectonic regime of the present day is compressional, having caused the formation of buckles or "pop-ups" at a number of localities in the vicinity of Ottawa and Cornwall (Williams and Telford, 1986; Williams, 1991).

Jointing and faulting in the area can be related to the tectonic history of the Ottawa Valley rift zone. Williams (1991) reports that the Paleozoic rocks contain joint sets striking at approximately 015°, 055°, 100° and 145°, with the 100° trend being the most common and the 055° orientation the least common. The principal joint planes are moderately (30 cm to

1 metre) to widely (greater than 1 metre) spaced. Solution processes have commonly widened joints in carbonate strata; calcite and minor pyrite, barite, celestite or gypsum are often found infilling joints (Williams and Telford, 1986, Williams, 1991).

As stated earlier, the Paleozoic sedimentary rocks of the Ottawa-St. Lawrence Lowland are primarily flat-lying. However, in the northern part of the Lowland, extensional tectonics have caused intense normal faulting, with the faults forming the northern boundary of the Paleozoic formations and separating them from the Precambrian rocks (Wilson, 1946). Williams and Telford (1986) report that faults are steeply dipping, striking southeast to northwest.

Wilson (1946) refers to two major faults, the Hazeldean and Gloucester Faults, in the Ottawa region. The Hazeldean Fault is inferred to affect the study area, entering it from the northwest, crossing it in a gently curving arc and exiting in the northeast (Figure 2). The trace of the Gloucester Fault, which also runs generally southeasterly, lies north and east of the Hazeldean and runs north of the northeast corner of the study area. Between them, an uplifted, gently tilted block exposes strata of the March and Oxford Formations just inside the northeast corner of the study area. The Oxford Formation is inferred to underlie most of the remainder of the area, which is characterized by very little rock exposure, other than a few isolated outcrops of the Oxford and March Formations in the north half. No other known or inferred faults have been reported in the study area.

2.3 STRATIGRAPHY

Table 1, compiled from Wilson (1946) and Williams and Telford (1986) summarizes the Paleozoic stratigraphy underlying the study area. The lithostratigraphic terminology used in the thesis is from Williams and Telford (1986).

Period	Group	Formation
Lower Ordovician	Beekmantown	Oxford
		March
Cambrian	Potsdam	Nepean
		Covey Hill

Table 1 - The Paleozoic stratigraphy underlying the study area.

2.3.1 *The Precambrian Record*

Rocks of the Precambrian complex not only border, but also unconformably underlie and occur as inliers in the Paleozoic sedimentary rocks of the Ottawa-St. Lawrence basin. The Precambrian complex consists of highly deformed metasedimentary and metavolcanic rocks which have been intruded, deformed, and metamorphosed by felsic to mafic plutons. These rocks are strongly faulted, jointed and deformed (Bélanger and Harrison, 1980).

2.3.2 *The Paleozoic Record*

A major unconformity separates the Precambrian basement and the overlying Paleozoic rocks. In the Ottawa-St. Lawrence Lowland, the Paleozoic sequence is up to 1200 metres

thick (Williams, 1991). However, the Lowland is like a bowl, deeper in the middle than around the edges. As a consequence, formations tend to increase in thickness toward the east and, where Paleozoic stratigraphy is not disturbed by faulting, progressively younger formations outcrop with distance from the Precambrian border. Since the study area lies relatively close to the western border of the Lowland, the only part of the Paleozoic stratigraphic sequence represented within it is comprised of the Covey Hill, Nepean, March and Oxford Formations (described in detail in Appendix 1). As the basin deepens toward the east from a terrestrial to a shallow marine environment, these units represent gravel and conglomerate, sandstone, sandy dolostone and dolomite, respectively.

The Covey Hill Formation, which is the lowermost Paleozoic unit, unconformably overlies the Precambrian basement and may appear intermittently in the study area. This unit consists of non-calcareous feldspathic conglomerate and quartz sandstone (Williams and Telford, 1986; Lewis, 1971; Williams and Wolf, 1982; Williams and Rae, 1983).

The weathering and erosion that exposed the roots of the Precambrian mountains which now surround the Ottawa-St. Lawrence Lowland would have produced an extensive regolith over the ancestral Lowland. Wolf and Dalrymple (1984) conclude that at the western edge of the Ottawa-St. Lawrence Lowland, the Covey Hill Formation was formed in a setting which was transitional between a distal alluvial fan and a proximal braided fluvial environment. Based on grain size and the scale of sedimentary structures, they postulate an enormous drainage basin and attribute the scarcity of outcrops of such rocks today to either pre- or post-Nepean erosion.

Where the Nepean Formation overlies the localized Covey Hill Formation, Williams (1991) reports that this contact is unconformable and represents the uppermost common occurrence of feldspar, or the first appearance of quartz arenite. "Where the Covey Hill

Formation is absent and the Nepean Formation rests directly on the Precambrian basement, the basal beds often are conglomeratic and consist of quartzite clasts in a quartzose matrix" (Williams, 1991).

Most authors describe the upper contact of the Nepean with the March Formation as conformable (Wilson, 1946; Carson, 1982; Brand and Rust, 1977; Williams and Telford, 1986). There has been some discussion about the best definition of this boundary. Wilson (1946) placed it at the base of the lowest dolomitic or calcareous bed. However, since calcareous sandstone beds occur particularly near the top of the Nepean, other authors (Williams and Telford, 1986; Williams, 1991) prefer to place the contact at the base of the lowest dolomitic layer.

Williams and Telford (1986) report that, in the Ottawa area, the thickness of the Nepean Formation ranges from 60 to a minimum of 159 metres. The formation subcrops throughout the study area and one outcrop occurs immediately to the north of the northeastern corner of the study area.

Wilson (1946) describes the Nepean as a coarse-grained, cream-coloured quartz sandstone. According to Williams (1991, p. 43), "the lower part of the formation is non-calcareous, and the upper part becomes increasingly calcareous towards the top. The sandstones are thinly bedded to massive (beds are up to 2 metre-thick channel fills) and usually are well sorted, rarely containing any quartz pebbles and cobbles". Wilson (1946) points out that near the top of the formation the cement may also be of rust-staining iron oxide.

Wolf and Dalrymple (1984, 1985) identify two terrestrial and three marine facies in the Nepean. While the terrestrial facies predominate in the Gananoque map area (31C/8), the marine facies are dominant in the Ottawa-St. Lawrence Lowland. Of these, the most

common alternates between whiter, thicker and more resistant cross-bedded units and darker, less resistant bioturbated units. This facies is interpreted as being deposited in an environment alternating between a subtidal to lower intertidal setting (the cross beds) and a shallow-water environment where decreasing energy levels and sediment movement rates allowed organisms to colonize.

The March Formation is conformably overlain by the Oxford Formation and constitutes a transition zone between the underlying sandstone of the Nepean Formation and the overlying dolomite of the Oxford Formation. The lower contact is described above in the discussion of the Nepean Formation. Wilson (1946), with the agreement of Williams (1991), places the contact with the Oxford at the highest occurrence of sand in any quantity, although Williams (p. 57) modifies the definition as "the upper limit of common occurrence of quartz sand".

Bélanger and Harrison (1980) report a thickness of 10 meters for the March Formation. However, Williams and Telford (1986) report that the formation ranges from 18 to 20 meters in thickness in the Ottawa area, and Williams (1991) notes that, based on two drill holes, the thickness at South Gloucester is 16.2 metres. The formation outcrops in the northeast corner of the study area (Figure 2) and subcrops throughout the north central part beneath overlying surficial deposits.

The March Formation consists of interbedded quartz sandstone, dolomitic quartz sandstone, sandy dolostone, and dolostone (Wilson, 1946; Bond and Greggs, 1973, Williams and Telford, 1986). Shaly partings are found throughout the formation and the dolostones and sandy dolostones contain glauconitic partings.

Williams (1991) reports a supra- to subtidal environment of deposition for the March Formation, with supratidal to intertidal deposition and hypersalinity implied by the presence of calcite-filled vugs, replacing original sulphate nodules.

The Oxford Formation is disconformably overlain by the Rockcliffe and this upper contact with the overlying shales and sandstones is clearly defined by the change in lithology (Wilson, 1946). The lower contact is described above in the discussion of the March Formation.

In the Ottawa area, the thickness of the Oxford ranges from 62 to 102 meters (Williams and Telford, 1986). The formation outcrops in the northeast corner of the study area (Figure 2) and subcrops throughout much of the remainder beneath overlying surficial deposits.

Bond and Greggs (1976) subdivide the Oxford into a lower sandy unit and an upper dolomitic unit in which quartz is absent to rare. The dolostones are light to medium brownish to greenish grey in colour, thinly to thickly bedded with minor amounts of quartz sand in some beds as well as quartz sandstone interbeds up to 30 cm thick. Calcite- and quartz-filled vugs occur as well as chert nodules, stromatolites and shaly interbeds which are often glauconitic. Some calcite-filled vugs and some of the thin interbeds contain pyrite. Wilson (1946) characterized the Oxford in the western edge of the Ottawa-St. Lawrence basin as very impure, containing a great deal of mud with some sand.

The depositional environment inferred from the presence of algal laminations and calcite-filled vugs (originally sulphate nodules) is that of a hypersaline, intertidal, carbonate flat environment (Greggs and Bond, 1976; Williams and Telford, 1986).

Figure 3 - Detailed surficial deposits (from Bélanger and Harrison, 1980).

2.3.3 *The Cenozoic Record*

The surficial deposits in the area are of importance to this study only to the degree that they either inhibit or facilitate recharge of precipitation to the underlying bedrock aquifer (Figure 3). The record of Paleozoic deposition in the area ends with the Ordovician Queenston Formation. Any younger rocks that may have existed were eroded during the long period of emergence which preceded Cenozoic deposition. In fact, most of the Cenozoic Era passed without record, with only Pleistocene and Recent sediments of the Quaternary Period, consisting of till, late marine deposits, and lacustrine and fluvial muds and sands (Wilson, 1946), succeeding the Ordovician rocks. These sediments are described in greater detail in Appendix 1.

Very few wells finish in the sediments of the Quaternary and therefore they are of limited potential in terms of modelling groundwater flow within them. An attempt was made to use the data contained in the MOE drilling reports to map surficial deposits, but had to be abandoned because, although overburden data exists for almost every one of the 2,987 well records in the study, no coherent spatial pattern emerged.

Most of the surface of the study area is covered by these sediments, with bedrock exposed in only a relatively small part. Figure 3 is a detailed map of the distribution of the surficial materials in the study area. A further account of the physiography of these deposits within the study area will be found in Chapter 3.

Chapter 3 HYDROGEOLOGICAL SETTING

3.1 CLIMATE AND GROUNDWATER INFILTRATION

Although the climate of Ottawa is described as "continental" with cold winters and warm summers, it is often affected by "maritime" air from both the Atlantic Ocean and the Gulf of Mexico (Crowe, 1984). The average monthly precipitation ranges from 60.3 to 88.4 mm (Environment Canada, 1984) and there is no pronounced dry season. Mean annual precipitation is 879.3 mm with well over half of that falling between December and March in the form of snow. Average monthly temperatures range from a low in January of -10.9 °C to a high in July of 20.6 °C. Atmospheric pressure normals are lowest in the period from April to July and highest in early fall. These figures represent climatic normals for the Ottawa-Macdonald-Cartier International Airport for the period from 1951 to 1980, representing the core of the time frame within which wells included in the study were drilled (1947 to 1992).

Brandon (1960) reports that a record was kept of the depth to water in a drilled well (43 feet) in west Ottawa throughout 1953. Data for this well indicates that maximum recharge occurs in late March to early April, with water levels falling throughout the summer (except after a period of heavy rain) to a minimum in late August. This is a result of increased evapotranspiration in the summer months, when most precipitation is either evaporated back to the atmosphere, absorbed by vegetation and transpired back to the atmosphere, or lost as runoff. In the autumn, when evapotranspiration has ceased, a certain amount of recharge again occurs in the time before the ground freezes. Allowing for variations in the magnitude of water-level fluctuations, the annual trend of the hydrograph remains unchanged from year to year (Brown, 1967).

Charron (1978) calculates runoff, infiltration and groundwater storage for the interstream area between the Ottawa and St. Lawrence Rivers based on a mean annual precipitation of 940 mm. Mean annual runoff is reported at 330 mm and mean annual evaporation at 500 mm, leaving a mean annual groundwater infiltration of 110 mm (figures cited to nearest whole number). If the October to December mean runoff of approximately 25 mm is taken as the average base-flow contribution rate from groundwater, then the total annual base-flow contribution from groundwater would equal 100 mm. This means that approximately 10 mm of the mean annual infiltration would remain as groundwater storage.

3.2 SURFACE WATER

Relief in the study area is generally low, ranging from a minimum of 80 metres above sea level in the northern reaches of the Rideau River valley to a maximum of 110 metres above sea level in the northeast corner (Plate 1, see Appendix 5). The boundaries of the area were selected to center on Manotick and to encompass anticipated recharge from west of the Rideau River in the Kars esker and from east of the river at the height of land. The northern and southern boundaries were chosen to be a reasonable distance north and south of Manotick on Long Island.

There are no lakes in the area, although in the eastern half there are a number of small areas of open water as well as swampy areas. In the far eastern portion of the area, the North Castor and Middle Castor Rivers and the Rideau Front aquifer in the surficial sands and gravels are described (Chin *et al.*, 1980) as being in the watershed of the South Nation River but the bedrock underlying them was included for completeness. The Rideau River is the main surface water feature in the area. It enters from the south, flowing in a north-northwesterly direction as far as Long Island and from there north toward the city of

Ottawa. The headwaters of the Rideau River are in Burrige Lake in the Precambrian Shield (Ontario Department of Energy and Resources Management, 1968) at approximately 163 metres (535 feet) above sea level. It is fed by a number of tributary lakes, rivers and creeks, including the Jock River, the Rideau's largest tributary, in the study area itself. The total drop of the Rideau River from its source to its mouth at the Ottawa River is approximately 120 metres (400 feet) over a distance of some 140 kilometres (85 miles) for an average gradient of 0.86 metres per kilometre. Approximately 35 metres of this drop occurs in the last ten kilometres before the Ottawa River and therefore the average gradient over all but the last ten kilometres is approximately 0.65 metres per kilometre (85 metres over 130 kilometres).

3.3 PHYSIOGRAPHY

The study area encompasses parts of three of the physiographic units of the Ottawa-St. Lawrence Lowland described by Chapman and Putnam (1984). All three are characterized by glacial and postglacial deposits. They are the Ottawa Valley clay plains, the Russell and Prescott sand plains and the North Gower drumlin field. The relief of the area is moderate, ranging from approximately 110 to 80 metres above sea level (Plate 1).

Johnston (1919) reported that the Champlain clays are best developed in stream valleys and depressions, although their distribution is irregular. South of Black Rapids (in the Rideau River, 1.5 km north of the study area), they are spread out extensively on both sides of the Rideau River valley. Well records used in this study confirm the intermittent distribution of clays throughout the entire study area. Woelfle (1983) describes an area corresponding to the Ottawa Valley clay plains within the study area as one of low relief and low permeability surficial materials consisting of glacial tills and marine silts and clays.

The northeast quadrant of the study area lies in the Russell and Prescott sand plains. It consists of areas of thin, highly permeable, marine (Champlain Sea) sands and gravels and thicker post-Champlain Sea sands, originally built as a continuous delta by the Ottawa River and its north-bank tributaries into the Champlain Sea (Chapman and Putnam, 1984). The area includes a highly permeable, ice-contact ridge of stratified sands and gravels called the Bowesville ridge, which extends in a southeasterly direction from the Ottawa-Macdonald-Cartier Airport (Woelfle, 1983). This northeast quadrant also includes the main bedrock outcrops in the study area which, as mentioned previously, is characterized by very little bedrock exposure. Here, moderately permeable dolostones and sandstones of the Oxford and March Formations are seen at the surface or covered by a relatively thin overburden veneer primarily of the permeable materials of the Russell and Prescott sand plains.

The southern half of the study area is located in the North Gower drumlin field (Putnam and Chapman, 1984). The drumlins found here are scattered and some are not completely formed; they are separated by lowlands occupied by poorly-drained marine clays or silts, although they themselves have good drainage. One other feature which adds complexity is the Kars esker, running north from Kars to the border of the City of Nepean. Excavations in this ridge reveal esker structure at its base, overlain by stratified beach gravel (Putnam and Chapman, 1984).

Given this description and the nature of surficial deposits depicted in Figure 3, any bedrock aquifer underlying the area might be considered to be only semi-confined.

3.4 REGIONAL HYDROSTRATIGRAPHY AND BEDROCK GROUNDWATER FLOW SYSTEMS

The study area constitutes a local groundwater drainage basin within the larger regional hydrogeological setting. At the local scale, bedrock topography and the presence of fractures provide controls on the direction of groundwater movement which will be investigated further in later chapters.

A number of studies have focussed on or discussed aspects of the hydrogeology of the Ottawa region in general and will be used in the following description of the regional hydrostratigraphy and groundwater flow systems in the study area. Scott's (1967) study of groundwater in Canada included a regional look at the Ottawa-St. Lawrence Lowlands. Like Scott, Brandon (1960), Robinson (1991) and Owen (1953) assessed the groundwater potential and well yields of the various rock units, with Owen focussing specifically on Gloucester Township and Robinson on Manotick itself. Charron's (1978) hydrochemical study of groundwater flow between the Ottawa and St. Lawrence Rivers is restricted to the area east of Carleton and Grenville Counties. (The area that is the focus of this study is located entirely within Grenville County.) Chin *et al.* (1980) looked in detail at the water resources of the South Nation River, immediately to the east of the study area. Woelfle (1983) comments on the general rate and direction of groundwater movement in the Ottawa area.

Very few wells in the study area are finished in the Precambrian crystalline basement since sufficient water is normally obtained before reaching these depths. However, this lithology can locally supply enough water for a home from fractures and joints near the surface, and deep drilling is not recommended.

Although fewer in number than the wells finishing in the overlying Oxford and March Formations, the number of wells in the study area which utilize the Nepean sandstone as a groundwater source is nevertheless significant (some 20 per cent of the total number of wells included). Two nearly vertical and one horizontal joint set paralleling the flat-lying bedding planes within the Nepean sandstone permit movement of water, with joints at the top and bottom of the formation reportedly yielding the most water. Average yields of 10 gpm are commonly obtained, with yields of up to several hundred gpm possible in places where fractures are well developed throughout a substantial thickness. Robinson (1991) reports that specific capacities are lower than expected, ranging from 2.2 to 10 Lpm/m.

The majority of wells included in the study finish in either the Oxford or March Formation. The strata of these two units are transected by a well-developed system of vertical joints. The presence of bedding planes and open fractures along joint planes make these strata useful aquifers. Several aquifer zones are reported, with average well yields varying from 5 to 50 gpm and even higher (up to 150 gpm) where fractures are particularly well developed and favourable recharge conditions exist. Aquifer development in the Oxford Formation is variable, with wells of large and small productivity often found in close proximity to each other. In Manotick, Robinson (1991) reports that the average specific capacity for wells in the Oxford and March Formations is 35.8 Lpm/m, with a range of 3.0 to 149.0 Lpm/m.

In general, faulting and associated fracturing can increase the capacity of rocks to transmit water. However, such faults and fault zones can also actually form boundaries to groundwater movement in cases where they have been sealed by calcite infilling. In assessing the exceptional pressures in a flowing well north of the fault inferred across the north half of the study area (Hazeldean Fault), Owen (1953) concluded that the fault is

sealed and that groundwater percolating through the March Formation accumulates against it, creating a groundwater source under pressure.

Groundwater drainage basins and recharge and discharge zones have been determined for some of the areas adjacent to the study area. Brandon (1960) concludes that water in the drainage basin west of the main Gloucester Fault block is moving northward towards Lac Deschênes. A regional northward flow was also determined by Charron (1978) for the area east of Ottawa. He used hydrogeochemical data (the Chebotarev sequence and distribution of dissolved solids) to assess the regional groundwater flow system and found that the major regional flow in the eastern portion of his study area terminates in the Alfred Bog, with a minor discharge at the mouth of the South Nation River. A separate study of the basin of the South Nation River (Chin *et al.*, 1980) places the extreme eastern part of the present study area in that drainage basin.

Finally, Woelfle (1983) reported that the probable general direction of groundwater movement in the bedrock is northward toward the Ottawa River. However, precise directions and rates of movement are difficult to predict because of the irregularity of fractures in the rock and the possibility of high movement rates along some fractures. In addition, site-specific variations in direction and flow rate are likely to exist as a function of local topographic and hydrogeologic features; for example, local flow in the study area is predicted to be directed toward the Rideau River.

Chapter 4 DATA SOURCES

4.1 WATER WELL RECORDS

Much of the data for this thesis were obtained from Ontario Ministry of the Environment water well records. A print-out of all records in the Ministry of the Environment Water Well Information System (Ground Water Bulletin Report) as of May 14, 1991 was obtained for the townships of Gloucester, Nepean, Osgoode and North Gower, since the study area straddles all four townships. This information system lists wells drilled between the years 1947 and 1984, inclusively. Approximately 1,350 wells were originally selected. The study area was subsequently expanded and new wells were added from the MOE Well Data System printout. The final study area comprises wells located within the following UTM co-ordinates: N5017000, E440000 in the northwest and N5003000, E458000 in the southeast. In addition, in order that the data base for this study be as up-to-date as possible, copies of individual records for the expanded area, dating from 1984 to the spring of 1992 were personally obtained from undigitized records stored at the MOE offices in Kingston, Ontario. This brought the data base up to a total of 2,987 well records.

For every well drilled, an MOE well record is completed by the driller. Records listed in the Water Well Information System printout include the following information: the original owner's name, the lot and concession number of the well, its UTM easting and northing co-ordinates, an assigned MOE well number, the surface elevation of the well (in feet), the date of drilling, the driller's licence number, the diameter of the cased well (in inches), the kind of water (fresh, salty, sulphurous, mineralized), the depth(s) from the surface at which water was found (in feet), the depth to the static level as measured from

the surface (in feet), the depth from the surface at which the pump was installed (in feet), the test rate (in gallons per minute), the test time (in hours and minutes), the water use (domestic, stock, irrigation, industrial, commercial, municipal, public supply, etc.), and the depths in feet to which the various lithological formations extend. With the exception of a small hand-drawn sketch map in place of UTM easting and northing co-ordinates, the water well records personally obtained from the MOE offices in Kingston provide the same information.

Certain caveats apply in the use of well record data. In the Water Well Data System, the Universal Transverse Mercator Grid eastings and northings given for each well have been assigned on the basis of the sketch map provided by the driller on the Water Well Record, showing the location of the well. In some cases, these maps are inadequate to permit the accurate siting of the well; for example, north arrows are sometimes omitted; street and road names may not be labelled or may be labelled incorrectly; distances are sometimes inaccurate. In addition, in very rare cases, the township, lot or concession may be incorrectly reported on the record. Another limitation is the fact that elevation is estimated by interpolation between contours on the topographic map of the area. Furthermore, although well drillers often know their area well, distinguishing among the lithologies encountered might pose a challenge even to a trained expert, as can be seen from the descriptions of the various stratigraphic units (Appendix 1). Finally, it must be assumed that in the entry of data in 2,987 records, each of which corresponds to numerous fields, some errors will have occurred.

Nevertheless, the data exist and are useful if the limitations are taken into account. In this study, because of the manner in which data were interpolated (see section 5.2), it is considered that any anomalous, incorrectly sited well log would have minimal influence. Lithological units have been logged exactly as they were entered in the records, with no

attempt being made to plot the carbonate formations (Oxford and March) separately since it is very difficult to distinguish the two in the records. The lithological information supplied by drillers was necessarily taken at face value since any attempt to reinterpret would simply add another level of uncertainty. The one exception to this was in regard to the top of the sandstone. The March Formation is a transition zone of sandy dolomite, and in some cases, well record entries alternate between carbonate and sandstone before finally recording sandstone. Although it is certainly possible that the two lithologies may continue to alternate beyond the point where the well finishes, the top of the Nepean is assumed to correspond to the elevation indicated in the last entry of sandstone in the well record.

Finally, it is appropriate to note that, while well drillers are indeed not geologists, many have spent years working in this area and are very familiar with the lithologies they expect to encounter.

4.2 GEOCHEMISTRY AND ISOTOPE DATA

Because it was not possible to sample a subset of wells evenly distributed throughout the study area, it was decided to select wells along two appropriate cross-sections. Ideally, the wells to be sampled would have been selected along groundwater flow paths as determined from the average potentiometric surface. However, because of the concentration of wells along roads and the added difficulty of linking an actual well to a record, it was decided that sampling cross-sections would necessarily follow roads that corresponded as closely as possible to anticipated flow paths. Two cross-sections (Figures 4a and 4b), were selected as likely to provide the most useful data based on what had been determined to date about regional flow patterns and geology.

A roughly east-west cross-section line was chosen to follow as closely as possible the groundwater movement from the edges of the study area to its discharge in the Rideau River. From the west side, this section runs east toward the Rideau River, starting at a point approximately 4 km west of Highway 16. It follows Regional Road 8 on the west side of the Rideau River, turns south along Regional Road 13 in Manotick (Main Street) and then runs east again along Regional Road 8. It continues along Regional Road 8, crossing Long Island and Regional Road 19, to a point approximately 3 km east of Highway 31.

A second, approximately north-south, cross-section was selected to intersect the bedrock and high in the northeast (Plate 2a, see Appendix 5). This section starts just south of Rideau Road on Bowesville Road and continues south to Regional Road 8. After a short turn to the west along Regional Road 8 it continues south along Manotick Station Road, crosses Highway 25 and ends at a point approximately 1.5 km south of this intersection.

The groundwater sampling program was undertaken in March of 1993. The location of each well sampled for geochemistry and isotope analysis is shown in Figure 4.

Appendix 2 (Table A2-1) contains a listing of each sampled well according to sampling line, depth and finishing lithology. In some cases it was necessary to sample wells located some distance from the defined cross-section line. However, in no case did such a distance exceed 1 km. Wells were selected with a view to obtaining a balance of finishing lithologies and depths, while choosing wells for which well records were available.

Where this was not possible, alternative (perhaps less ideal) well records were matched to

Figure 4 (a) Location of geochemistry samples along E-W and N-S sampling lines

Figure 4 (b) - Enlargement of the Manotick area showing location of geochemistry samples.

wells in the field. In some cases, where even an alternative could not be found, appropriately-located residences/homeowners were approached in the field in order to minimize the length of gaps in the sampling line. In such cases, residents were sometimes able to provide the names of original owners, traceable to well records; in others, it was necessary to rely on the memory of residents for details concerning their wells.

In the field, care was taken to ensure that untreated water was sampled directly from the well. The water was allowed to run for a minimum of ten minutes in order to clear pipes and cause the pump to start up, delivering fresh well water. Faucet screens were removed, where possible.

Field measurements were made of temperature, pH, titrated alkalinity and electrical conductivity; these are listed in Appendix 2 (Table A2-2). The pH meter was calibrated at the start of each day in two buffer solutions which bracketed the range of values encountered in the samples taken and which were maintained at the same average temperature as the groundwater encountered. One 250 ml bottle of unfiltered groundwater was collected at each sampling well for laboratory analysis of major and trace ion constituents. Another 250 ml sample was collected and filtered (45µm pore diameter filter paper). Concentrated nitric acid was added to this filtered aliquot to keep cations and metals in solution. In some cases, another 60 ml sample was collected for isotope analysis.

All of the geochemical analyses were carried out by Bondar-Clegg & Co. Ltd. of Ottawa. Cations were analysed by Inductively Coupled Plasma. Anions were analysed by Ion Chromatography. Appendix 2 (Table A2-3) contains a complete listing of all analysed constituents and their lower detection limits. This listing also includes computed values such as TDS and hardness as well as footnotes describing how the latter were calculated.

Stable isotope analyses were performed at the Stable Isotope Laboratory, Ottawa-Carleton Geoscience Centre. Oxygen-18 contents were determined by CO₂-water equilibration at 25°C using an automated system. Deuterium contents were determined by the analysis of H₂ generated via reduction of water on zinc at 430°C. Analytical precisions are ± 0.10 permil and ± 1.3 permil (SMOW), respectively. Results are reported in Appendix 3 (Table A3-1).

All tritium analyses were performed by liquid scintillation counting at the Environmental Isotope Laboratory, Department of Earth Sciences, University of Waterloo. Results (Table A3-1, Appendix 3) are expressed in tritium units (T.U.; one T.U. is defined as one atom of ³H per 10¹⁸ atoms of ¹H). Analytical precision is given as ± 8 T.U.

4.3 GEOPHYSICAL DATA

Geophysical data from maps compiled by the Geological Survey of Canada were also used. A horizontal gradient of Bouguer gravity anomalies map (Figure 5) encompassing the Manotick study area (outlined) was prepared by the Geophysics Division of the Geological Survey of Canada, Natural Resources Canada. Innes (1967) noted that in the preparation of a Bouguer anomaly map, observations are reduced to sea level and corrections are made for the mean shape of the earth and its rotation. Then, in order to facilitate the comparison of gravity signatures in different regions and the location of abrupt lateral variations in density, further processing is applied to the gravity data and the maximum value of the horizontal gradient (slope) of the Bouguer anomaly at every point (grid cell) on the Bouguer anomaly map is calculated (Goodacre *et al.*, 1987). The result is

Figure 5 - Horizontal gradient of Bouguer gravity anomalies; study area outlined in black. Compiled by the Geophysics Division, Geological Survey of Canada, Natural Resources Canada.

a horizontal gradient map. The absolute value of the horizontal gravity gradient vector (the horizontal gradient) at a cell on the map is determined by the least squares fitting of a plane to the gravity values contained in a 5 x 5 array of cells (an area 25 x 25 km) centered on

the cell in question. The slope of the plane, without regard to direction, represents the horizontal gradient of the Bouguer anomaly field at the cell in question.

4.4 SEISMIC DATA

Three hundred and nine geographically-referenced shallow seismic bedrock elevation data points were provided by the Terrain Sciences Division, Geological Survey of Canada. These data were imported into AutoCad and a contour drawing was produced by interpolation using QuickSurf.

Chapter 5 DATA ANALYSIS AND RESULTS - PHYSICAL HYDROGEOLOGY

5.1 WELL DATA MANAGEMENT - COMPILATION AND DESCRIPTION OF DATABASES

The process of using a GIS (geographical information system) begins with the creation of a data base, which is a collection of information about "things" in the real world and their relationships to each other (Aronoff, 1993). In this case, the "things" are wells, which have a fixed, spatial relationship to each other; in addition, each well is associated with a unique set of physical dimensions. Once the spatial and associated physical information is captured and stored in the data base, it can be retrieved, manipulated and displayed by the GIS.

The data base for this project consists primarily of information taken from a total of 2,987 well records in the Ontario Ministry of the Environment Water Well Information System, as described previously (section 4.1). The relevant information contained in these records was entered into a number of dBase III+ files, which were subsequently transferred to three main FoxPro files, WATER.dbf, ROCK.dbf and WELLBOT.dbf. Table 2 shows how these files are structured and the information they contain. Each file contains one record for every well in the study area, and each well record consists of various data or attribute fields as described below. In all three files, data are keyed to a field entitled "Wellno". This primary key, or label, is a unique alphanumeric tag assigned to every well and is used as the link among all data files related to an individual well. If each file is thought of as a two-dimensional table, using the relational model, a search can be made of any single table using any of the attribute fields, singly or together. Searches of related

attributes that are stored in different tables can be carried out by linking two or more tables by means of any attribute they share in common (Aronoff, 1993). In this case, the "Wellno" field is used for this purpose. Thus, using this relational structure or

DATA BASE FILE	FIELD NAME	TYPE	WIDTH
WATER.DBF	WELLNO	Character	7
	X	Numeric	11
	Y	Numeric	11
	WATSURF	Numeric	6
	BEDROCK	Character	7
	WELLTYPE	Character	5
ROCK.DBF	WELLNO	Character	7
	BEDELEV	Numeric	7
	NEPEANSS	Numeric	7
	CARBTHICK	Numeric	7
	ELEVATION	Numeric	7
WELLBOT	WELLNO	Character	7
	ELEVATION	Numeric	5
	TOTDP_M	Numeric	5
	WELLBOT	Numeric	6

Table 2 - Structure and content of databases used in this study.

relational data model, spatial and attribute well data can be stored, retrieved and queried in a simple and efficient manner.

The ROCK.dbf file contains information relating to bedrock at the location of the well. In addition to the key field, "Wellno", this file contains the following attributes for a given well: "Bedelev" is the elevation of the bedrock surface in the well; "Nepeanss" is the elevation of the upper surface of the Nepean sandstone in the well; "Carbthick" is the thickness of the Oxford and/or March units in the well; "Elevation" is the elevation of the ground surface at the site of the well. All elevations in these field types are standardized in centimetres above mean sea level so that all subsequent surfacing and modelling operations can be in real and standard values.

The WATER.dbf file includes information relating to the individual well and its location. In addition to the key field, "Wellno", the WATER.dbf file contains the following fields: "Watsurf" is the elevation (above mean sea level) of the static water surface in the well; "Bedrock" indicates whether the well finishes in bedrock or in overburden; "Welltype" indicates whether the well finishes in the Oxford or March Formation (CARB) or in the Nepean Formation (SS); "X" and "Y", represent UTM easting and northing co-ordinates. These co-ordinates were assigned either in the Ontario Ministry of the Environment Water Well Information System, in the case of wells drilled between 1947 and 1984, inclusively, or by manual digitization of well locations, in the case of wells drilled between 1985 and 1992.

The WELLBOT.dbf file contains information relating to the elevation of the finishing depth of each well. In addition to the key field, "Wellno", this file contains an "Elevation" field, recording the elevation of the ground surface at the site of the well, a "Totdp_m" field, recording the total depth of the well in metres, and a "Wellbot" field, which subtracts "Totdp_m" from "Elevation" to give the elevation above mean sea level of the bottom of the well.

Within the FoxPro data base management environment, these master files were used to produce other simplified or enhanced files — for example, by removing, adding or subtracting field entries — tailored to the specific purpose of each surface or map to be prepared. These individual georeferenced data base files were subsequently translated directly into the GIS environment to become point attribute tables, used for surfacing and modelling.

5.2 DEVELOPMENT AND PRODUCTION OF BASIC SURFACES

In addition to attribute data, each record contained in the databases described above also contains, or is linked to, a spatial component of geographic information: these are the X and Y co-ordinates for every well. Thus, depending upon the map to be produced, appropriate attribute values (ex., bedrock surface elevation, static elevation, etc.) can be assigned to each well, with the result, in each case, being a geographically referenced point data set.

There are two ways of representing this spatial component: the vector model and the raster model. In the vector model, objects or attributes in the real world are depicted by the points and lines that represent their boundaries. In a raster model, which is used almost exclusively in this project, the space is divided into cells or pixels, which are usually square and equally sized. The position of objects or attributes is defined by the row and column (x, y) position(s) of the cell(s) they occupy in Cartesian space. In the raster model, resolution is limited by the size of the cells. Unless otherwise indicated, for each raster surface map produced, the approximately 18- by 20-km study area is divided into an array of 599 by 680 pixels, each of which represents an area approximately 30 x 30 metres on the ground.

Since the data base contains spatial and attribute data for a total of 2,987 wells, many pixels do not contain real data points. Therefore, one of a variety of interpolation procedures must be chosen in order to produce a raster surface map which represents a continuous array of values. Interpolation is the procedure of predicting the value of unknown cells using the known values of neighboring cells (Aronoff, 1993). The quality of the interpolation was assessed by comparing manually prepared drawings of the potentiometric and bedrock surfaces with the corresponding computer-generated surfaces.

The interpolation used is a **full 2nd degree moving surface***. In this procedure, a new surface is calculated for each cell, based on the real input point data that occur within the limiting distance, according to the formula:

$$z = a + bx + cy + dxy + ex^2 + fy^2 \quad (1)$$

and the value is entered in that cell. The constants associated with each term are a function of the real data points (input values) that occur within the weighted distance. Each constant is also a function of the weight term, W . An **exact-solution weight method** is used, in which W is defined as

$$W = [1/(D/d_0)^n] - 1,$$

where:

W = the calculated weight,

D = the distance to a known point measurement,

d_0 = the **limiting distance**, and

n = the **value constant**

* Terms in boldface are found in the Glossary of Computer Terms, Appendix 4.

In this study, the limiting distance is 3,500 metres, unless otherwise indicated and the value constant is 1.25. It was found that this limiting distance was the shortest that produced acceptable edge effects and interpolation gaps. The value constant has the effect of decreasing the influence of known values with distance from the unknown cell, until the limiting distance is reached. This weight method produces **exact solution surfaces**, or surfaces which respect the values of known points, because when the distance between an output pixel and an input data point is zero, then the weight is infinite. Thus, this weight method forces output values to equal input data point values at the location of the points. The result can be the presence of "bull's-eyes" around anomalous points; in some cases, these "bull's-eyes" were smoothed by one or more low-pass, 5x5 smoothing **filters**.

Most surfaces were produced in the above-described manner. However, the Digital Terrain Model and the bedrock surface based on seismic data were produced by **linear interpolation** from contoured maps (Gorte and Koolhoven, 1990).

The colour palettes chosen for each image were selected to best depict the feature being represented. This was done using a colour **look-up table (LUT)**. Within each look up table, combinations of intensities can be adjusted by the user.

The following is a description of each of the basic surfaces, which were prepared as described above. In addition, for reference purposes they have been combined by map algebra (see section 5.3) with a surface georeferenced to the same co-ordinates and depicting only the Rideau and Jock Rivers. Some surfaces have been trimmed to eliminate edge effects; all are found in Appendix 5.

5.2.1 *Digital Terrain Model*

The Digital Terrain Model (Plate 1) was produced by interpolation from elevation contours. It is based on NTS sheets 31 G/5 (Ottawa sheet) and 31 G/4 (Kemptville sheet), which were manually digitized and encoded for elevation for the study area. The resulting line drawing was imported into the GIS environment, where it was georeferenced and interpolated (Gorte and Koolhoven, 1990). The unusual appearance of the northern and eastern parts of the image results from the fact that only the area corresponding to the original 1350 wells was digitized, encoded for elevation and imported into the GIS. The interpolation was extrapolated into the expanded study area to allow for complete coverage of the data set. The original 9 kilometre by 10 kilometre area was expanded 280% to an area 14 kilometres by 18 kilometres by adding an approximately equal area on each side. Data coverage for all other interpolated plots is complete.

5.2.2 *Carbonate Thickness (Carbonate Thickness Map)*

The Carbonate Thickness Map (Plate 2a) was produced by the main point interpolation method described earlier (5.2) and is based on 388 points. These points represent wells in which carbonate thickness is known because, in each case, the well extended into the Nepean sandstone. The thickness was computed by subtracting the value for the elevation of the top of the Nepean sandstone from that recorded for the top of the Oxford Formation. In this case, the result is not strictly speaking an interpolated surface, but rather an interpolated thickness or isopach map (Hamilton and Jones, 1992). It represents a minimum thickness of this unit since the Oxford Formation subcrops and the upper portion of the unit has been eroded.

5.2.3 Distribution of Wells beginning in Sandstone

The number of points used in this plot is less than the total number of wells finishing in sandstone (see section 5.2.4). The difference is accounted for by the number of wells in which the first lithology encountered is sandstone and which contain no carbonate in their logs. These parts of the study area where sandstone is at the bedrock surface do not correspond to zero values in the Carbonate Thickness Map because, in order to produce the latter, the data base was queried for wells beginning in carbonate. This means that the Carbonate Thickness Map interpolates over these "holes" or areas of no carbonate, and that there are areas of the preceding map which indicate that carbonate is present when, in fact, it is not. Plate 3 shows that there is a fairly general distribution throughout the study area of wells beginning in sandstone, with some concentration along the Rideau River north of Long Island. It is assumed that these areas are limited in scope; they appear to correspond with some of the thinnest areas of carbonate, particularly in the northern section of the Rideau River.

5.2.4 Nepean Sandstone Elevation (Nepean Sandstone Elevation Surface)

The Nepean Sandstone Elevation Surface (Plate 2a) was produced by the main point interpolation method described in section 5.2. It is based on the elevation (AMSL) of the top of the Nepean sandstone as first encountered in the drilling of each of the 562 wells which finish in that formation. Therefore, it is representative of a modelled surface which predicts the present-day orientation and form of the Nepean sandstone.

For an explanation of the criteria used to distinguish between the Nepean and the March Formations, see section 4.1.

5.2.5 *Bedrock Surface (Bedrock Surface from Well Data)*

The Bedrock Surface from Well Data (Plates 2a and 4) was produced by applying the main point interpolation method described earlier (section 5.2) to all 2,987 bedrock wells (wells which finish in bedrock) in the data base. The known values used in the interpolation represent the elevations, above sea level, of the first bedrock surface lithology encountered in the drilling of each well. In virtually all cases in the study area, the first lithology encountered is the Oxford Formation. This surface then represents the pre-overburden, paleo-bedrock surface topography.

5.2.6 *Average Regional Potentiometric Surface*

The Average Regional Potentiometric Surface (Plates 2a and 2b) was produced by applying the selected interpolation procedure to the elevation above sea level of the static water level in all of the 2,987 bedrock wells, whether they were finished in a carbonate or sandstone unit and without regard to the date that levels were measured. This surface then represents a first-order regional surface, spanning the history of data collection: 1947 to 1992.

Strictly speaking, the concept of a potentiometric surface is only applicable to horizontal flow in a horizontal, confined aquifer (Freeze and Cherry, 1979). In such an aquifer, because equipotential lines are vertical, the value of the potentiometric surface is unaffected by completion depth. In this study, neither the groundwater flow nor the aquifer is perfectly horizontal. Moreover, the aquifer is not always confined and completion depths vary. However, the assumption is made that the aquifer and flow are horizontal in order to obtain a first-order estimate of the potentiometric surface, in this case, based on all wells, as well as to obtain separate estimated potentiometric surfaces based on wells finishing in the carbonate (section 5.2.8) and wells finishing in the sandstone (section 5.2.9). This type of potentiometric surface is really a map of hydraulic head contours on a

two-dimensional, roughly horizontal cross-section of varying elevation (matching finishing depths) taken through the three-dimensional head pattern that exists in the subsurface in the area.

This process also ignores the fact that the finishing depths of the wells used in all three of these surfaces vary greatly. Given the fractured nature of the aquifer, it is quite possible that a relatively shallow well may exist very close to a much deeper well, with correspondingly different heads. The two head values would plot in close proximity to each other and the result may be an anomalously high or low value which must be dealt with by the interpolation method. An attempt is made later in this study to deal with changes such as these which occur in the vertical direction.

5.2.7 Bedrock from Seismic (Bedrock Elevations from Seismic Data)/Bedrock Surface from Well Data

A contour drawing based on 309 shallow seismic bedrock elevation data points (section 4.4), was interpolated from its isolines (contours) (Gorte and Koolhoven, 1990) to produce the Bedrock from Seismic Surface (Plate 4). For validation purposes, it is depicted beside the Bedrock Surface from Well Data, with both trimmed to the dimensions of the seismic map.

5.2.8 PS Finish in Carbonate (Potentiometric Surface for Wells Finishing in Carbonate)

The Potentiometric Surface for Wells Finishing in Carbonate (Plate 5) represents the average regional potentiometric surface for all wells finishing in carbonate. It was produced by applying the selected interpolation procedure to the elevation above sea level of the static water levels in all of the 2,425 wells in the study area which finish in a carbonate unit, either the Oxford or March Formation.

5.2.9 PS Finish in Sandstone (Potentiometric Surface for Wells Finishing in Sandstone)

The Potentiometric Surface for Wells Finishing in Sandstone (Plate 5) represents the average regional potentiometric surface for all wells finishing in sandstone. It was produced by applying the selected interpolation procedure to the elevation above sea level of the static levels in all of the 562 wells in the study area which finish in the sandstone of the Nepean Formation.

5.3 DEVELOPMENT AND PRODUCTION OF ENHANCED SURFACES

The enhanced surfaces prepared for this study were produced either by map algebra performed on existing surfaces or by manipulation of the data base with a view to obtaining a desired georeferenced attribute. In each case, the same dimensions as those used in the basic surfaces are maintained: 599 by 680 pixels, except in the case of air photos, which are 947 by 1224 pixels.

5.3.1 Manotick — Bedrock Well Locations

The Manotick — Bedrock Well Locations Surface (Plate 6), is an air photo mosaic with all bedrock well locations in the study area represented by blue circles (designed to be large enough and bright enough to be distinguishable against the background).

The air photo mosaic was prepared by first scanning the four air photos which cover the study area. Approximately 5 identifiable tie points per photo were then assigned UTM co-ordinates and the photos were then merged and trimmed to the area of the study. The well locations were then appended in a data base table, with symbol annotation parameters as described above and displayed on top of the georeferenced air photo mosaic.

5.3.2 *Modelled Bedrock Surface*

In Plate 7, the Modelled Bedrock Surface is shown for validation purposes together with the Bedrock Surface from Well Data, which was derived from well data, and the Bedrock Surface from Seismic Data, which was derived from seismic data. The Modelled Bedrock Surface represents the arithmetic addition of two basic surfaces: the Nepean Sandstone Elevation Surface and the Carbonate Thickness Map. The significance of this surface relates to surface validation and is explained in section 5.4.

5.3.3 *IHS (Intensity-Hue-Saturation) Transform of Air Photo Mosaic and Mean Potentiometric Surface*

While it is impossible to assign two values to one pixel, an **intensity-hue-saturation transform** (Drury, 1993; Harris and Murray, 1990) makes it possible to combine different sorts of imagery. In this case, Plate 8 appears to depict a combination of the air photo mosaic and the potentiometric surface. To prepare this IHS transform surface, **intensities** were assigned to the air photo and **hues** (colour) to the potentiometric surface; the **saturation** values were not used (set to 1 in order to keep all pixels at a common base level).

5.3.4 *Incremental Potentiometric Surfaces*

Each of the incremental potentiometric surfaces depicted here (Plate 9) was produced by isolating the data for all wells finishing within successive five-metre thick, horizontal slices through the aquifer. These exclusive data sets were then used to generate separate potentiometric surfaces based on the static elevations in only those wells finishing in a given five-metre slice. In order to develop this series of 9 surfaces, a histogram of the data base was prepared showing the number of wells finishing in all 5-metre depth classes in the aquifer. The classes ranged from 25-30 metres above sea level (i.e., the deepest wells), to 90-95 metres above sea level (i.e., the shallowest wells). Categories at both

extremes were eliminated because they contained too few wells to permit a valid interpolation. The classes retained are described in Table 3.

Interpolation Surface	Well finishing depth (MASL)	Number of wells per finishing depth class
PS50	45-50	120
PS55	50-55	178
PS60	55-60	262
PS65	60-65	336
PS70	65-70	443
PS75	70-75	440
PS80	75-80	338
PS85	80-85	299
PS90	85-90	166

Table 3 - Incremental potentiometric surfaces, their finishing depth ranges and number of wells.

Each of these interval data sets was then interpolated using the procedure described above (an exact, full second order, moving surface interpolation from points). However, because each surface contained a reduced number of data points, the limiting distance was increased from 3.5 km (section 5.2) to 10 km in order to avoid interpolation gaps.

5.3.5 Incremental Potentiometric Surface Changes

The maps depicted in the Incremental Potentiometric Surface Change series (Plate 10) do not represent interpolated surfaces (hence no point count is given). Rather, they were prepared by performing map algebra on the previous series of maps. Each of the first eight maps represents the mathematical difference between the values of two successive 5-metre intervals. For example, DPS9085 represents the values obtained when the potentiometric surface in the 85-80 metre interval is subtracted from that in the 90-85 metre

interval, and so on. The ninth and final map in the series, DPS9050 represents the difference between PS90 and PS50 (i.e., PS90-PS50). Because of local variations, the value for DPS9050, or the difference between data at the highest and lowest finishing depths, is often less than the difference between intermediate depth slices.

5.3.6 Multi-Level Modelled Potentiometric Profiles

The symbols used with the air photo mosaic in Plate 6 to depict well locations were changed to small filled circles. Two cross-section lines, digitized as vector lines, were also added to the air photo mosaic to create the Manotick — Bedrock Wells and Section Lines image (Plate 11).

In order to create the Multi-Level Modelled Potentiometric Profiles seen in Plate 12, the potentiometric surface was sampled at 100-metre intervals along each cross-section line and the surface pixel values placed into a georeferenced table. Each of the points sampled is associated with a record in all of the databases for the nine incremental potentiometric surfaces, PS50 to PS90, described in section 5.3.4 (Plate 9). Thus, separate cross-section lines were produced depicting values sampled along each line as it crosses each of the nine incremental potentiometric surfaces. The Average Regional Potentiometric Surface was also sampled along the cross-section lines and included on the drawings. The resultant superimposed multi-layered potentiometric profiles cross-section depicts the real static height variation for the range of finishing depths along each section.

5.3.7 Vertical Potentiometric Surface Variation

In order to look at vertical variations in head, an image depicting the Vertical Potentiometric Surface Variation (Plate 13) was prepared by plotting incremental potentiometric surface values against the finishing depth interval for each corresponding pixel in the nine incremental potentiometric surfaces, and then plotting a best-fit, straight

line through the points. Figure 6 (a) shows a cross-section through an idealized regional potentiometric surface in a homogeneous, isotropic aquifer. Figure 6 (b) shows the modelled profiles along the cross-section of the potentiometric head at each of three finishing-depth increments as well as the average regional potentiometric surface (ARPS). At the location of pixel "B", the head at each of the three incremental potentiometric surfaces is sampled and the resulting values plotted (Figure 6 (c)), against finishing depth interval in cartesian space, from lowest to highest above mean sea level. The negative slope of the best fit straight line plotted through the points indicates an increasing head with depth, or discharge at pixel B; similarly, a positive slope would indicate recharge.

Figure 6 - Idealized description of the development of the Vertical Potentiometric Surface Variation surface.

In the same way, the Vertical Potentiometric Surface Variation surface represents a plot of the slope of the best-fit line as calculated at each pixel. The slope was obtained by the linear least-squares regression method and was calculated for each pixel as follows:

$$m = \frac{\sum_{i=1}^n (x_i - \bar{x}) (y_i - \bar{y})}{\sum_{i=1}^n (x_i - \bar{x})^2} \quad (2)$$

where x_i is the top elevation of the i -th five-metre interval, $\bar{x}$ is the average top elevation of all nine intervals, y_i is the potentiometric surface elevation for the i -th five-metre interval and $\bar{y}$ is the average potentiometric head for all nine intervals.

5.3.8 Correlation Coefficient for Vertical Potentiometric Surface Variation

This surface (Plate 14) was prepared in order to obtain an indicator of the strength of the linear relationship plotted above between the two variables, finishing-depth interval and potentiometric surface elevation. It was developed by calculating, at each pixel, the coefficient of correlation between the two variables. This quantity, denoted by the symbol r , was computed as follows:

$$r = \frac{\sum_{i=1}^n (x_i - \bar{x}) (y_i - \bar{y})}{\sqrt{\sum_{i=1}^n (x_i - \bar{x})^2 \sum_{i=1}^n (y_i - \bar{y})^2}} \quad (3)$$

where the variables x_i , $\bar{x}$, y_i , and $\bar{y}$ are as described in section 5.3.7.

5.3.9 Integrated Horizontal and Vertical Potentiometric Gradients

The Integrated Horizontal and Vertical Potentiometric Gradients surface (Plate 15)

represents a combination of three concepts at each pixel: the background depicted behind the arrows in this surface is the vertical potentiometric surface variation (i.e., the slope of the linear interpolation of incremental potentiometric surface values vs. finishing depth), as described above (Plate 13); the magnitude of the regional potentiometric surface gradient (representing both vertical and horizontal components of flow) is proportional to the arrow length and the direction of the regional potentiometric surface gradient is depicted by the arrow direction.

In order to obtain the surface of symbolized points combined with the background vertical potentiometric surface variation, the original Average Regional Potentiometric Surface (Plate 2b) was first sampled at a coarser grid size (16 pixels to 1) to obtain a point with X and Y co-ordinates associated with the center of a coarser array of 783 points. The edge effects were then masked in order that all points would be in areas of high confidence in terms of the interpolation. Then, sampling the original finer grid at the points closest to the 783 points chosen above, two separate filters were applied — a dx and a dy filter — to produce two different maps, depicting the slope in the x direction and the slope in the y direction, respectively. By map algebra (Schetselaar and Veldkamp, 1992), these two maps were combined in a specific slope function [$\text{slope}(\text{dx}, \text{dy})$] which determines the magnitude of maximum slope at each pixel sampled. In the same way, another map algebra function [$\text{aspect}(\text{dx}, \text{dy})$] calculated the direction of these maximum slopes. Then, for each of the 783 georeferenced points, these two attributes (magnitude and direction) were symbolized in a table containing the X and Y co-ordinates of each symbol (arrow center), its size (proportional to magnitude of flow gradient) and rotation (depicting direction of maximum flow gradient). The symbol file was then displayed directly on top of the background co-referenced vertical gradient image for a complete tri-featured map

product depicting the spatial distribution of vertical gradient, and the magnitude and direction of the average regional potentiometric surface gradient

5.3.10 *Flow Patterns along Sampling Lines*

Plate 16 is an image which combines the arrows depicting flow direction and magnitude in Plate 15 and the location of wells sampled for geochemical analysis.

5.4 SURFACE VALIDATION

In this study, because of the uncertainties associated with the well data set (see section 4.1) and with interpolation in the case of surfaces based on a limited number of points, the co-validation of separately derived surfaces provides a very useful and important check on the interpolation technique and on any modelling procedures based on it.

Plate 7 shows a good correlation between the Bedrock Surface from Seismic Data, obtained from independent seismic data (sections 4.4 and 5.2.7), and the Bedrock Surface from Well Data (section 5.2.5), derived by applying the main point interpolation method (section 5.2) to the full well data set. More detailed statistical correlation analysis between these surfaces was beyond the scope and needs of this study. However, as a first order estimate, the correlation seen between these two surfaces helps to validate interpolations performed by this method.

In the case of the Modelled Bedrock Surface (Plate 7), the GIS was used to model the bedrock surface by adding together two surfaces which had themselves been interpolated using the GIS. Any differences result from the fact that all three surfaces have different point densities and different point distributions, and the modelled surface represents the

addition of an interpolated surface and an interpolated isopach map. Nevertheless, the Nepean Sandstone Elevation Surface, which was interpolated from only 562 points, and the Carbonate Thickness Map surface, interpolated from only 388 points, were combined to produce a modelled bedrock surface which bears a very close resemblance to both the bedrock surface interpolated from 2,987 points and the bedrock surface obtained from seismic data. Thus the Modelled Bedrock Surface is a co-validated surface, increasing confidence in and validating interpolations performed by the same method.

Finally, although each of the images in the series of Incremental Potentiometric Surfaces (Plate 9) is based on a limited number of mutually exclusive data points which are less than evenly distributed, the same overall pattern is seen in all. Once again, the fact that different, exclusive data sets produce similar surfaces is a strong indication that the overall phenomenon is being modeled in a reasonable fashion and that the interpolation method is a valid one.

Chapter 6 DATA ANALYSIS AND RESULTS - ISOTOPES AND GEOCHEMISTRY

6.1 DATA VERIFICATION

6.1.1 Data Check 1

A charge-balance error for each analysis was calculated as follows:

$$E = \frac{\sum zm_c - \sum zm_a}{\sum zm_c + \sum zm_a} \times 100 \quad (4)$$

where E is the charge-balance error expressed in percent, z is ionic valence, m_c is the cation species molality, and m_a the anion species molality. These errors are reported in Appendix 2 (Table A2-4). Five of the 47 analyses have errors in excess of 5%; all are less than 10%, which is the error reported as acceptable by the analysing laboratory.

6.1.2 Data Check 2

One means of obtaining an approximate data accuracy check is by using measurements of conductivity in microsiemens per centimetre and total dissolved solids (TDS) in milligrams per litre (Hem, 1989). This method is referred to in this thesis as data check 2. The TDS value should generally equal the conductivity times an adjustment factor of between 0.55 (for water in which anions are predominantly chloride and bicarbonate) and 0.75 or more (for water in which anions are predominantly sulfate). The two parameters, TDS and conductivity, are listed for each sample in Appendix 2 (Table A2-4) together with the adjustment factor which applies (referred to as check 2 in the table). The deviation

between the TDS and conductivity for each sample was calculated as a percentage of 0.60. This value was used for all samples since sulfate anions never predominate over chloride and bicarbonate. The average deviation for all wells is 7.33%. If a maximum acceptable deviation is taken to be 10.99%, there are ten samples which have unacceptably high deviations. A possible explanation will be addressed in the next section.

6.1.3 *Data Check 3*

A third method of chemical verification, called check 3 in this thesis, involves comparing the conductivity ($\mu\text{S}/\text{cm}$) for a sample with the total cations for that sample in milliequivalents per liter (epm) multiplied by 100 (anions may also be used) (Hem, 1989). While these two values should not necessarily be exactly equal, this check is regarded as slightly less variable than check 2 because charge is taken into account in epm values. These two parameters are compared in Appendix 2 (Table A2-4). In each case, the difference is calculated as a percentage of the larger value. The average discrepancy between the two values is 9.81%. Again, if a maximum acceptable deviation is taken to be 10.99%, there are 24 samples which have unacceptably high deviations.

Since check 1 does not reveal any unacceptable results in the chemistry analyses, it is assumed that the TDS values used in check 2 and the totals of milliequivalents per litre used in check 3 are reliable, since they are based on the chemistry analyses. Therefore, where both check 2 and check 3 are unacceptably high, it is suggested that the electrical conductivity values measured in the field are suspect. This occurs in the case of six samples: 22, 26, 31, 42, 45 and 47. In the case of twenty-two samples, either check 2 or check 3 is unacceptably high: check 2 in four cases, check 3 in eighteen cases. In the four former cases, the choice of an inappropriate adjustment factor could account for the unacceptably high deviations. The eighteen cases where check 3 is unacceptable are not

explained. However, since check 1 and check 2 are favourable, the samples were retained for study.

6.2 DATA ANALYSIS TECHNIQUES AND RESULTS

It should be noted that certain samples which are located in the vicinity of the intersection of the two sampling lines, may be included in plots for both lines.

6.2.1 *Piper Diagrams*

Four Piper diagrams were plotted (section 7.2.1): one for wells finishing in carbonate and one for wells finishing in sandstone on the east side of the west arm of the Rideau River, and two similar diagrams for wells located west of the west arm. This method, published by Piper in 1944, is a standard means of depicting a large volume of chemistry data for multiple samples. In a Piper diagram, each major cation (Ca^{+2} , Mg^{+2} and Na^{+}) in a given sample is plotted in the lower left trilinear field according to its ppm value expressed as a percentage of the sum of the equivalents for all the cations. Similarly, for each sample the three major anions (HCO_3^{-} , SO_4^{2-} , Cl^{-}) are plotted in the lower right trilinear field. Each of the two points is then traced up into the diamond along a line parallel to the outside edge of its respective triangle, and the sample plots in the diamond where the two lines intersect.

6.2.2 *Water Parameter Profiles*

A number of diagrams showing changes in individual geochemical parameters (chloride, conductivity, TDS) along the two sampling cross-sections have been prepared (section 7.2.3). In this case, for each sample, the magnitude of the parameter in question is plotted on the ordinate and the sample's relative location is plotted on the abscissa. On east-west

Year of recharge	Mean annual ^3H concentration in precipitation (TU) (N_0)	Resultant theoretical ^3H concentration in 1993 (TU) (N)
1953	27	3
1954	302	34
1955	45	5
1956	146	19
1957	120	16
1958	515	73
1959	540	81
1960	147	23
1961	212	36
1962	983	175
1963	2940	552
1964	1561	310
1965	865	182
1966	583	129
1967	311	73
1968	211	52
1969	244	64
1970	204	57
1971	194	57
1972	88	27
1973	93	31
1974	102	35
1975	88	32
1976	67	26
1977	52	21
1978	75	33
1979	41	19
1980	56	27
1981	56	29
1982	47	26
1983	49	28
1984	44	27
1985	34	22
1986	40	27
1987	39	28
1988	38	29
1989	44	35
1990	38	32
1991	41	37
1992	41	39
1993	41	41

Table 4 - Mean annual tritium concentrations in precipitation at Ottawa, and the corresponding theoretical concentration, generated by radioactive decay, which would have been observed in 1993 in groundwater that had been recharged in each respective year. (Data from R. Drimmie, University of Waterloo)

cross-sections, relative locations are given as sample distances from the west arm of the Rideau River. On north-south cross-sections, relative locations are plotted as sample distances from the north end of the cross-section. In each case, separate cross-sections were prepared for wells finishing in carbonate and for wells finishing in sandstone on the assumption that similar patterns would imply that the two lithologies function as a single aquifer.

6.2.3 *Isotope Plots*

Tritium, which is a radioactive isotope of hydrogen, has a short half-life of 12.43 years. It was injected into the atmosphere during the 1950s and 1960s by atmospheric nuclear testing, overshadowing natural production at times by several orders of magnitude. Although few reliable measurements were made of natural tritium levels in the atmosphere before that time, background levels in precipitation reportedly ranged from approximately 4 to 25 TU for various locations (Fritz and Fontes, 1980), with levels in the Ottawa area estimated at 15 TU (Michel, pers. comm.). Table 4 lists the mean annual tritium concentration in precipitation at Ottawa for each year between 1953 and 1993, inclusive (Drimmie, pers. comm.). It also lists the corresponding theoretical concentration, resulting from radioactive decay, which would have been observed in 1993 for groundwater that had been recharged in each respective year. N is calculated from the radioactive decay equation: $N = N_0 e^{-\lambda t}$, where N = tritium concentration at time t (years before 1993), N_0 = initial tritium concentration, and $\lambda = 0.693/12.43$. These data are plotted in Figure 7.

Any water with tritium concentrations above background levels must have been recharged subsequent to the time of atmospheric nuclear testing. Depending upon the currently measured tritium concentration of a sample, it can be classified as belonging to various

Figure 7 - Tritium concentrations in precipitation at Ottawa, Ontario, from 1953 to 1993.

relative age groups according to the data in Table 4:

- i) Tritium values that are now less than 6 T.U. (no tritium detected) represent groundwater that was at least 40 years old in 1993, or water recharged prior to thermonuclear testing in 1953.
- ii) Present tritium concentrations ranging from 6 to 34 T.U. may represent groundwater recharged between 1953 and 1957; concentrations of 20 to 40 T.U. could also represent recent groundwater recharge in the years since 1972.

iii) Groundwater which now contains 40 to 90 T.U. may have been recharged between 1958 and 1961 (before the 1963 peak) or between 1967 and 1971 (after the 1963 peak).

iv) Current tritium values in excess of 90 T.U. would represent groundwater recharged between 1962 and 1966, with peak tritium values of approximately 550 T.U. representing water recharged in 1963.

The distribution of tritium values in sampled wells is discussed in section 7.2.2.

To shed light on whether the carbonate and sandstone units function as one aquifer and because of the few sandstone data points, tritium was plotted against depth in a single plot for all wells (section 7.2.2). For the same reasons, tritium was plotted against chloride in a single plot for all wells (section 7.2.2).

Deuterium and ^{18}O compositions of water are usually measured with respect to SMOW (Standard Mean Ocean Water) since precipitation that recharges groundwater originates from the evaporation of ocean water. However, the isotopic composition of rain or snow in most areas is not the same as that of ocean water. As precipitation moves away from the equator toward higher latitudes, heavier isotopes are progressively lost from the vapor as precipitation in a temperature-controlled process of fractionation. The ^{18}O and ^2H contents of waters are usually expressed as delta permil values ($\delta\text{‰}$) relative to SMOW. The global meteoric relationship between ^{18}O and ^2H in samples of precipitation from sites throughout the world, developed by Craig (1961), can be described by the equation: $\delta^2\text{H} = 8\delta^{18}\text{O} + 10\text{‰}$ and is known as the Global Meteoric Water Line (GMWL). Local variations in precipitation caused by isolated evaporation effects and seasonal effects can modify this line, producing a Local Meteoric Water Line (LMWL) which reflects local

climate and which must therefore vary with time. Two equations of the LMWL for Ottawa, Ontario have been calculated as: (i) $\delta^2\text{H} = 7.63\delta^{18}\text{O} + 6.53$ based on data for 1975 to 1982, and (ii) $\delta^2\text{H} = (7.68 \pm 0.12)\delta^{18}\text{O} + (9.50 \pm 1.48)$ based on data for 1970 to 1978 (Fritz *et al.*, 1987). The first LMWL is plotted with the GMWL in Figure 8.

Figure 8 - Global Meteoric Water Line (GMWL) and Local Meteoric Water Line for Ottawa, Ontario (LMWL).

In section 7.2.2, $\delta^{18}\text{O}$ and $\delta^2\text{H}$ values for wells sampled in this study are plotted against both calculated local meteoric water lines.

Finally, $\delta^{18}\text{O}$ values are plotted against chloride and well depth in section 7.2.2. In both cases, values are plotted on a single plot for all wells because it was considered that a distinct correlation in the case of either lithology would be evident.

Chapter 7 DISCUSSION OF RESULTS

7.1 PHYSICAL HYDROGEOLOGY AND GEOLOGY

One of the main objectives of this study has been to characterize groundwater flow in and around Manotick by determining its patterns and controls. To this end, the computer-generated surfaces described earlier were prepared in order to depict, insofar as possible, the actual flow patterns as well as features in the subsurface which may control them, and to comment on the nature of the aquifer(s) exploited.

In analysing any of these computer-generated surfaces, it is important to take into account the nature of the data used in preparing them. A number of limitations are listed in sections 4.1 and 5.2.6. In addition, it should be noted that the well records used span 45 years; they also span all seasons and all drillers. The fact that the static level in an open well or portion of a well is an average of any potential heads encountered above the finished depth must be borne in mind. Thus, the picture presented is a general one and must be viewed from a regional perspective. If this approach is taken, a fair degree of consistency is seen within and among the various plots.

With regard to data distribution, a total of 2,987 bedrock wells were plotted (Plate 6) in the 250 km² of the study area, averaging 12 wells per km². There are clearly areas of particular density, notably the immediate Manotick area itself. However, primarily because of human development patterns along road networks, the remainder of the wells are evenly distributed throughout the entire area.

Although it was not an original objective of this study to investigate the subsurface geology of the area, analysis of the MOE well records suggested the presence of an interesting anomaly in the thickness of the carbonate unit in the southeast part of the study area. The computer-generated surfaces appear to confirm its presence as does geophysical data for the area. This anomaly is discussed in section 7.1.4.

7.1.1 *General Aquifer Definition and Description*

When the average potentiometric surface obtained solely from wells completed in carbonate is compared with that obtained from wells finishing in sandstone (Plate 5), the two patterns are seen to be quite similar to each other and to a pattern common to many images in this study, referred to as the primary subsurface pattern. While the data sets used for the two surfaces have a similar spatial variability, being controlled by the same network of roads, they are, nevertheless, mutually exclusive sets of data. The similarity between the two potentiometric surface patterns suggests that basic flow is independent of lithology and that the carbonate and sandstone units function together as one aquifer.

Further support for a single flow regime may be found in Plate 9 (Incremental Potentiometric Surfaces). Each of the images in the series of surfaces seen here represents a potentiometric surface which is based on the static elevations in all wells finishing in successive five-metre thick horizontal slices through the aquifer. However, because of the variation in the sandstone surface elevation, at least some of the incremental slices must intersect both lithologies. Despite this, the same overall pattern — which is similar to the primary subsurface pattern observed above — continues to repeat itself, relatively undisturbed, in each of the images in the series.

Differences in elevation usually provide the driving mechanism for the movement of groundwater (Domenico and Schwartz, 1990). The two lithologies, carbonate and

sandstone, which appear to function as one aquifer, are the similar in their surface topographies. This can be seen by comparing the Nepean Sandstone Elevation Surface and the Bedrock Surface from Well Data (Plate 2a), which actually depicts the eroded top of the Oxford Formation. Both surfaces are dominated by a single high in the upper right quadrant; the carbonate (bedrock) surface has three discrete highs on the west side of the Rideau River while, on this same side of the river, the sandstone surface has one high corresponding to the northern high in the carbonate and a single second high situated approximately beneath the southern two highs in the carbonate. The lower right quadrants of both surfaces are dominated by topographic depressions, which are connected to major lows running north-south for the full length of the study area and corresponding to the location of the Rideau River.

Finally, given the additional facts that the contacts between all bedrock units in the area are conformable, that no aquitard or aquiclude separates them and that, as shown in Table 5, hydraulic conductivity and permeability have similar ranges in sandstone and in limestone and dolomite it is reasonable to conclude that the two lithologies function as a single aquifer.

Lithology	Hydraulic Conductivity Range (cm/s)	Permeability Range (cm ²)
Limestone/dolomite	10 ^{-3.5} - 10 ^{-7.5}	10 ^{-8.5} - 10 ^{-12.5}
Sandstone	10 ^{-3.5} - 10 ⁻⁸	10 ^{-8.5} - 10 ⁻¹³

Table 5 - Comparison of hydraulic conductivity and permeability ranges for limestone/dolomite and sandstone (Freeze and Cherry, 1979).

7.1.2 *Groundwater Flow Pattern and Controls*

A detailed depiction of the overall flow pattern is seen in the Integrated Horizontal and Vertical Potentiometric Gradients surface (Plate 15). Ignoring, for the moment, the significance of the background (which will be discussed later in this section), the arrows themselves describe the overall direction of groundwater movement, combining horizontal and vertical components of flow. By their relative lengths, they show that the steepest gradients are in the vicinity of the main potentiometric highs and lows, and that the main drain (zone of groundwater discharge) in the immediate Manotick area is the west arm of the Rideau River.

From the Average Regional Potentiometric Surface (Plate 2b), a general approximation of the pattern of groundwater flow in the area, from relative highs to relative lows, can be interpreted. This pattern will be referred to as the primary subsurface pattern. It shows that the highest potentials in the area occur in the northeast quadrant; on the west side of the Rideau River a secondary high occurs near the western edge of the study area. Flow is driven by these potentiometric highs toward potentiometric lows in the vicinity of the Rideau and Jock Rivers, with the lowest values found around the north end of the Rideau River as it exits the study area. The Average Regional Potentiometric Surface also shows heads decreasing to the east from the high in the northeast quadrant. This is consistent with the study mentioned earlier of the basin of the South Nation River (Chin *et al.*, 1980), which places the extreme eastern part of the present study area in that drainage basin. Finally, another relative low, oriented in an E-W direction in the southeast quadrant of the area, receives flow from higher heads to its north and south.

The IHS transform (Plate 8) facilitates the location of these highs and lows in the field and shows that the overall change in head in the area is from a high of approximately 110

metres to a low of approximately 75 metres above sea level. This represents a potential average hydraulic gradient of approximately 35 metres over as little as 8-10 kilometres.

The Average Regional Potentiometric Surface (Plate 2b) mirrors the primary pattern of highs and lows seen in the DTM (Plate 1) and the Bedrock Surface from Well Data (Plates 2a and 4). This is consistent with the concept that differences in ground surface elevation provide the driving mechanism for the movement of groundwater (Domenico and Schwartz, 1990). In this study, the ground surface elevation is largely a function of the bedrock elevation (Bedrock Surface from Well Data), which is thus responsible for the movement of groundwater flow (Average Regional Potentiometric Surface).

The primary subsurface pattern is again observed in the surface depicting the orientation and form of the top of the Nepean sandstone (Plate 2a), which is characterized by an elevational high in the northeast and two discrete elevation highs along the western margin of the study area. Topographic depressions in the sandstone surface are located along the rivers, with a major topographic depression corresponding to the E-W-oriented low described above in the southeast quadrant of the Average Regional Potentiometric Surface.

In the Carbonate Thickness Map (Plate 2a), however, the primary subsurface pattern is not repeated. Rather, the impression is one of relatively even thickness, with local thickening in the area of the Jock River and in the southeast over the E-W oriented depression described above in the sandstone surface. Thus, the carbonate appears to be a relatively uniform layer overlying the sandstone. The deformation which would have affected all of the bedrock strata is now preserved only in the Nepean, with its effects in the overlying carbonate moderated by glacial erosion. Therefore, it is the Nepean sandstone (perhaps along with the basement) which appears to be the source of bedrock topography and,

ultimately, of groundwater flow patterns in the bedrock. The deformation referred to above will be discussed further in section 7.1.4.

Given the limitations which prevail, groundwater flow patterns in the area are examined in only slightly more detail, with the focus being primarily on movement in the vertical direction. Such a focus is particularly appropriate because this is not strictly a case of horizontal flow in a horizontal aquifer. At the same time, completion depths vary greatly. This means that because equipotential lines are not vertical, wells finishing at different depths will have different static elevations. This can occur in the case of wells located in close proximity to each other and be a source of difficulty in interpolations based on all wells. By isolating wells which finish within a narrower range in elevation this problem is minimized. This procedure also makes it possible to compare head values among adjacent increments and to predict vertical components of flow.

As mentioned in the previous section, each of the images in the series of Incremental Potentiometric Surfaces (Plate 9) represents a potentiometric surface based on the static elevations in all wells finishing in successive five-metre thick horizontal slices through the aquifer. Although each of these images is based on a limited number of mutually exclusive points which are less than evenly distributed, the same overall pattern is seen in all. Moreover, it is a pattern which is similar to the primary subsurface pattern observed above.

In a homogeneous, isotropic aquifer, the same relative pattern may be expected from slice to slice, but with increasing depth, the absolute value of the potentiometric heads should be lower in recharge zones and higher in discharge zones. In the present case, the aquifer is neither homogeneous nor isotropic. From slice to slice, in recharge areas, the pattern is one of either similar or decreasing absolute potentiometric head values, while in discharge

areas absolute values are generally lower than in recharge areas, but also either similar or decreasing from slice to slice. This suggests a fracture flow regime with a bias in favour of vertically downward to sub-horizontal flow.

The Incremental Potentiometric Surface Change series of maps (Plate 10) provides a more direct indication of how consistently the head pattern changes in a vertical sense. In the series of surfaces presented in this image, the primary subsurface pattern is not observed, nor is any other consistent pattern. Positive values indicate recharge or areas of decreasing head with depth (downward vertical flow); negative values indicate the opposite. In a homogeneous, isotropic aquifer, values should be consistently positive in recharge areas and consistently negative in discharge areas. No such consistent patterns are seen here, and there is an overall impression of more recharge, or vertical movement in a downward direction, than of discharge. The large areas where the change in head over a given five-metre interval is above or near zero reinforce the suggestion that the primary flow directions are vertically downward to sub-horizontal.

The last surface in this series, DPS9050, represents the overall difference between PS90 and PS50. In this image, it is interesting to note the large areas of near-zero values, indicating that, in many cases, between the highest and lowest interval there is a smaller change in head than there is between adjacent intervals — a point which will be considered later in this section. The exception to the near-zero values in DPS9050 is a large egg-shaped area in the north-central to northwest area of the map, where positive pixel values are indicative of "recharge" — precisely where the Rideau River exits the study area and values indicative of discharge would be expected.

Two cross-sections (Plates 11 and 12) were prepared to examine this more closely. They show 2-dimensional profiles comprised of each incremental potentiometric surface from

PS90 to PS50 as well as the Average Regional Potentiometric Surface, ARPS. Insofar as possible, these cross-sections were selected to cross areas of both the highest and lowest potentials, while at the same time taking in as many data points as possible. In a homogeneous, isotropic aquifer, the profile of the individual lines in each cross-section would be similar to what is seen here, with higher values in recharge zones to the east and west, and lower values in the vicinity of the surface drainage (Rideau River). However, in recharge zones, PS90 would be higher than PS80, which would be above PS70, and so on. A cross-over would take place at the hinge line separating recharge zone from discharge zone, and in the latter areas, PS90 would be lower than PS80, which would be lower than PS70, and so on. In other words, in recharge areas heads would decrease with depth, while in discharge areas heads would increase with depth. In this case, no systematic cross-over of lines is seen in either profile. Rather, when the lines do cross each other, they appear to do so at random, perhaps in response to the presence of fractures. This type of pattern seems to be particularly common in recharge areas and at depth. Elsewhere, lines generally remain parallel with one another, dropping to their lowest values in the vicinity of the Rideau River, but maintaining a "recharge" sequence. In the northern cross-section, lines are spread much farther apart and values are much lower. This seems to imply that while water is moving horizontally toward the Rideau River and, at least in the vicinity of the river, in a northward direction, there is a general potential for downward movement of groundwater. Thus, the impression is one of recharge everywhere, including the "discharge" zone, in the sense that it is "recharging" itself, as it "discharges" the local watershed.

In order to further characterize the vertical movement of water throughout the area, a surface (Plate 13) was prepared depicting the slope of a best-fit straight line for a plot, at each pixel, showing how the incremental potentiometric surface value varies with increasing elevation of finishing-depth increment (section 5.3.7). Plate 14 depicts the

correlation coefficient for each pixel in Plate 13 (section 5.3.8). We have seen previously (Plate 10) that between the 90-85 metre interval and the 50-45 metre interval there is often a smaller change in head than there is between adjacent intervals. Therefore, rather than simply plotting the overall change in potentiometric surface over the total change in finishing depth, the approach adopted here ensures that all points are used and that larger head differences which may exist between intervals are not masked.

The Vertical Potentiometric Surface Variation (Plate 13) is characterized by a positive overall slope throughout the study area, which means increasing head with higher finishing depth, or recharge everywhere. A closer look at this surface reveals a roughly concentric pattern of positive slope values, which begin at very low values around the eastern, western and southern edges of the area (around 0.1) and gradually increase as they converge on a high which corresponds to the egg-shaped area of "recharge" described previously in the north-central to northwest area of the map. Here, contour intervals are fairly close together indicating rapidly increasing lower heads with lower finishing depths, and slope values are as high as 0.8, confirming that in this "discharge" area there is also a strong vertical "recharge" component.

The correlation coefficients plotted for these slope values (Plate 14) also exhibit a roughly concentric pattern. Values range from 0.5 around the eastern, western and southern edges of the map area, with a large area of approximately 0.8 to 1.0 in the north-central and central portions. Thus, there is a very good positive correlation between head and finishing elevation in these areas. Areas where the correlation coefficient is lower correspond largely to areas of higher potentiometric head. A lower correlation coefficient is indicative of greater deviation from the straight line and a non-linear change in potentiometric head with depth. This is consistent with the more prevalent random cross-

over of lines seen in zones on higher head in the cross-sections depicted in Plate 12 (see above).

There are no data available for the centre of the Rideau River and all interpolations have simply reached across it. It is not impossible, therefore, that a fault located below the river itself could be the cause of drainage at depth in that area. However, while depressions can be seen in the bedrock surface topography (Plate 2a) and the Nepean sandstone topography (Plate 2a) in the area of the "drain" in the Rideau River, there is no indication of a break in topography, and values are equivalent on either side. Carbonate thickness is also fairly even in the area of the "drain". Thus, it is suggested that any structural drain here is an open fracture or joint rather than a fault, since there appears to be no displacement.

Alternatively, or in addition, it is possible that the study area represents a local or intermediate system of groundwater flow which is connected to the intermediate or regional-scale system through the Rideau River. At the scale of this study, the primary orientation of groundwater movement is in an east-west direction, from recharge zones to the east and west toward lower potentiometric values in the vicinity of the main surface drainage in the area, the Rideau River. It has been shown that drainage here appears to continue horizontally northward along the river as well as vertically downward at that location. In this way, possibly through a fracture zone, the local or intermediate system may discharge into the intermediate or regional system of groundwater flow, which has been determined to be northward toward the Ottawa River (Woelfle, 1984; Charron, 1978).

7.1.3 *Geology*

Examination of the individual well records for a number of particularly deep wells in the southeast quadrant of the study area reveals that the elevation of the Nepean sandstone

surface suddenly drops off while the thickness of the overlying carbonate package increases (Plate 2a), with the overall result being a slight decrease in the elevation of both the bedrock surface (Plate 2a) and the ground surface (Plate 1).

It is interesting to note that while the thickness of the carbonate remains relatively uniform throughout most of the rest of the study area, the topography of the surface of the Nepean sandstone is similar to that of the overall Bedrock Surface from Well Data (Plate 2a). As mentioned previously, this seems to suggest that it is the sandstone itself, together with the underlying basement, which is responsible for the topography of the bedrock surface. Given the depositional history of these units, it seems unlikely that such a steep break in the surface of the Nepean Formation is erosional in nature. Rather, it seems more consistent with the faulting which is known to have affected strata elsewhere in the vicinity (section 2.2). Because the contact between the carbonate and the sandstone is known to be conformable, faulting would have postdated deposition and affected both lithologies. Subsequent erosion would have levelled the top of the carbonate. No wells penetrate the full thickness of the Nepean sandstone south of the fault and therefore it cannot be compared with the thickness of the formation on the north side.

To the north of this fault, the bedrock and sandstone surfaces (Plate 2a) appear to be folded upward between this fault and the Hazeldean Fault underlying the Jock River to the northwest (Figure 2), which also seems to have the same orientation. Such upwarping of the sedimentary strata may contribute to the secondary porosity and permeability of the aquifer through the creation of fractures.

A Horizontal Gradient of Bouguer Gravity Anomalies map was prepared for the area as described in section 4.3. A Bouguer anomaly map reflects lateral density variations in the outer portions of the earth (Innes, 1967). Bouguer anomalies may be caused not only by

near-surface bodies, but also by structures that affect the entire crust and even by variations in the density of the mantle. Relatively positive anomalies occur in areas of high density, while negative anomalies are produced by areas underlain by low-density rocks. To facilitate the comparison of gravity signatures in different regions and the location of abrupt lateral variations in density, the horizontal gradient map was prepared.

The southeast quadrant of the study area cuts the edge of a northeast-to-southwest trending linear anomaly (Figure 5). Values for this anomaly within the study area range from zero to as high as 2.175 mGal/km. Immediately southeast of where the study area cuts the anomaly, values are in excess of 3.00 mGal/km. South of the study area, the course of the Rideau River turns southwest to follow this zone of extremely high values, where three recent seismic events have been recorded (Warner Miles, pers. comm.).

Horizontal gradient values for all of Canada range from nearly zero up to approximately 3 mGal/km, with most areas of the country exhibiting a gravity gradient of less than 0.5 mGal/km. The most prominent zones of high horizontal gradient, greater than about 1.5 mGal/km are generally observed over: a) continental margins, b) boundaries between geological structural provinces and c) boundaries of major igneous intrusions (Goodacre *et al.*, 1987). Therefore, a significant change in lateral density occurs, or is beginning to occur at the edge of the study area. If a fault zone lies here, the sediment package may be downdropped on the south side and, therefore, much thicker than it is on the north side, where the relatively denser basement would be closer to the surface.

A significant depression in the Average Regional Potentiometric Surface (Plate 2b) coincides with the location of this presumed fault, which therefore may be acting as a subsurface drain. Potentiometric values are as low as those in the vicinity of the Rideau River, although no significant surface drainage feature exists here. A marshy area or

swamp is located in the area. However, since bedrock potentiometric levels are so low, with recharge the general rule throughout the area (Plate 13) and the correlation coefficient between 0.6 and 0.8 at this location (Plate 14), this surface water must represent an overburden drainage feature, isolated from bedrock drainage patterns, with the bedrock aquifer being a confined aquifer at this location. Geochemical and isotopic evidence of a fault in this location is discussed in section 7.2.6.

7.1.4 Validity of Modelling

In and of itself, a GIS is particularly appropriate to a study such as this because this type of system is specifically designed to handle spatially related data. While much is possible in the GIS environment, care must be taken to ensure that the approach adopted is valid. Finally, the validity of the actual modelling performed is dependent upon the quality of the data available and the degree to which the limitations surrounding the data affect the techniques used.

With regard to the validity of the general approach taken in the investigation of groundwater flow direction, the Average Regional Potentiometric Surface (Plate 2b), like the Horizontal and Vertical Potentiometric Gradients surface (Plate 15), combines horizontal and vertical components of flow. The Vertical Potentiometric Surface Variation depicts flow in a strictly vertical sense. The concept of a potentiometric surface is only strictly applicable to horizontal flow in a horizontal, confined aquifer; in this case the aquifer is not always confined nor is it perfectly horizontal. However, the assumption is made that the aquifer and flow are horizontal in order to obtain a first-order estimate of the average regional potentiometric surface based on all wells, as well as separate estimated potentiometric surfaces based on carbonate and sandstone wells. This type of potentiometric surface is really a map of hydraulic head contours on a two-dimensional

cross-section of widely varying elevation (matching finishing depths) taken through the three-dimensional head pattern that exists in the subsurface in the area.

In considering vertical flow by comparing wells finishing in five-metre horizontal increments, the surfaces produced are a map of hydraulic head contours on a two-dimensional cross-section which is much closer to being horizontal and which is taken through the three-dimensional head pattern that exists in the subsurface in the area.

However, these surfaces do not exist in isolation because the static level in an open well is an average of any potential heads encountered above the finished depth. Thus, the head values in each slice are really an average of the heads above it and within it. However, since this is true, for example, of two successive slices, and all values above them are common to both, it is the differential between contiguous slices which is significant in terms of the interpolation.

The limitations of the data used have been described earlier and they have been taken into account: no attempt has been made to analyze any one part of the study area or any one feature in great detail. A general perspective has always been the main objective. The primary subsurface pattern generated in the GIS has been consistently reproduced from the large data set as well as from smaller subsets of it. Any anomalous values are immediately obvious and, because of the interpolation method chosen, of limited impact. The most reliable surface is the bedrock surface: it does not change from season to season or from year to year and one can be confident that it is easily recognizable by all drillers. Not only is the primary subsurface pattern seen in the bedrock and sandstone surfaces, but it is also seen in the Average Regional Potentiometric Surface and in the separate potentiometric surfaces based on sandstone and carbonate wells.

The interpolation method itself has been co-validated by the production of similar surfaces from mutually exclusive sets of data (Plate 9), by the combination of modelled surfaces (Plate 7) and based on a separate (seismic) data set (Plate 4).

7.1.5 Summary - Physical Hydrogeology and Geology

It is fairly clear from the foregoing that the study area is served by a single bedrock aquifer comprised of the carbonate Oxford and March Formations and the sandstone Nepean Formation. Average groundwater flow in this aquifer is from potentiometric highs in the northeast and along the western edge of the area toward potentiometric lows in the vicinity of the Rideau and Jock Rivers. The high in the northeast also drives flow toward the South Nation River drainage basin, of which the extreme eastern edge of the study area is part, and toward an east-west oriented potentiometric low in the southeast quadrant of the study area. More will be said in section 7.2 about the actual source of the groundwaters which follow this pattern.

A slightly closer look at subsurface flow patterns shows that the average groundwater flow pattern described above also comprises a significant vertically downward component throughout the study area. Movement in this direction is particularly strong in the area where the Rideau River exits the study area. It is suggested that such a pattern is not inconsistent with a fault below the river and/or with a connection to a higher order system of groundwater flow at this location.

The topography of both the bedrock and Nepean sandstone surfaces (Plate 2a) is characterized by a pattern which is very similar to that of the Average Regional Potentiometric Surface (Plate 2b). Thus, since differences in elevation provide the driving mechanism for the movement of groundwater, the primary control of flow direction appears, at least to some degree, to be related to the bedrock surface topography. Since

the latter is a reflection of the topography of the Nepean sandstone surface and possibly of the basement topography as well, it is the Nepean Formation, or perhaps the basement, which is ultimately responsible for groundwater flow patterns in the area.

Local control of groundwater flow seems to be exerted by a geological fault, in the southeast quadrant of the study area, which is acting as a subsurface drain. Analysis of the well records led to the discovery of this fault, which appears to affect the Paleozoic strata and which, according to the geophysical results, may also affect the Precambrian basement at this location. Geochemical and isotopic evidence of a fault in this location is discussed in section 7.2.4.

7.2 GEOCHEMICAL AND ISOTOPIC NATURE AND BEHAVIOR OF GROUNDWATER

7.2.1 *Hydrochemical Facies*

A Piper diagram makes it possible to characterize differences and similarities in major-ion chemistry in groundwater flow systems and thus to group waters as identifiable facies.

An initial analysis of all four plots Piper plots for this study (Figures 9-12) shows a similar distribution of samples from dominantly $\text{HCO}_3^-/\text{CO}_3^{2-}$ in terms of anions toward a minor dominance by Cl^- in some samples, and from dominantly Ca^{2+} and Mg^{2+} in terms of cations toward a minor dominance by Na^+ in a few samples.

A closer look at the plots for samples west of the Rideau River (Figures 9 and 10) reveals that two-thirds of the carbonate wells are primarily $\text{Mg}^{2+} + \text{Ca}^{2+}$ and $\text{HCO}_3^-/\text{CO}_3^{2-}$, and one-third are dominantly Cl^- and $\text{Ca}^{2+} + \text{Mg}^{2+}$, resulting in a spread of samples across

Figure 9 - Piper plot for wells finishing in sandstone, west of the Rideau River.

Figure 10 - Piper plot for wells finishing in carbonate, west of the Rideau River.

Figure 11 - Piper plot for wells finishing in sandstone, east of the Rideau River.

Figure 12 - Piper plot for wells finishing in carbonate, east of the Rideau River.

2

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the left and top quadrants of the Piper diagram. The very small population of sandstone wells are dominated by $\text{Ca}^{2+} + \text{Mg}^{2+}$ cations and Cl^- anions.

The carbonate and sandstone plots for the east side (Figures 11 and 12) reveal a similar distribution across primarily the left and top quadrants of the Piper diagram, with only one sandstone well and two carbonate wells plotting in the right quadrant, and with the dominant anion being Cl^- and the primary cation Na^+ .

The source of Mg^{2+} , Ca^{2+} , and $\text{HCO}_3^-/\text{CO}_3^{2-}$ in the samples from carbonate wells is clearly the dissolution of calcite and dolomite. This process begins with the production of carbonic acid when dissolved CO_2 in recharging precipitation, augmented by CO_2 from plant respiration and the oxidation of organic matter in the unsaturated zone, combines with H_2O as follows:

Limestone and dolomite are then dissolved according to the following equations:

A similar Piper plot distribution of ions in many sandstone wells may be explained by the infiltration into the sandstone beds of water which first passed through overlying carbonate layers. In fact, while only four (36, 38, 41, 47) of the 16 sampled sandstone wells have no overlying carbonate, all four without overlying carbonate plot in the left quadrant (7 of the 16 plot in the top and right quadrants despite having overlying carbonate). Another source of a carbonate signature in sandstone wells may be the

presence of a carbonate cement in the sandstone, since this type of cement is particularly common near the top of the Nepean Formation.

Chloride levels in samples taken from carbonate wells may reflect the dissolution of road salt. In addition, shaly partings in the March Formation and shaly interbeds in the Oxford Formation (Appendix 1) may retain chloride and be responsible for small amounts in solution. Recalling that all sampled sandstone wells which do not originate in carbonate plot in the left quadrant of the Piper diagram, road salt and shales may also explain higher chloride levels in sandstone wells which start in carbonate.

In the case of all wells plotting in the right quadrant, the primary cation is Na^+ . In the case of the two wells finishing in carbonate, this Na^+ may be the direct result of cation exchange in shaly interbeds in the Oxford Formation or shaly partings in the March Formation (see Appendix 1). In sample No. 8, the only well finishing in sandstone to plot in this quadrant, the Na^+ may also be the product of such exchanges by recharge through the overlying carbonate beds into the sandstone.

Where sulfate is found in the water, it may have been contributed from the oxidation of pyrite or dissolution of barite, celestite and/or gypsum, which are reported to infill joints in the Paleozoic rocks (Williams and Telford, 1986; Williams, 1991).

7.2.2 *Nature of Recharge*

From the Piper plots, it is not possible to identify any particular trend along a "flow" system. Within the distribution across the Piper diagrams wells plot randomly, without any obvious relationship to their geographic distribution. This seems consistent with a fracture flow regime, which would facilitate random mixing. Such random mixing would also be facilitated by the occurrence of recharge to the bedrock throughout the study area.

A close examination of the distribution of surficial materials in the area, which include sandy glacial and fluvioglacial deposits (Figure 3), reveals that such recharge to the bedrock would be possible.

A number of the sampled wells were also analysed for tritium (Appendix 3). Within error (± 8 TU) and with one exception, all tritium values fall within the 20-40 T.U. category, representing recharge (section 6.2.3) between 1972 and 1993. Theoretically, the two lowest values (15 and 16 T.U.) could represent recharge between 1953 and 1957. However, if this were the case, one would expect to see at least some evidence of bomb tritium somewhere in the area in the form of somewhat higher values due to mixing; no such evidence is seen.

The only sample containing no detectible tritium was taken from a sandstone well, which is also the deepest well analysed. Without further information, all that can be said about its age is that it is at least 40 years old and must have been recharged sometime before 1953. This well will be discussed at greater length in section 7.2.4.

The use of tritium in groundwater analysis is qualitative, with some age groupings (section 6.2.3) overlapping and the additional problem of the possibility of mixing between very old and very young water (Eriksson, 1985). Mixing in the study area is likely given the jointed and faulted nature of the lithologies concerned. Mixing can occur within a well and, as mentioned previously, when newly recharging water combines with existing groundwater. This could explain the lack of any obvious pattern in the tritium values observed along the inferred flow lines represented by the sampling lines (Figure 13).

Figure 13 - Distribution of tritium values in sampled wells.

Groundwater mixing could also explain the complete lack of correlation between tritium and well depth (Figure 14) and tritium and chloride (Figure 15) in the case of both carbonate and sandstone wells. A correlation between tritium values and these two parameters may have suggested a relationship between length of flow path and mean residence time.

Since the tritium results seem to point toward recent recharge, it is not surprising that the $\delta^{18}\text{O}$ and $\delta^2\text{H}$ results indicate the source of the groundwater is precipitation (Figures

16(a) and 16(b)). All of the 14 samples analysed plot within error, on one of the average local meteoric water lines for Ottawa (Fritz *et al.*, 1987).

Figure 14 - Plot of tritium values vs. well depth for sampled wells (numbers refer to sample numbers; diamonds represent wells finished in sandstone).

As in the case for tritium and chloride, there seems to be a complete lack of correlation between $\delta^{18}\text{O}$ and chloride (Figure 17) and between $\delta^{18}\text{O}$ and well depth (Figure 18) in the case of both carbonate and sandstone wells. This supports the idea that the groundwaters are young in age and well mixed.

7.2.3 Directional Components of Groundwater Flow

Certain parameters can be expected to increase in concentration along flow lines. These include chloride, conductivity and TDS, all of which were plotted separately along both E-W and N-S sampling lines for both carbonate and sandstone wells (Figures 19 and 20).

Figure 15 - Plot of tritium values vs. chloride for sampled wells (numbers refer to sample numbers; diamonds represent wells finished in sandstone).

In all cases, the similarity in the patterns between carbonate and sandstone profiles is noteworthy, and further confirms the degree to which the two lithologies function as one aquifer.

As previously mentioned, the sampling lines do not follow flow lines precisely (Plate 16). Furthermore, it is not advisable to look at the flow lines as derived from the Average Regional Potentiometric Surface at the scale of the individual well. However, certain patterns do emerge in the parameter profiles which are consistent with the pattern of arrows depicting flow directions.

(a)

(b)

Figure 16 - $\delta^{18}\text{O}$ and $\delta^2\text{H}$ values for sampled wells (numbers refer to sample numbers; diamonds represent wells finished in sandstone); data plotted against two local meteoric water lines for Ottawa: (a) $(\delta^2\text{H} = 7.63\delta^{18}\text{O} + 6.53)$; (b) $(\delta^2\text{H} = (7.68 \pm 0.12)\delta^{18}\text{O} + (9.50 \pm 1.48))$, Fritz *et al.*, 1987).

Figure 17. Plot of $\delta^{18}\text{O}$ vs. chloride for sampled wells (numbers refer to sample numbers; filled squares represent wells finishing in sandstone).

Figure 18. Plot of $\delta^{18}\text{O}$ vs. well depth for sampled wells (numbers refer to sample numbers; filled squares represent wells finishing in sandstone).

Generally speaking, the east-west sampling line (Figure 19) shows an increase in all parameters from the edges of the study area toward the Rideau River. Looking more closely, on the west side of the River, the profiles of all three parameters in both sandstone and carbonate wells rise steadily toward the river, consistent with the general direction of arrows in this area (Plate 16). Also consistent with the pattern of arrows, on the east side of the river, is a general increase in all three parameters between sample 11 in the carbonate profile and the Rideau River, and sample 47 in the sandstone profile and the river. East of these two samples, the pattern of arrows shows stronger components of flow across the sampling line than along it. This is reflected in the peaks and lows seen in the parameter profiles. These changes in direction may be related to the fact that the extreme eastern edge of the study area has been placed in the drainage basin of the South Nation River (Chin *et al.*, 1980).

Comparing the patterns of peaks and lows in all the water parameter profiles (chloride, TDS and conductivity) east of the river along the east-west sampling line, peaks are seen at approximately the 0, 5 and 10-kilometre points in both sandstone and carbonate wells. As stated above, in both carbonate and sandstone wells on the west side of the river, and from sample number 11 in the carbonate and number 47 in the sandstone on the east side, there is a steady increase in parameter values along the flow paths, as described above. The matching patterns of peaks and lows in all water parameter profiles for sandstone and carbonate wells along the E-W sampling line is consistent with their functioning as a single aquifer.

Along the north-south sampling line (Figure 20), with the exception of the most northerly well in each lithology, the profile for all parameters and both lithologies is a general decrease from north to south. At the location of the most northerly well in each lithology, the surficial deposits are primarily sand (Figure 3). Good potential recharge here may help

explain why chloride, conductivity and TDS values are low in these wells. Points 42 and 35 on the carbonate plots and 37 and 41 on the sandstone plots are in an area of till, where infiltration may be reduced and therefore recharge in the immediate vicinity cannot dilute the high parameter values in these wells which may result from their location at some distance from the potentiometric high in the Bowesville Ridge to the east (Plate 16). From this point south, the sampling line is crossed by flow lines, at angles ranging from oblique to acute. This is consistent with fluctuating parameter values. The fact that they are quite low relative to the higher values seen in the north may be explained by recharge through a linear feature of sandy surficial deposits to the east (Figure 3). Thus, while this cross-section was selected primarily to intersect the highest bedrock elevations in the study area (Plate 2a), which is where the highest well potentials in the area are located, and while preliminary investigations had shown that there was the possibility of at least a component of flow in a southerly direction from this potentiometric high (Plate 2b), there are certainly also components of flow which cross the line.

Along the north-south sampling line, the water parameter profiles (Figure 20) of chloride, TDS and conductivity for both sandstone and carbonate wells have peaks at approximately the 2 and 10-12-kilometre points. A peak at about the 4-kilometre point in the sandstone profile is not matched at that location by a peak in the carbonate profile because there is actually no carbonate data available for that section of the line. The reasonably good agreement between the two lithologies at the 2 and 10-12 kilometre points along the N-S sampling line again suggests that they function as one aquifer.

Figure 19 - Water parameter profiles showing changes in conductivity, TDS and chloride in sandstone and carbonate wells along the E-W sampling line.

Figure 20 - Water parameter profiles showing changes in conductivity, TDS and chloride in sandstone and carbonate wells along the N-S sampling line.

7.2.4 *Samples 8 and 27*

At 280 feet, the well from which sample 8 was taken is the deepest well sampled and finishes in the Nepean sandstone at the edge of the inferred fault zone discussed in section 7.1.4. Recalling the Piper diagrams (Figures 9 to 12), this sample and sample 27 are among the most strongly sodium- and chloride-type of all those analysed. (Sample 46, which is spatially unrelated, also has a strong sodium and chloride signature that the homeowner suggests may be explained by salt on his driveway.) As the first sample north of sample 8, sample 27 is also at the edge of the inferred fault zone, although it finishes in the carbonate at 105 feet. In neither case is a water softener in use, but excess sodium could be explained by cation exchange in shales in the Oxford and March Formations. Sample 8 is the only well sampled which contains no detectible tritium. Although sample 27 was not analyzed for tritium, being a shallower well and more open to surface recharge, it might be expected to contain detectible amounts of that isotope. Although this does not prove the existence of a fault, it is not inconsistent with a separate recharge source at least for sample number 8 and possibly for sample number 27 as well.

7.2.5 *Summary - Geochemical and Isotopic Nature and Behaviour of Groundwaters in the Study Area*

Deuterium and $\delta^{18}\text{O}$ values indicate that the source of groundwater in the study area is precipitation. In general, it can be said of all the study area wells whose waters were analysed that they are dominantly Ca^{2+} , Mg^{2+} and $\text{HCO}_3^-/\text{CO}_3^{2-}$ waters with some elevated Na^+ and Cl^- . Although in most cases the water is very hard (>180 mg/L of CaCO_3), water quality is generally acceptable for domestic use throughout the area, with only one sampled household using a softener. It is of note that TDS values are less than 1000 ppm in all except three cases (two of which are in the village of Manotick itself, where salt levels may be expected to be higher). This represents a marked contrast with

the TDS values of up to 10,000 ppm reported in the area immediately to the east of the study area (Briggs, 1995).

Clearly, sandstone and carbonate wells overlap in most areas in all four Piper diagrams, indicating that the two lithologies function as one aquifer. The water parameter profiles for chloride, conductivity and TDS offer further evidence of a single bedrock aquifer in the study area. In the case of both E-W and N-S sampling lines, the overall patterns developed in all parameters in both the sandstone and carbonate profiles are notably similar.

Several factors suggest that recharge is occurring throughout the study area, mixing recent precipitation with existing groundwater. Mixing may also be facilitated by fracture-flow, given the jointed nature of the aquifer (Williams, 1991). The Piper plots show no geographically determined mixing trend from sample to sample. The lack of any pattern in tritium values also suggests that the groundwaters are subject to mixing. Finally, mixing is also suggested by the fact that neither tritium nor $\delta^{18}\text{O}$ levels correlate with well depth and by the further lack of correlation between $\delta^{18}\text{O}$ values and chloride levels.

An increasing trend in chloride, conductivity and TDS levels along the E-W sampling line toward the Rideau River from the western end of the line and from a certain point east of the river shows that these segments of the sampling line correspond with the direction of groundwater flow; east of the eastern segment, there appears to be some degree of mixing at an angle to the line. In the N-S flow section, no clearly defined trend in geochemical parameters is seen. These patterns are in agreement with the orientation of the computer-derived flow arrows.

The source of excess chloride in some samples is inconclusive. Modern tritium values rule out the waters of the Champlain Sea as a source. It is possible that some extra chloride may enter the groundwater through leaching from clays and shales. Samples 8 and 27 are almost exclusively the most strongly sodium- and chloride-type of waters analysed. Their location at the edge of an inferred fault zone and the lack of detectable tritium in sample 8 suggest the possibility of a separate recharge source and offer further evidence of the presence of a fault zone.

Chapter 8 CONCLUSIONS AND RECOMMENDATIONS

Computer modelling of data derived from Ontario Ministry of Environment water well records has shown that Manotick and the surrounding area are served by a single bedrock aquifer comprised of the carbonate Oxford and March Formations and the sandstone Nepean Formation. Average groundwater flow in this aquifer is from potentiometric highs in the northeast and along the western edge of the area toward potentiometric lows in the vicinity of the Rideau and Jock Rivers. The steepest gradients are in the vicinity of the main potentiometric highs and lows, and the main drain (zone of groundwater discharge) in the immediate Manotick area is the west arm of the Rideau River. A closer look at subsurface flow patterns reveals that a significant vertically downward component exists throughout the study area, with a particularly strong drain located in the vicinity of the north end of the Rideau River within the study area. It is suggested that such a pattern is not inconsistent with a fault below the river and/or with a connection to a higher order system of groundwater flow at this location.

Computer modelling also shows that the topography of both the bedrock and Nepean sandstone surfaces (Plate 2a) is characterized by a pattern which is very similar to that of the Average Regional Potentiometric Surface (Plate 2b). Thus, a primary control of groundwater flow direction appears to be related to bedrock surface topography. Because the carbonate units (Oxford and March Formations) are of a relatively uniform thickness, the bedrock surface topography is a reflection of the surface topography of the Nepean sandstone. Therefore, it is the Nepean Formation which is ultimately responsible for groundwater flow patterns in the area.

Examination of MOE well records has revealed a potential offset in the bedrock strata in the southeast quadrant of the study area. The southeast corner of the area intersects a fault zone which affects the Paleozoic units and which, according to the geophysical results, may also affect the Precambrian basement at this location. Local groundwater flow seems to be affected by this fault, which acts as a subsurface drain. There is also geochemical and isotopic evidence of a fault at this location.

Geochemical and isotopic analysis of the nature and behavior of groundwaters in the area confirm the computer findings that the two lithologies function as one aquifer. Clearly, the chemical composition of water from both the sandstone and carbonate wells is similar as depicted in the Piper diagrams and along both sampling lines. This composition has a dominantly $\text{HCO}_3^-/\text{CO}_3^{2-}$ and $\text{Ca}^{2+}/\text{Mg}^{2+}$ signature; water is generally fresh, with TDS values <1000 ppm in all except three cases, and very hard (>180 mg/L of CaCO_3).

Sampling was not extensive enough to compare geochemical and isotopic results with the overall direction of groundwater flow as described by computer modelling. However, an increasing trend exists in chloride, conductivity and TDS levels along the E-W sampling line toward the Rideau River from the western end of the line and from a certain point east of the river. East of that point, there appears to be some degree of mixing. This pattern is in agreement with the orientation of computer-derived arrows depicting the direction of groundwater flow across and along the profile line. In the N-S section, no clearly defined trend in geochemical parameters is seen; however, this is also consistent with computer modelling, which shows that this sampling line does not correspond with a single flow direction.

Geochemical and isotopic evidence suggest that the source of groundwater in the study area is recent precipitation which recharges throughout much of the area and mixes with

existing groundwater. Further mixing may be facilitated by the fracture flow which is anticipated given the jointed nature of the Paleozoic rocks in the Ottawa area .

In itself, this study is useful because, by depicting the pattern of groundwater movement, it makes it possible to anticipate the potential impact of development in various parts of the Manotick area. However, because of the nature of the data used, the work involved in preparing the data base for the GIS was very time-consuming and the results are only useful up to a point. If the data contained in MOE well records were available digitally, much time would be saved. If the reliability of the data was improved, a much closer look could be taken at a small subset of an area of any size. An accurate, digital data base would make it possible to process large amounts of information by season or by year, by depth or by driller, or to otherwise customize the data for specific purposes and thus to draw more specific conclusions with greater reliability.

This study represents a useful application of a GIS. Further work might involve a closer look at the Manotick area itself (provided that data of sufficient quality are available), the north-end drain, and the fault zone in the southeast . This could be done using either the present GIS or one of the recently developed systems offering a truly three-dimensional format for studying spatially-related data. A more detailed look at the north-end drain could provide data for below the river which might verify or disprove the presence of a fault. With regard to the fault zone in the southeast, because the study area cuts into but does not encompass the entire zone suggested by the geophysical data, it would be useful to extend the data base to include wells located within the fault zone itself and thus to eliminate any possible edge effects. Work might include cross-sections through this zone showing the offset in bedrock lithologies and the average regional potentiometric surface. A closer look at potentiometric head at various depths within the aquifer at this location might help to assess the degree to which the zone is acting as a subsurface drain.

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Appendix 1

Description of Cambro-Ordovician and Quaternary Units Occurring within the Study Area

Cambro-Ordovician
Potsdam Group
Covey Hill Formation

It was proposed by Williams and Wolf (1982) that the part of the Potsdam Group (Table 1) which underlies the Nepean Formation in Ontario be termed "Covey Hill Formation", correlating it with a formation originally described in the Montreal area. Based on well-record data, this lowermost Paleozoic unit, which unconformably overlies the Precambrian basement, may appear intermittently in the study area. Williams (1991) reports that it outcrops and subcrops southwest of the study area, along the margin of the Ottawa-St. Lawrence Lowland in the Westport (31C/9) and Perth (31C/16) map areas.

According to Williams and Telford (1986), this unit only occurs locally in the Ottawa area, ranging in thickness from zero to 8.8 metres. It consists of non-calcareous feldspathic conglomerate and quartz sandstone (Williams and Telford, 1986; Lewis, 1971; Williams and Wolf, 1982; Williams and Rae, 1983). Several isolated outcrops of this facies, found in a downfaulted block in the Big Rideau Lake area, were described by Wolf and Dalrymple (1984, p. 244) as "poorly sorted, massive to cross-stratified, feldspathic conglomerates and cross-stratified pebbly arkoses". While the conglomerate is dominant, sandstone interbeds are up to 3 metres thick (Williams, 1991).

According to Williams and Telford (1986, p. 5):

"The sandstones and the matrix of the conglomerates consist of fine to coarse quartz sand and angular pink feldspar grains. The subrounded to well rounded quartz grains contain variable amounts of hematite coating that typically give the rock a laminated appearance. The conglomerates contain pebble- to boulder-size subangular to well rounded clasts derived from a variety of Precambrian rock types (typically quartzite, marble, granite, and gneiss). The conglomerates are generally massive, and range in colour from light grey to dark grey to reddish brown. The sandstones are thinly to thickly bedded and well to poorly sorted, commonly

containing scattered pebbles and cobbles, and range in colour from light grey to reddish brown to green".

The weathering and erosion that exposed the roots of the Precambrian mountains which now surround the Ottawa-St. Lawrence Lowland would have produced an extensive regolith over the ancestral Lowland. Lewis (1971) proposes that the Covey Hill Formation represents the remains of some of this regolith, transported and deposited before Cambrian sedimentation began, although the author does not speculate about the mechanisms of transport and deposition. Wolf and Dalrymple (1984) conclude that at the western edge of the Ottawa-St. Lawrence Lowland, the Covey Hill Formation was formed in a setting which was transitional between a distal alluvial fan and a proximal braided fluvial environment. Based on grain size and the scale of sedimentary structures, they postulate an enormous drainage basin and attribute the scarcity of outcrops of such rocks today to either pre- or post-Nepean erosion.

Ordovician

Potsdam Group

Nepean Formation

The Cairnside Formation of Quebec, which may correlate with the mature Nepean sandstone, is described by Lewis (1971) as representing another portion of the regolith covering the ancestral Lowland or, more likely, a product of the later reworking of Covey Hill type sediments. Wilson (1946) placed the lower, unconformable boundary of the Nepean at the top of the Precambrian; however, recognition of the underlying Covey Hill Formation led Williams (1991) to redefine the lower contact. Where the Nepean overlies the localized Covey Hill Formation, Williams (1991) reports that this contact is unconformable and represents the uppermost common occurrence of feldspar, or the first appearance of quartz arenite. "Where the Covey Hill Formation is absent, and the Nepean

Formation rests directly on the Precambrian basement, the basal beds often are conglomeratic and consist of quartzite clasts in a quartzose matrix" (Williams, 1991).

Although Greggs and Bond (1972) and Bond and Greggs (1973) suggest that the upper contact with the March Formation may be disconformable, most authors describe this contact as conformable (Wilson, 1946; Carson, 1982; Brand and Rust, 1977; Williams and Telford, 1986). There has been some discussion about the best definition of this boundary. Wilson (1946) placed it at the base of the lowest dolomitic or calcareous bed. However, since carbonate-cemented beds occur particularly near the top of the Nepean, other authors (Williams and Telford, 1986; Williams, 1991) prefer to place the contact at the base of the lowest dolomitic layer.

Williams and Telford (1986) report that, in the Ottawa area, the thickness of the Nepean Formation ranges from 60 to a minimum of 159 metres. The formation subcrops throughout the study area and, although no outcrops occur within the study area, one outcrop is located immediately to the north of the northeastern corner of the area.

Wilson (1946) describes the Nepean as a coarse-grained, cream-coloured quartz sandstone. It weathers to a grey colour, with rust spots. The latter are the result of iron from detrital pyrite, magnetite, or ilmenite grains (Williams, 1991). Other authors (Williams and Wolf, 1982; Williams and Rae, 1983; Williams and Telford, 1986) describe it as fine- to coarse-grained, weathering white to reddish brown. Cross-bedding, ripple marks and burrows are common as is a pebble- to cobble-size conglomerate at the base. According to Williams (1991, p. 43), "the lower part of the formation is non-calcareous, and the upper part becomes increasingly calcareous towards the top. The sandstones are thinly bedded to massive (beds up to 2 metres thick fill channels) and usually are well sorted, rarely

containing any quartz pebbles and cobbles". Wilson (1946) points out that near the top of the formation the cement may also be of rust-staining iron oxide.

The following approximate chemical composition, based on the average of a number of drillcore analyses, is reported by Williams (1991): 96.6% SiO₂, 0.2% Fe₂O₃, 1.1% Al₂O₃, 1.8% CaO, and 0.1% MgO.

Wolf and Dalrymple (1984, 1985) identify two terrestrial and three marine facies in the Nepean. Of the terrestrial facies, which predominate in the Gananoque map area (31C/8), the most common is characterized by large cross beds composed of regular layers of well-sorted, well-rounded, medium-grained quartz grains. In places, cross beds are separated by thin layers of poorly-sorted conglomerate. The cross beds are interpreted as an aeolian dune complex and the conglomerate layers as stream deposits. Of the marine facies, which are dominant in the Ottawa-St. Lawrence Lowland, the most common alternates between whiter, thicker and more resistant cross-bedded units and darker, less resistant bioturbated units. This facies is interpreted as being deposited in an environment alternating between a subtidal to lower intertidal setting (the cross beds) and a shallow-water environment where decreasing energy levels and sediment movement rates allowed organisms to colonize.

The conodont fauna at the Nepean-March boundary near Ottawa is significantly younger than that which is found at the base of the March Formation further south in the Brockville area. On this basis, Brand and Rust (1977) conclude that the seas which deposited the Nepean transgressed in a northward direction over time.

Beekmantown Group

March Formation

In the study area, the March Formation conformably overlies the Nepean (as described above) and is, in turn, conformably overlain by the Oxford Formation. The March Formation constitutes a transition zone between the underlying Nepean sandstone and the overlying Oxford dolomite — Williams (1991, p. 48) states that "the sandstone beds are commonly dolomitic, and the dolostone beds commonly sandy". Both Wilson (1946) and Williams (1991) place the contact with the Oxford at the highest occurrence of sand in any quantity, although Williams (p. 57) modifies the definition as "the upper limit of common occurrence of quartz sand". Others (Bond and Greggs, 1973; Williams and Wolf, 1982; Williams and Rae, 1983) have placed it at the base of the lowermost dolomitic unit.

Bélanger and Harrison (1980) report a thickness of 10 metres for the March Formation. However, Williams and Telford (1986) report that the formation ranges from 18 to 20 metres in thickness in the Ottawa area, and Williams (1991) notes that, based on two drill holes, the thickness at South Gloucester is 16.2 metres. The formation outcrops in only a few isolated places in the study area (Figure 2); it subcrops throughout the northwestern part beneath overlying surficial deposits and throughout the southern half beneath the overlying Oxford.

This formation consists of interbedded quartz sandstone, dolomitic quartz sandstone, sandy dolostone, and dolostone (Wilson, 1946; Bond and Greggs, 1973, Williams and Telford, 1986). Shaly partings are found throughout the formation and the dolostones and sandy dolostones contain glauconitic partings; many brown-weathering spots are present, the result of iron derived from detrital pyrite, magnetite, or ilmenite grains (Williams, 1991). Williams and Telford (1986, p. 6) describe the March as follows:

Quartz sandstones of the March Formation are lithologically similar to those of the underlying Nepean Formation. They are thinly to thickly bedded, fine to coarse grained, well sorted, and white to light grey, brown, reddish brown, and green in colour. The quartz grains are subrounded to well rounded. As in the Nepean Formation, the sandstones contain two common types of cementing materials: quartz cement, which renders the rock more resistant to weathering; and calcite cement, which results in a more friable rock. Crossbedding, ripple marks, and burrows are common. The dolomitic quartz sandstones and sandy dolostones are light to medium brownish to bluish grey in colour, and brownish grey to buff to reddish brown weathering. They are thinly to thickly bedded and contain finely to medium crystalline carbonate and well rounded, fine to coarse grained quartz sand. Some dolomitic sandstone beds are calcareous, and some sandy dolostone beds are calcitic. Burrows and calcite-filled vugs are common. The dolostones are light to medium brownish to greenish grey in colour, and weather light grey to buff and reddish brown. They are thinly to thickly bedded, sublithographic to medium crystalline, and calcitic to non-calcitic. Algal lamination and calcite-filled vugs are common.

The following approximate chemical composition, based on the average of a number of drillcore analyses, is reported by Williams (1991): 41.1% SiO₂, 0.72% Fe₂O₃, 2.77% Al₂O₃, 19.9% CaO, and 10.1% MgO.

Williams (1991) reports a supra- to subtidal environment of deposition for the March Formation, with supratidal to intertidal deposition and hypersalinity implied by the presence of calcite-filled vugs, replacing original sulphate nodules. Bond and Greggs (1973) divide the formation into two dominant lithologies: a lower, highly bioturbated, blue-grey dolomitic quartz sandstone with a high proportion of carbonate cement, and an upper pale yellow-grey to yellow-brown, calcareous and siliceous quartz sandstone, noting the occurrence of beds of each lithology within the other. The lower of the two is considered a deeper-water deposit, in which a high calcareous mud fraction was dolomitized following deposition. A minor calcite spall content seems to indicate a later period of diagenesis. The upper lithology appears to have been deposited in a shallower marine environment in which the sedimentation rate was too great to permit the destruction of primary structures by bioturbation.

Beekmantown Group

Oxford Formation

The Oxford Formation is disconformably overlain by the Rockcliffe and this upper contact with the overlying shales and sandstones is clearly defined by the change in lithology (Wilson, 1946). The lower contact is described in the above section on the March Formation.

In the Ottawa area, the thickness of the Oxford ranges from 62 to 102 metres (Williams and Telford, 1986). Although there are only a few isolated outcrops of this formation throughout the study area (Figure 2), it subcrops throughout much of the remainder beneath overlying surficial deposits.

Bond and Greggs (1976) subdivide the Oxford into a lower sandy unit and an upper dolomitic unit in which quartz is absent to rare. The dolostones are light to medium brownish to greenish grey in colour. Thinly to thickly bedded, the dolostones have minor amounts of quartz sand in some beds as well as quartz sandstone interbeds up to 30 cm thick. Calcite- and quartz-filled vugs occur as well as chert nodules, stromatolites and shaly interbeds which are often glauconitic. Some calcite-filled vugs and some of the thin interbeds contain pyrite. Dessication cracks are present as well as stylolites and soft-sediment deformation features, and there is evidence of burrowing activity (Bond and Greggs, 1976; Williams and Wolf, 1982; Williams and Rae, 1983; Williams and Telford, 1986; Williams, 1991). Wilson (1946) characterized the Oxford in the western edge of the Ottawa-St. Lawrence basin as very impure, containing a great deal of mud with some sand.

The chemical composition is approximated by Williams (1991) as follows: 9.34% SiO₂, 1.00% Fe₂O₃, 4.94% Al₂O₃, 26.48% CaO, 17.29% MgO, and 39.79% CO₂.

The depositional environment inferred from the presence of algal laminations and calcite-filled vugs (originally sulphate nodules) is that of a hypersaline, intertidal, carbonate flat environment (Greggs and Bond, 1977; Williams and Telford, 1986).

Pleistocene and Recent

Till in the Ottawa area varies in thickness, but is generally thin (Fulton *et al.*, 1987). It is the most extensive of the Quaternary sediments in the area. Generally sandy, it is usually thin but may be thicker in local depressions. Below 200 metres asl, it is generally covered by lacustrine and marine sediments (Kettles and Shilts, 1987). The carbonate content of the silt-clay fraction of till in low-lying areas underlain by flat-lying Paleozoic rocks is high, usually greater than 10%. Carbonate content increases rapidly where ice moved from an area of crystalline rocks to an area underlain by Paleozoic carbonates (Kettles and Shilts, 1987). In some areas, the till surface was moulded into drumlins.

When the glaciers began to retreat from the area a number of complex sand, gravel and till moraine ridges were formed at their margins. For example, the Ottawa-Macdonald-Cartier International Airport is situated on the Bowesville moraine (Johnson, 1917), a wave-modified feature consisting primarily of stratified sand and gravel and including lenses of till (Gadd, 1963). Glaciofluvial deposits are abundant in the area. As the Wisconsinan ice-sheet retreated, subglacial streams formed eskers, outwash deposits and deltas. Examples of such deposits are found in several places in the Ottawa area. Subaqueous outwash deposits have been identified in pits along a series of ridges south of the Ottawa River (Rust, 1987; Rust 1977). These are interpreted as overlapping facies of subaqueous fans

that were deposited within or at the mouth of meltwater channels. Ridges such as these rise above or are buried by marine sediments of the Champlain Sea (Gadd, 1987).

Beneath the lowest Champlain Sea sediments, thin glaciolacustrine beds were deposited as ice continued to melt (Fulton *et al.*, 1987). For example, the late-glacial Rideau valley drained toward the south (Gadd, 1962). Just before marine submergence, the valley contained a glacial lake, whose varved sediments may be seen along the Rideau River between Long Island and the Ottawa-Macdonald-Cartier International Airport in some 10 feet of section overlying glacial till.

Sediments such as these grade upward into massive marine clays of the Champlain Sea. The sea flooded all of the area south of the Ottawa River, leaving only the Madawaska Highlands and the Gatineau Hills exposed. Finally, as the sea regressed, beach sands and gravels were deposited where ridges of glaciofluvial deposits projected through the marine basin fill. In addition, a thin layer of littoral and sublittoral sand was deposited over the finer Champlain Sea deposits in much of the basin. The marine clay of the Champlain Sea varies in thickness from approximately a metre where it is found in pockets on bedrock, to in excess of 60 metres where it has survived in large, continuous units (Bélanger and Harrison, 1980).

As the earth's crust slowly rebounded, the seas regressed accompanied by the formation of a delta which prograded eastward in the Ottawa Valley as the Ottawa River and its tributaries cut channels in the marine and deltaic deposits (Fulton *et al.*, 1987), and the depositional environment progressed from marine, through shallow estuarine, to the beginning of fluvial erosion (Bélanger and Harrison, 1980). As fresh-water drainage began, fine sediments were eroded from older glacial and marine sediments and deposited on wide estuarine, fluvial and lacustrine terraces. At the present time, sediments from the

erosion of local bedrock are being added to these eroded products of the older glacial and marine sediments as modern drainage cuts into them (Gadd, 1962).

Appendix 2

Geochemistry Data

Table A2-1 • Geochemistry Sample Well Data

Table A2-2 • Field Data

Table A2-3 • Water Well Chemistry

Table A2-4 • Geochemistry Data Verification

Table A2-1 • Geochemistry Sample Well Data

Wells were selected with a view to obtaining a balance of finishing lithologies and depths, while choosing wells for which well records were available. In some cases, observing these criteria would have left an unacceptably long gap in the sampling line and a well was chosen for which limited information was available: a question mark beside a sample number indicates no data available.

E-W SAMPLING LINE			N-S SAMPLING LINE		
Sample No.	Depth (ft.)	Lithology	Sample No.	Depth (ft.)	Lithology
1	60	Carbonate	8	280	Sandstone
2	88	Carbonate	9	80	Carbonate
3	83	Carbonate	10	105	Sandstone
4	155	Sandstone	13	93	Carbonate
5	85	Carbonate	26	63	Carbonate
6	76	Carbonate	27	105	Carbonate
7	110	Carbonate	28	118	Carbonate
10	105	Sandstone	33	175	Sandstone
11	86	Carbonate	34	58	Carbonate
12	83	Carbonate	35	51	Carbonate
14	60	Carbonate	36	95	Sandstone
15	78	Carbonate	37	95	Sandstone
16	123	Sandstone	38	97	Sandstone
17	132	Sandstone	39	51	Carbonate
18	?	?	41	120	Sandstone
19	56	?	42	118	Carbonate
20	120	Carbonate	45	120	Sandstone
21	?	?			
22	?	?			
24	80	Carbonate			
25	84	Carbonate			
29	60	Carbonate			
30	95	Sandstone			
31	85	Carbonate			
32	48	Carbonate			
34	58	Carbonate			
36	95	Sandstone			
40	?	?			
43	75	Carbonate			
44	178	Sandstone			
46	45	Carbonate			
47	105	Sandstone			
48	105	Sandstone			

Table A2-1 - Basic Sample Well Data - Listing Sample No., Finishing Depth (ft.), Lithology (Note: a question mark indicates no data available; No 23 was not used for any sample).

Table A2-2 • Field Data - Spring 1993

Homeowner/Sample No.	Temperature (°C)	pH	HCO₃⁻*	Conductivity (µS/cm)
CFRA/1	10.0	7.4	143	400
Rooney/2	10.0	7.1	239	570
McNeil/3	12.0	7.3	220	630
Youmans/4	10.0	7.1	297	1180
St. James Rectory/6	12.0	7.3	274	1240
RCVA/7	12.0	7.0	329	1520
Anderson/8	11.9	7.7	164	750
Aitken/9	10.0	7.4	270	630
McCuaig. G/10	12.0	7.5	217	740
Hutt/11	10.0	7.3	272	630
Gouin/12	9.0	7.7	210	570
Miles/13	11.0	7.7	263	600
Bekker/14	11.0	7.6	253	790
Gray/15	11.0	7.4	289	1190
Rooke/16	12.5	7.4	246	1390
Riley/17	12.5	7.4	246	1540
Manotick School/18	12.0	7.0	352	1840
Manotick Curling/19	12.5	6.9	309	1500
Gale Real Estate/20	13.0	6.9	380	2430
Manotick Library/21	11.5	7.3	286	1020
Sundance/22	3.0	7.1	420	820
Desnoyers/24	13.9	7.5	174	380
Paytler/25	10.0	7.4	231	690
Lanthier/26	7.4	10.1	232	400
Caroll/27	10.5	7.6	940	235
Koel/28	7.0	7.3	298	750
Albion Sun Vista/29	7.0	7.6	190	420
Adams&Kennedy/30	9.0	7.3	242	520
Licari/31	11.0	7.2	255	660
MacIntyre/32	12.0	8.0	130	280
Micucci/33	9.5	7.3	297	560

Table A2-2 (continued) • Field Data - Spring 1993

	Temperature (°C)	pH	HCO₃^{-*}	Conductivity (µS/cm)
Bakker's Store/34	8.5	7.4	366	800
Marcantonio/35	10.0	7.1	292	1160
McCuaig L./36	11.0	7.6	163	400
Hoar/37	9.0	7.0	316	1310
Wagg/38	9.0	7.2	196	380
Heyn/39	9.5	6.8	344	1080
Courville**/40	11.5	7.4	275	820
Gilchrist/41	9.5	7.1	263	760
Coxall/42	13.0	6.9	360	1430
Quaile/43	10.0	7.2	335	770
Lessick/44	13.0	7.2	290	930
Thompson/45	8.0	7.4	209	430
Wallace/46	11.5	7.1	434	4680
Campbell/47	14.0	6.8	245	391
Southside/48	8.0	7.2	340	760
*Titrated alkalinity				
**Probable water softener				

Table A2-3 - Water Well Chemistry

Note: In the following table HCO_3^- , CO_3^{2-} , TDS and Hardness (as CaCO_3) were computed as follows:

$$\text{HCO}_3^- = [\text{Titrated alkalinity (CaCO}_3\text{) in mg/L}] \times 1.22^*$$

$$^* = [(2 \times \text{mol.wt. HCO}_3^-) / \text{mol.wt. CaCO}_3]$$

$$\text{CO}_3^{2-} = \text{mg/L HCO}_3^- \times 0.4917 \text{ (Hem, 1989)}$$

$$\text{TDS} = \text{Sum chloride to strontium ppm values plus CO}_3^{2-} \text{ (computed)}$$

$$\text{Hardness (as CaCO}_3\text{)} = (\text{meq/L Ca}^{2+} + \text{Mg}^{2+}) \times 50$$

Constituents	Detection limits (ppm)	CFRA/1 (ppm)	epm	Rooney/2 (ppm)	epm	McNeil/3 (ppm)	epm
Cl	0.10	25.00	0.71	27.00	0.76	45.00	1.27
NO3	0.10			0.51	0.01		
SO4	0.01	24.80	0.52	40.00	0.83	41.50	0.86
Fe	0.2			0.3	0.01	1.6	0.06
Mn	0.02					0.04	0.001
Mg	0.2	16.1	1.32	26.2	2.15	29.1	2.39
Ca	0.2	54.4	2.71	76.5	3.82	78.3	3.91
Na	0.2	5.7	0.25	10.3	0.45	10.3	0.45
K	0.5						
Cu	0.005						
Zn	0.020	0.11	0.003	0.05	0.002		
Ba	0.040	0.24	0.003	0.14	0.002	0.13	0.002
Sr	0.020	0.17	0.004	0.16	0.004	0.30	0.007
HCO3*		174.35	2.86	291.39	4.78	268.23	4.40
Total		300.87		472.55		474.50	
Total cations			4.30		6.44		6.82
Total anions			4.08		6.38		6.53
% Error			2.58		0.43		2.12
CO3*		85.73		143.28		131.89	
TDS*		212.25		324.44		338.16	
Hardness*		201.93		298.60		315.01	
* See Covering							
page, Table A2-3							

Constituents	Youmans/4 (ppm)	epm	St. James Rectory/5 (ppm)	epm	St. James Church/6 (ppm)	epm
Cl	171.00	4.82	196.00	5.53	268.00	7.56
NO3						
SO4	78.00	1.62	79.00	1.64	97.00	2.02
Fe	1.0	0.04	1.2	0.04	0.8	0.03
Mn	0.03	0.001	0.03	0.001	0.03	0.001
Mg	55.8	4.59	47.7	3.92	55.5	4.56
Ca	91.0	4.54	93.7	4.68	103.7	5.17
Na	69.7	3.03	87.4	3.80	117.7	5.12
K	6.8	0.17	5.9	0.15	8.1	0.21
Cu						
Zn	0.11	0.003				
Ba	0.24	0.003	0.09	0.001	0.06	0.001
Sr		0.00	2.87	0.07	2.71	0.06
HCO3*	362.11	5.94	334.06	5.48	401.12	6.58
Total	835.79		847.95		1054.72	
Total cations		12.38		12.66		15.16
Total anions		12.39		12.65		16.16
% Error		-0.03		0.03		-3.20
CO3*	178.05		164.26		197.23	
TDS*	651.73		678.15		850.83	
Hardness*	456.49		429.92		486.94	
* See Covering page, Table A2-3						

Constituents	RCVA/7 (ppm)	epm	Anderson/8 (ppm)	epm	Aitken/9 (ppm)	epm
Cl	225.00	6.35	114.00	3.22	35.20	0.99
NO3						
SO4	75.00	1.56	47.90	1.00	73.00	1.52
Fe	1.00	0.04			0.6	0.02
Mn	0.03	0.001				
Mg	45.3	3.73	16.8	1.38	41.8	3.44
Ca	82.4	4.11	22.8	1.14	73.8	3.68
Na	113.5	4.94	109.0	4.74	7.3	0.34
K	7.9	0.20	7.8	0.20	3.5	0.09
Cu						
Zn					0.03	0.001
Ba	0.07	0.001	0.06	0.001	0.15	0.002
Sr	2.98	0.07	1.59	0.04	0.77	0.02
HCO3*	323.09	5.30	199.95	3.28	329.19	5.40
Total	876.27		519.92		565.77	
Total cations		13.08		7.50		7.59
Total anions		13.21		7.49		7.91
% Error		-0.48		0.03		-2.06
CO3*	158.86		98.32		161.86	
TDS*	712.04		418.29		398.44	
Hardness*	391.86		125.97		356.01	
* See Covering						
page, Table A2-3						

Constituents	McCuaigG/10 (ppm)	epm	Hutt/11 (ppm)	epm	Gouin/12 (ppm)	epm
Cl	109.00	3.07	18.50	0.52	39.00	1.10
NO3						
SO4	54.40	1.13	55.50	1.16	47.00	0.98
Fe	1.9	0.07	0.9	0.03	0.3	0.01
Mn	0.05	0.002	0.03	0.001		
Mg	37.3	3.07	33.6	2.76	28.3	2.33
Ca	73.2	3.65	77.5	3.87	63.3	3.16
Na	18.0	0.78	9.5	0.41	19.8	0.86
K	2.7	0.07	3.4	0.09	2.4	0.06
Cu						
Zn						
Ba	0.15	0.002	0.12	0.002	0.14	0.002
Sr	0.45	0.01	0.17	0.004	0.67	0.02
HCO3*	232.00	3.80	331.63	5.44	256.04	4.20
Total	529.17		530.85		456.96	
Total cations		7.65		7.17		6.44
Total anions		8.01		7.12		6.28
% Error		-2.26		0.37		1.27
CO3*	114.07		163.06		125.89	
TDS*	411.24		362.28		326.81	
Hardness*	336.01		331.52		274.30	
* See Covering page, Table A2-3						

Constituents	Miles/13 (ppm)	epm	Bekker/14 (ppm)	epm	Gray/15 (ppm)	epm
Cl	2.31	0.07	89.00	2.51	186.00	5.25
NO3						
SO4	32.50	0.68	40.00	0.83	73.00	1.52
Fe	0.2	0.007	0.4	0.01	1.4	0.05
Mn			0.04	0.001	0.02	0.001
Mg	28.6	2.35	30.5	2.51	42.9	3.53
Ca	69.2	3.45	79.1	3.95	73.0	3.64
Na	2.2	0.10	45.3	1.97	102.0	4.44
K	2.2	0.06			9.7	0.25
Cu	0.01	0.32				
Zn	0.04	0.001				
Ba	0.11	0.002	0.15	0.002		
Sr	0.64	0.01	0.14	0.003	3.41	0.08
HCO3*	320.65	5.26	308.46	5.06	349.91	5.74
Total	458.65		593.09		841.34	
Total cations		6.30		8.45		11.98
Total anions		6.00		8.40		12.51
% Error		2.45		0.26		-2.13
CO3*	157.66		151.67		172.05	
TDS*	295.67		436.30		663.48	
Hardness*	290.25		322.77		358.53	
* See Covering						
page, Table A2-3						

Constituents	Rooke/16 (ppm)	epm	Riley/17 (ppm)	epm	Manotick School/18 (ppm)	epm
Cl	264.00	7.45	288.00	8.12	366.00	10.32
NO3						
SO4	88.00	1.83	94.00	1.96	84.00	1.75
Fe	3.2	0.11	0.8	0.03	0.4	0.01
Mn	0.03	0.001			0.08	0.003
Mg	38.1	3.13	37.0	3.04	66.9	5.50
Ca	79.1	3.95	83.3	4.16	148.8	7.43
Na	139.5	6.07	168.6	7.33	122.9	5.35
K	7.0	0.18	7.4	0.19		
Cu						
Zn	0.03	0.001				
Ba					0.24	0.003
Sr	3.63	0.08	4.40	0.10	0.28	0.006
HCO3*	299.93	4.92	299.93	4.92	429.16	7.04
Total	922.51		983.43		1218.75	
Total cations		13.53		14.85		18.30
Total anions		14.20		15.00		19.11
% Error		-2.42		-0.50		-2.17
CO3*	147.48		147.48		211.02	
TDS*	770.06		830.98		1000.61	
Hardness*	354.02		359.97		646.34	
* See Covering						
page, Table A2-3						

Constituents	Manotick Curling/19 (ppm)	epm	Gale Real Estate/20 (ppm)	epm	Manotick Library/21 (ppm)	epm
Cl	268.00	7.56	490.00	13.82	146.00	4.12
NO3						
SO4	72.00	1.50	106.00	2.21	64.00	1.33
Fe	1.4	0.1	0.6	0.02	0.3	0.01
Mn	0.06	0.002	0.21	0.01	0.04	0.001
Mg	59.9	4.93	76.2	6.27	45.2	3.72
Ca	131.4	6.56	152.9	7.63	102.3	5.10
Na	78.7	3.42	217.6	9.46	40.1	1.74
K	0.5	0.01	6.1	0.16	1.4	0.04
Cu					0.03	0.95
Zn	0.12	0.004	0.03	0.001		
Ba	0.33	0.005	0.24	0.003	0.22	0.003
Sr	0.33	0.007	0.91	0.02	0.65	0.01
HCO3*	376.74	6.18	463.30	7.60	348.70	5.72
Total	989.48		1514.08		748.94	
Total cations		14.99		23.57		11.59
Total anions		15.24		23.63		11.17
% Error		-0.83		-0.12		1.82
CO3*	185.24		227.80		171.46	
TDS*	797.98		1278.59		571.70	
Hardness*	574.14		694.81		441.09	
* See Covering page, Table A2-3						

Constituents	Sundance/ 22 (ppm)	epm	Desnoyers/24 (ppm)	epm	Paytler/25 (ppm)	epm
Cl	54.00	1.52	7.50	0.21	80.50	2.27
NO3	11.00	0.18			1.10	0.02
SO4	65.00	1.35	32.50	0.68	64.80	1.35
Fe	0.2	0.007			0.2	0.01
Mn	0.26	0.009				
Mg	40.6	3.34	16.6	1.37	20.4	1.68
Ca	117.7	5.87	55.5	2.77	94.4	4.71
Na	9.9	0.43	4.3	0.19	30.8	1.34
K	78.2	2.00			1.9	0.05
Cu	0.01	0.32			0.01	0.32
Zn			0.03	0.001	0.07	0.002
Ba	0.17	0.002	0.17	0.002	0.14	0.002
Sr	0.22	0.005	0.12	0.003	0.13	0.003
HCO3*	512.07	8.40	212.14	3.48	281.64	4.62
Total	889.33		328.86		576.06	
Total cations		11.98		4.33		8.11
Total anions		11.45		4.37		8.26
% Error		2.26		-0.47		-0.91
CO3*	251.78		104.31		138.48	
TDS*	629.04		221.03		432.90	
Hardness*	460.60		206.73		319.41	
* See Covering page, Table A2-3						

Constituents	Lanthier/ 26 (ppm)	epm	Carroll/27 (ppm)	epm	Koel/28 (ppm)	epm
Cl	11.30	0.32	80.00	2.26	55.30	1.56
NO3						
SO4	33.90	0.71	127.00	2.64	94.50	1.97
Fe	0.3	0.01			1.7	0.06
Mn	0.02	0.001			0.03	0.001
Mg	20.2	1.66	20.3	1.67	50.0	4.11
Ca	53.9	2.69	31.4	1.57	86.5	4.32
Na	3.1	0.13	133.1	5.79	14.2	0.62
K	4.5	0.11	5.3	0.14	4.5	0.12
Cu						
Zn						
Ba	0.09	0.001			0.11	0.002
Sr	1.11	0.03	3.45	0.08	0.23	0.005
HCO3*	282.86	4.64	286.52	4.70	363.33	5.96
Total	411.23		687.07		670.42	
Total cations		4.64		9.24		9.23
Total anions		5.66		9.60		9.49
% Error		-9.97		-1.91		-1.37
CO3*	139.08		140.88		178.65	
TDS*	267.45		541.43		485.74	
Hardness*	217.54		161.81		421.41	
* See Covering page, Table A2-3						

Constituents	Albion Sun Vista/29 (ppm)	epm	Adams & Kennedy/30 (ppm)	epm	Licari/31 (ppm)	epm
Cl	27.50	0.78	8.40	0.24	78.80	2.22
NO3						
SO4	33.80	0.70	56.80	1.18	63.50	1.32
Fe	0.4	0.01	0.7	0.03	0.2	0.007
Mn			0.03	0.001	0.06	0.002
Mg	24.1	1.98	28.9	2.38	38.0	3.13
Ca	53.2	2.65	77.5	3.87	89.3	4.46
Na	5.7	0.25	7.4	0.32	17.8	0.77
K	2.9	0.07	2.0	0.05	3.0	0.08
Cu						
Zn	0.03	0.001				
Ba	0.32	0.005	0.13	0.002	0.16	0.002
Sr	0.34	0.008	0.15	0.003	0.28	0.006
HCO3*	231.65	3.80	295.05	4.84	310.90	5.10
Total	379.90		477.09		602.03	
Total cations		4.98		6.65		8.45
Total anions		5.28		6.26		8.64
% Error		-2.87		3.02		-1.13
CO3*	113.90		145.08		152.87	
TDS*	262.15		327.11		444.00	
Hardness*	231.83		312.20		379.05	
* See Covering page, Table A2-3						

Constituents	MacIntyre/32 (ppm)	epm	Micucci/33 (ppm)	epm	Bakker's Store/34 (ppm)	epm
Cl	5.30	0.15	8.10	0.23	102.00	2.88
NO3			2.30	0.04		
SO4	21.00	0.44	55.30	1.15	70.50	1.47
Fe	0.3	0.01	0.2	0.01	0.6	0.02
Mn	0.03	0.001			0.04	0.001
Mg	12.0	0.99	32.9	2.71	35.1	2.89
Ca	40.6	2.03	71.5	3.57	98.8	4.93
Na	4.4	0.19	9.1	0.39	38.2	1.66
K	1.5	0.04	2.0	0.05	2.5	0.06
Cu			0.03	0.95		
Zn	0.02	0.001				
Ba	0.31	0.004	0.10	0.001	0.15	0.002
Sr	0.33	0.007	0.27	0.006	0.15	0.003
HCO3*	158.50	2.60	270.00	4.426	265.00	4.34
Total	244.29		451.75		613.01	
Total cations		3.27		7.687		9.57
Total anions		3.19		5.842		8.69
% Error		1.24		13.634		4.83
CO3*	77.93		132.76		130.30	
TDS*	163.72		314.51		478.31	
Hardness*	150.64		313.67		390.83	
* See Covering page, Table A2-3						

Constituents	Marcantonio/35 (ppm)	epm	McCuaig L/ 36 (ppm)	epm	Hoar/37 (ppm)	epm
Cl	186.00	5.25	21.30	0.60	200.00	5.64
NO3	1.23	0.02				
SO4	43.00	0.90	44.60	0.93	75.00	1.56
Fe			0.4	0.01	0.3	0.01
Mn			0.02	0.001	0.04	0.001
Mg	30.1	2.48	20.9	1.72	43.8	3.60
Ca	98.4	4.91	52.9	2.64	122.0	6.09
Na	98.1	4.27	7.6	0.33	76.3	3.32
K			4.6	0.12	3.2	0.08
Cu	0.01	0.32				
Zn						
Ba	0.17	0.002	0.17	0.002	0.19	0.003
Sr	0.15	0.004	2.42	0.055	0.48	0.01
HCO3*	356.01	5.84	198.73	3.26	385.27	6.32
Total	813.17		353.62		906.61	
Total cations		11.98		4.88		13.12
Total anions		12.00		4.79		13.52
% Error		-0.11		0.94		-1.52
CO3*	175.05		97.72		189.44	
TDS*	632.21		252.61		710.78	
Hardness*	369.28		217.92		484.49	
* See Covering page, Table A2-3						

Constituents	Wagg/38 (ppm)	epm	Heyn/39 (ppm)	epm	Courville/40 (ppm)	epm
Cl	6.80	0.19	140.00	3.95	69.00	1.95
NO3			0.66	0.01		
SO4	35.80	0.75	82.30	1.71	61.50	1.28
Fe	0.4	0.01	0.3	0.01		
Mn	0.06	0.002				
Mg	19.6	1.61	44.2	3.63	0.4	0.03
Ca	49.4	2.47	112.0	5.59	1.1	0.05
Na	5.0	0.22	66.1	2.88	183.2	7.97
K	1.8	0.05	1.8	0.05		
Cu			0.01	0.32	0.02	0.64
Zn						
Ba	0.28	0.004	0.07	0.001		
Sr	0.27	0.006	0.17	0.004		
HCO3*	238.97	3.92	419.41	6.88	335.28	5.50
Total	358.38		867.01		650.50	
Total cations		4.37		12.48		8.69
Total anions		4.86		12.55		8.73
% Error		-5.31		-0.30		-0.20
CO3*	117.50		206.22		164.86	
TDS*	236.91		653.83		480.08	
Hardness*	203.85		461.18		4.39	
* See Covering						
page, Table A2-3						

Constituents	Gilchrist/41 (ppm)	epm	Coxall/42 (ppm)	epm	Quaile/43 (ppm)	epm
Cl	113.00	3.19	360.00	10.15	54.50	1.54
NO3			1.90	0.03		
SO4	46.10	0.96	71.50	1.49	69.50	1.45
Fe	1.0	0.04	0.4	0.01	1.6	0.06
Mn	0.06	0.002			0.21	0.01
Mg	31.3	2.57	53.7	4.42	37.9	3.12
Ca	93.1	4.65	159.0	7.93	129.0	6.44
Na	31.3	1.36	89.9	3.91	11.7	0.51
K	2.0	0.05	3.1	0.08	1.9	0.05
Cu			0.04	1.27		
Zn			0.03	0.001		
Ba	0.21	0.003	0.15	0.002	0.30	0.004
Sr	0.34	0.008	0.54	0.01	0.22	0.005
HCO3*	320.65	5.26	438.92	7.20	408.44	6.70
Total	639.09		1179.22		715.23	
Total cations		8.68		17.64		10.18
Total anions		9.41		18.87		9.68
% Error		-4.01		-3.37		2.52
CO3*	157.66		215.82		200.83	
TDS*	476.10		956.12		507.62	
Hardness*	360.99		617.51		477.70	
* See Covering						
page, Table A2-3						

Constituents	Lessick/44 (ppm)	epm	Thompson/45 (ppm)	epm	Wallace/46 (ppm)	epm
Cl	107.00	3.02	16.30	0.46	1248.00	35.20
NO3	0.12	0.002			2.50	0.04
SO4	46.00	0.96	46.90	0.98	136.00	2.83
Fe			0.3	0.01	0.4	0.01
Mn	0.03	0.001	0.03	0.001		
Mg	39.8	3.273	20.5	1.69	70.1	5.76
Ca	70.3	3.51	69.8	3.48	252.0	12.57
Na	62.7	2.73	9.9	0.43	658.0	28.62
K	5.1	0.13	2.42	0.06	3.4	0.09
Cu	0.02	0.64			0.01	0.32
Zn	0.56	0.02			0.02	0.001
Ba	0.08	0.001	0.15	0.002	0.27	0.004
Sr	4.68	0.11	0.18	0.004	0.29	0.007
HCO3*	353.57	5.80	254.82	4.18	295.00	4.84
Total	689.96		421.34		2665.95	
Total cations		10.40		5.68		47.39
Total anions		9.78		5.62		42.91
% Error		3.09		0.58		4.96
CO3*	173.85		125.29		145.05	
TDS*	510.24		291.81		2516.00	
Hardness*	339.05		258.44		916.98	
* See Covering page, Table A2-3						

Constituents	Campbell/47 (ppm)	epm	Southside Trailer Park/48 (ppm)	epm
Cl	13.90	0.39	55.00	1.55
NO3	6.80	0.11	0.12	0.002
SO4	42.20	0.88	79.90	1.66
Fe			0.4	0.01
Mn			0.09	0.003
Mg	24.4	2.01	37.1	3.05
Ca	77.3	3.86	99.0	4.94
Na	12.8	0.56	19.3	0.84
K	1.3	0.03	3.1	0.08
Cu	0.01	0.32		
Zn				
Ba	0.10	0.001	0.11	0.002
Sr	0.10	0.002	1.04	0.02
HCO3*	295.02	4.84	414.53	6.79
Total	473.96		709.64	
Total cations		6.78		8.95
Total anions		6.22		10.01
% Error		4.31		-5.59
CO3*	145.06		203.82	
TDS*	324.00		498.93	
Hardness*	293.19		399.56	
* See Covering				
page, Table A2-3				

Table A2-4 • Geochemistry Data Verification

PARAMETER	CFRA/1	Rooney/2	McNeil/3	Youmans/4	St. James Rectory/5
Check 1:					
% Error = $[(\text{Total cations(epm)} - \text{Total anions(epm)}) / \text{Total cations(epm)} + \text{total anions(epm)}]] \times 100$	2.58	0.43	2.12	-0.03	0.03
Check 2:					
Total Dissolved Solids (TDS) (ppm)	212.25	324.44	338.16	651.73	678.15
Electrical Conductivity ($\mu\text{S/cm}$)	400.0	570.0	630.0	1180.0	1240.0
Check 2: (TDS/Conductivity=55to.75)	0.53	0.57	0.54	0.55	0.55
% Deviation from 0.60 as % of 0.60 (Abs. Val.)	11.56	5.13	10.54	7.95	8.85
Check 3:					
Electrical Conductivity ($\mu\text{S/cm}$)	400.0	570.0	630.0	1180.0	1240.0
Total meq/l(cations) x 100	429.70	643.80	681.60	1237.90	1266.20
Check 3: (Tot meq/l x 100)-Conductivity (Abs. Val.)	29.70	73.80	51.60	57.90	26.20
Difference as % of larger value	6.91	11.46	7.57	4.68	2.07
AVG. CHECK 2 (SUM % DEVIATIONS/47*)	8.18				
AVG. CHECK 3 (SUM DIFF. AS % OF LARGER VALUE/47*)	9.81				
*Note: Sample No. 23 not included					

PARAMETER	St.James Church/6	RCVA/7	Anderson/8	Aitken/9
Check 1:				
% Error = $[(\text{Total cations(epm)} - \text{Total anions(epm)}) / \text{Total cations(epm)} + \text{total anions(epm)}] \times 100$	-3.20	-0.48	0.03	-2.06
Check 2:				
Total Dissolved Solids (TDS) (ppm)	850.83	712.04	418.29	398.44
Electrical Conductivity ($\mu\text{S/cm}$)	1520.0	1310.0	750.0	630.0
Check 2: (TDS/Conductivity=.55to.75)	0.56	0.54	0.56	0.63
% Deviation from 0.60 as % of 0.60 (Abs. Val.)	6.71	9.41	7.05	5.41
Check 3:				
Electrical Conductivity ($\mu\text{S/cm}$)	1520.0	1310.0	750.0	630.0
Total meq/l(cations) x 100	1515.80	1308.20	749.70	758.90
Check 3: (Tot meq/l x 100)-Conductivity (Abs. Val.)	4.20	1.80	0.30	128.90
Difference as % of larger value	0.28	0.14	0.04	16.99
AVG. CHECK 2 (SUM % DEVIATIONS/47*)				
AVG. CHECK 3 (SUM DIFF. AS % OF LARGER VALUE/47*)				
*Note: Sample No. 23 not included				

PARAMETER	McCuaig G/10	Hutt/11	Gouln/12	Miles/13
Check 1:				
% Error = $\frac{[(\text{Total cations(epm)} - \text{Total anions(epm)}) / \text{Total cations(epm)} + \text{total anions(epm)}] \times 100}{}$	-2.26	0.37	1.27	2.45
Check 2:				
Total Dissolved Solids (TDS) (ppm)	411.24	362.28	326.81	295.67
Electrical Conductivity ($\mu\text{S/cm}$)	740.0	630.0	570.0	600.0
Check 2: (TDS/Conductivity=.55 to .75)	0.56	0.58	0.57	0.49
% Deviation from 0.60 as % of 0.60 (Abs. Val.)	7.38	4.16	4.44	17.87
Check 3:				
Electrical Conductivity ($\mu\text{S/cm}$)	740.0	630.0	570.0	600.0
Total meq/l(cations) x 100	765.50	716.90	643.70	598.10
Check 3: (Tot meq/l x 100)-Conductivity (Abs. Val.)	25.50	86.90	73.70	1.90
Difference as % of larger value	3.33	12.12	11.45	0.32
AVG. CHECK 2 (SUM % DEVIATIONS/47*)				
AVG. CHECK 3 (SUM DIFF. AS % OF LARGER VALUE/47*)				
*Note: Sample No. 23 not included				

PARAMETER	Bekker/14	Gray/15	Rooke/16	Riley/17	Manotick School/18
Check 1:					
% Error = $[(\text{Total cations(epm)} - \text{Total anions(epm)}) / (\text{Total cations(epm)} + \text{Total anions(epm)})] \times 100$	0.26	-2.13	-2.42	-0.50	-2.17
Check 2:					
Total Dissolved Solids (TDS) (ppm)	436.30	663.48	770.06	830.98	1000.61
Electrical Conductivity ($\mu\text{S/cm}$)	790.0	1190.0	1390.0	1540.0	1840.0
Check 2: (TDS/Conductivity=.55to.75)	0.55	0.56	0.55	0.54	0.54
% Deviation from 0.60 as % of 0.60 (Abs. Val.)	7.95	7.08	7.67	10.07	9.37
Check 3:					
Electrical Conductivity ($\mu\text{S/cm}$)	790.0	1190.0	1390.0	1540.0	1840.0
Total meq/l(cations) x 100	844.70	1198.40	1352.60	1485.10	1829.90
Check 3: (Tot meq/l x 100)-Conductivity (Abs. Val.)	54.70	8.40	37.40	54.90	10.10
Difference as % of larger value	6.48	0.70	2.69	3.56	0.55
AVG. CHECK 2 (SUM % DEVIATIONS/47*)					
AVG. CHECK 3 (SUM DIFF. AS % OF LARGER VALUE/47*)					
*Note: Sample No. 23 not included					

PARAMETER	Manotick Curling/19	Gale Real Estate/20	Manotick Library/21	Sun- dance/22
Check 1:				
% Error = $\frac{[(\text{Total cations(epm)} - \text{Total anions(epm)}) / (\text{Total cations(epm)} + \text{Total anions(epm)})] \times 100}{}$	-0.83	-0.12	1.82	2.26
Check 2:				
Total Dissolved Solids (TDS) (ppm)	797.98	1278.59	571.70	629.04
Electrical Conductivity ($\mu\text{S/cm}$)	1500.0	2430.0	1020.0	820.0
Check 2: (TDS/Conductivity=.55to.75)	0.53	0.53	0.56	0.77
% Deviation from 0.60 as % of 0.60 (Abs. Val.)	11.34	12.31	6.58	27.85
Check 3:				
Electrical Conductivity ($\mu\text{S/cm}$)	1500.0	2430.0	1020.0	820.0
Total meq/l(cations) x 100	1498.70	2357.10	1063.20	1166.70
Check 3: (Tot meq/l x 100)-Conductivity (Abs. Val.)	1.30	72.90	43.20	346.70
Difference as % of larger value	0.09	3.00	4.06	29.72
AVG. CHECK 2 (SUM % DEVIATIONS/47*)				
AVG. CHECK 3 (SUM DIFF. AS % OF LARGER VALUE/47*)				
*Note: Sample No. 23 not included				

PARAMETER	Desnoyers/24	Paytler/25	Lanthier/ 26	Carroll/27
Check 1:				
% Error = $\frac{[(\text{Total cations(epm)} - \text{Total anions(epm)}) / \text{Total cations(epm)} + \text{total anions(epm)}]}{100}$	-0.47	-0.91	-9.97	-1.91
Check 2:				
Total Dissolved Solids (TDS) (ppm)	221.03	432.90	267.45	541.43
Electrical Conductivity ($\mu\text{S/cm}$)	380.0	690.0	400.0	940.0
Check 2: (TDS/Conductivity = .55 to .75)	0.58	0.63	0.67	0.58
% Deviation from 0.60 as % of 0.60 (Abs. Val.)	3.06	4.57	11.44	4.00
Check 3:				
Electrical Conductivity ($\mu\text{S/cm}$)	380.0	690.0	400.0	940.0
Total meq/l/(cations) x 100	432.80	779.00	463.70	924.00
Check 3: (Tot meq/l x 100)-Conductivity (Abs. Val.)	52.80	89.00	63.70	16.00
Difference as % of larger value	12.20	11.42	13.74	1.70
AVG. CHECK 2 (SUM % DEVIATIONS/4*)				
AVG. CHECK 3 (SUM DIFF. AS % OF LARGER VALUE/4*)				
*Note: Sample No. 23 not included				

PARAMETER	Koel/28	Alblon Sun Vista/29	Adams& Kennedy/30	Licari/31
Check 1:				
% Error = $\frac{[(\text{Total cations(epm)} - \text{Total anions(epm)}) / \text{Total cations(epm)} + \text{total anions(epm)}]}{1} \times 100$	-1.37	-2.87	3.02	-1.13
Check 2:				
Total Dissolved Solids (TDS) (ppm)	485.74	262.15	327.11	444.00
Electrical Conductivity ($\mu\text{S/cm}$)	750.0	420.0	520.0	660.0
Check 2: (TDS/Conductivity= 55to.75)	0.65	0.62	0.63	0.67
% Deviation from 0.60 as % of 0.60 (Abs. Val.)	7.94	4.03	4.84	12.12
Check 3:				
Electrical Conductivity ($\mu\text{S/cm}$)	750.0	420.0	520.0	660.0
Total meq/l(cations) x 100	923.00	498.40	664.90	845.10
Check 3: (Tot meq/l x 100)-Conductivity (Abs. Val.)	173.00	78.40	144.90	185.10
Difference as % of larger value	18.74	15.73	21.79	21.90
AVG. CHECK 2 (SUM % DEVIATIONS/47*)				
AVG. CHECK 3 (SUM DIFF. AS % OF LARGER VALUE/47*)				
*Note: Sample No. 23 not included				

PARAMETER	MacIntyre/32	Micucci/33	Bakker's Store/34	Marcantonio/ 35
Check 1:				
% Error = [(Total cations(epm)-Total anions(epm))/ Total cations(epm) + total anions(epm))] x 100	1.24	13.63	4.83	-0.11
Check 2:				
Total Dissolved Solids (TDS) (ppm)	163.72	314.51	478.31	632.21
Electrical Conductivity (µS/cm)	280.0	560.0	800.0	1160.0
Check 2: (TDS/Conductivity=.55to.75)	0.58	0.56	0.60	0.55
% Deviation from 0.60 as % of 0.60 (Abs. Val.)	2.55	6.40	0.35	9.17
Check 3:				
Electrical Conductivity (µS/cm)	280.0	560.0	800.0	1160.0
Total meq/l(cations) x 100	326.70	673.40	957.00	1165.80
Check 3: (Tot meq/l x 100)-Conductivity (Abs. Val.)	46.70	113.40	157.00	5.80
Difference as % of larger value	14.29	16.84	16.41	0.50
AVG. CHECK 2 (SUM % DEVIATIONS/47*)				
AVG. CHECK 3 (SUM DIFF. AS % OF LARGER VALUE/47*)				
*Note: Sample No. 23 not included				

PARAMETER	McCuaigh/ 36	Hoar/37	Wagg/38	Heyn/39	Courville/ 40
Check 1:					
% Error = $\frac{[(\text{Total cations(epm)} - \text{Total anions(epm)})]}{[\text{Total cations(epm)} + \text{Total anions(epm)}]} \times 100$	0.94	-1.52	-5.31	-0.30	-0.20
Check 2:					
Total Dissolved Solids (TDS) (ppm)	252.61	710.78	236.91	653.83	480.08
Electrical Conductivity ($\mu\text{S/cm}$)	400.0	1310.0	380.0	1080.0	820.0
Check 2: (TDS/Conductivity = 55 to 75)	0.63	0.54	0.62	0.61	0.59
% Deviation from 0.60 as % of 0.60 (Abs. Val.)	5.25	9.57	3.91	0.90	2.42
Check 3:					
Electrical Conductivity ($\mu\text{S/cm}$)	400.0	1310.0	380.0	1080.0	820.0
Total meq/l(cations) x 100	488.00	1311.70	436.70	1216.00	805.60
Check 3: (Tot meq/l x 100)-Conductivity (Abs. Val.)	88.00	1.70	56.70	136.00	14.40
Difference as % of larger value	18.03	0.13	12.98	11.18	1.76
AVG. CHECK 2 (SUM % DEVIATIONS/47*)					
AVG. CHECK 3 (SUM DIFF. AS % OF LARGER VALUE/47*)					
*Note: Sample No. 23 not included					

PARAMETER	Gilchrist/41	Coxall/42	Qualle/43	Lessick/44
Check 1:				
% Error = $\frac{[(\text{Total cations(epm)} - \text{Total anions(epm)})]}{[\text{Total cations(epm)} + \text{total anions(epm)}]} \times 100$	-4.01	-3.37	2.52	3.09
Check 2:				
Total Dissolved Solids (TDS) (ppm)	476.10	956.12	507.62	510.24
Electrical Conductivity ($\mu\text{S/cm}$)	760.0	1430.0	770.0	930.0
Check 2: (TDS/Conductivity=.55to.75)	0.63	0.67	0.66	0.55
% Deviation from 0.60 as % of 0.60 (Abs. Val.)	4.41	11.44	9.87	8.56
Check 3:				
Electrical Conductivity ($\mu\text{S/cm}$)	760.0	1430.0	770.0	930.0
Total meq/l(cations) x 100	868.20	1637.10	1018.50	976.50
Check 3: (Tot meq/l x 100)-Conductivity (Abs. Val.)	108.20	207.10	248.50	46.50
Difference as % of larger value	12.46	12.65	24.40	4.76
AVG. CHECK 2 (SUM % DEVIATIONS/47*)				
AVG. CHECK 3 (SUM DIFF. AS % OF LARGER VALUE/47*)				
*Note: Sample No. 23 not included				

PARAMETER	Thompson/ 45	Wallace/46	Campbell/ 47	Southside Trailer Park/48
Check 1:				
% Error = $[(\text{Total cations(epm)} - \text{Total anions(epm)}) / \text{Total cations(epm)} + \text{total anions(epm)}] \times 100$	0.58	4.96	4.31	-5.59
Check 2:				
Total Dissolved Solids (TDS) (ppm)	291.81	2516.00	324.00	498.93
Electrical Conductivity ($\mu\text{S/cm}$)	430.0	4680.0	457.0	760.0
Check 2: $(\text{TDS}/\text{Conductivity} = .55 \text{ to } .75)$	0.68	0.54	0.71	0.66
% Deviation from 0.60 as % of 0.60 (Abs. Val.)	13.11	10.40	18.16	9.42
Check 3:				
Electrical Conductivity ($\mu\text{S/cm}$)	430.0	4680.0	457.0	760.0
Total $\text{meq/l}(\text{cations}) \times 100$	568.10	4707.10	645.90	895.10
Check 3: $(\text{Tot meq/l} \times 100) - \text{Conductivity (Abs. Val.)}$	138.10	27.10	188.90	135.10
Difference as % of larger value	24.31	0.58	29.25	15.09
AVG. CHECK 2 (SUM % DEVIATIONS/47*)				
AVG. CHECK 3 (SUM DIFF. AS % OF LARGER VALUE/47*)				
*Note: Sample No. 23 not included				

Appendix 3

Isotope Data

Table A3-1 • Isotope Data

Homeowner/ Sample No	$\delta^{18}\text{O}$ (permil) (± 0.1)	$\delta^2\text{H}$ (permil) (± 1.3)	^3H (Tritium Units) (± 8)
CFRA/1	-11.61	-81	27
Youmans/4	-11.26	-77	26
Rectory/5	-11.25	-77	26
RCVA/7	-11.40	-81	16
Anderson/8	-11.77	-83	<6
Manotick Curling/19	-11.08	-75	27
Paytler/25	-11.67	-79	36
Lanthier/26	-11.39	-78	32
Koel/28	-10.51	-74	22
Adams&Kennedy/30	-11.69	-83	28
Licari/31	-11.38	-79	42
Wagg/38	-11.92	-81	15
Quaile/43	-11.11	-76	28
Lessick/44	-11.22	-77	34

Table A3-1 - Isotope data.

Appendix 4

Glossary of Computer Terms

Glossary of Computer Terms

N.B. Terms and expressions in bold have separate entries.

exact-solution weight function The interpolation is executed with a user-defined weight function, which is applied to each output value. An exact-solution weight method is used, in which W is defined as

$$W = [1/(D/d_0)^n] - 1,$$

where:

W = the calculated weight,

D = the distance to a known point measurement,

d_0 = the **limiting distance**, and

n = the **value constant**

The **limiting distance** is the maximum distance surrounding a given output point in which the computer will search for known input values for the moving surface function. The **value constant** has the effect of decreasing the influence of known values with distance from the unknown cell, until the limiting distance is reached. This weight method produces **exact solution surfaces**, or surfaces which respect the values of known points, because when the distance between an output pixel and an input data point is zero, the weight is infinite.

filter A filter is used to improve the appearance of the spatial distribution of data in an image. In the filtering process, each pixel value in a raster map is replaced with a

new value. The new value is obtained by applying one of a number of possible functions to the pixel and its neighbours. The neighbours can be the 8 adjacent pixels (in a 3x3 filter) or the surrounding 24 pixels (in a 5x5 filter). Filters which emphasize high frequencies and suppress low frequencies are high-pass filters. Similarly, a low-pass filter emphasizes low frequencies and suppresses high ones.

full second degree This expression describes the polynomial regression function used to calculate a new surface at each unknown point. The regression surface is fitted to the point data within the limiting distance d_0 by a least squares fit. In this interpolation, a full second order polynomial surface is produced according to the formula:

$$z = a + bx + cy + dxy + ex^2 + fy^2.$$

hue See **intensity-hue-saturation (IHS) transform**

intensity See **intensity-hue-saturation (IHS) transform**

intensity hue saturation (IHS) transform In an intensity-hue-saturation transform, the computer combines different sorts of imagery by breaking down the colour assigned to each pixel into its component intensity, hue and saturation. Intensity refers to the grey scale: varying, but always equal amounts of red, green and blue (i.e. 1:1:1) combine to produce various shades of grey. Hue refers to a change in the proportion of each of the three primary colours. Saturation refers to a change in the amount of the resultant colour, producing a range from pure spectral hues through pastels to shades of grey. Different sorts

of imagery are combined by displaying one as intensity, another as hue and another as saturation.

limiting distance see exact-solution weight function

linear interpolation In the method used in this study (Gorte and Poolhoven, 1990), for every raster element between contours (isolines), a value is calculated as a weighted average of contour values, using as weight factors the inverse distances to the nearest and second-nearest contours.

look-up table (LUT) A look-up table is a mathematical formula used to convert one distribution of data to another. It is most conveniently remembered as a conversion graph. For example, in this study a look-up table was used to assign different colour combinations, within the byte range of the colour screen (from 0 to 255), to each pixel index value by varying intensities of red, green and blue.

A LUT was also used to perform contrast stretching when attribute values are compressed into a relatively small part of the 0-255 range. In most cases, a simple linear stretch was used to spread the range of data equally over the 0-255 range, with the minimum attribute value set to 0 and the maximum to 255. In this method, the computer simply replaces the input value with the corresponding output value from the LUT. Stepwise stretches were also occasionally used, applying different LUTs to different ranges in the data to obtain an optimal image. Important ranges of data are stretched at the expense of intermediate data, which are compressed into a narrower segment of the 0-255 range.

moving surface The production of a moving surface begins with an input data layer, A, of known, input points or pixels, interspersed with points or pixels containing no data, and ends with a surface, B, of pixels corresponding in size and number to layer A, in which all pixels have been assigned a value. The new surface is calculated by applying a polynomial regression formula (in this case, a **full second degree function**) at each location (pixel) in the output surface, based on known points on the input surface which are located within a specified limiting distance, d_0 , around the point. In the case of this study, an **exact-solution weight function**, W , is applied to each output value, z . The surface is recalculated for every pixel in the output map and is thus a pixel-by-pixel moving surface. The output value is calculated by summing all points within the limiting distance, d_0 (M):

$$\text{Output} = 1/M \sum (W * z).$$

saturation See **intensity-hue-saturation (IHS) transform**

value constant See **exact-solution weight function**

Appendix 5

Colour Plates - Computer-generated surfaces

Note: All are plotted on an orthogonal grid, oriented to North

Plate 1 - Digital Terrain Model.

0 100 200 meters

MANITOWIC

CANADA

DIGITAL TERRAIN MODEL

MANITOWIC CANADA

DIGITAL TERRAIN MODEL

Plate 2a -

**Top left: Carbonate Thickness Map;
top right: Nepean Sandstone Elevation Surface;
lower left: Bedrock Surface (BS) (from well data);
lower right: Average Regional Potentiometric Surface.**

Carbonate thickness

n. 300

Nepean Sandstone Elevation

n. 100

45 Meters Max. Thickness

Bedrock Surface

n. 200

100 M

Average Regional Potentiometric Surface

n. 250

Plate 2b - Average Regional Potentiometric Surface.

Average Regional Potentiometric Surface

7 km

Plate 3 - Distribution of Wells beginning in Sandstone.

**Plate 4 - Bedrock from Seismic (Bedrock Elevations from Seismic Data)/Bedrock Surface
from Well Data**

Bedrock from Wells

Bedrock from Seismic

Kn

**Plate 5 - Potentiometric Surface for Wells Finishing in Carbonate/Potentiometric Surface
for Wells Finishing in Sandstone**

Potentiometric Surface Carbonate Wells

20

1000

116

116

Potentiometric Surface Sandstone Wells

116

116

116

116

116

116

116

116

116

116

Plate 6 -- Manotick — Bedrock Well Locations Surface

MANDTICK - BEDROCK WELL LOCATIONS

**Plate 7 - Modelled Bedrock Surface/Bedrock from Seismic Data/
Bedrock from Well Data**

Modelled Bedrock Surface

1000

Water

(mSL)

Seismic

Wells

Plate 8 - Intensity-Hue-Saturation Transform

MEAN POTENTIOMETRIC SURFACE
MANOTICK CANADA

Full and order negative surface in 1987
HIS Team form 1 Airphoto II potentiometric surface 1.

Legend of the 1

1 10 20 30 40 50 60 70 80 90 100

Plate 9 - Incremental Potentiometric Surfaces

P399

N 466

P376

N 479

P389

Incremental
Potentiometric
Surfaces (AMSL)

P377

N 490

P370

N 411

P365

MANOTICK CANADA

P369

N 467

P315

N 178

P350

N 188

20 m 100'

Plate 10 - Incremental Potentiometric Surface Changes

Incremental
Potentiometric
Surface (HSL)
Change

MANOTICK CANADA

5 Km

3.5 meters

0

3.5 meters

3

OF/DE

3

PM-1 3½"x4" PHOTOGRAPHIC MICROCOPY TARGET
NBS 1010a ANSI/ISO #2 EQUIVALENT

PRECISIONSM RESOLUTION TARGETS

Plate 11 - Manotick — Bedrock Wells and Section Lines

MAINTIC DEBRICK WELLS & SECTION LINES

B

A

B

A

B

Plate 12 - Multi-Level Modelled Potentiometric Profiles

MULTI LEVEL MODELLED POTENTIOMETRIC PROFILES

12000 cm (ANSL)

11000

10000

9000

8000

7000

6000

5000

4000

3000

2000

1000

0

A

P300

P300

(SECTION A-A')

P300

(SECTION A-A')

10000

9000

8000

7000

6000

km (horizontal)

B'

P300

P300

(SECTION B-B')

(SECTION B-B')

Plate 13 - Vertical Potentiometric Surface Variation

Vertical Potentiometric Surface Variation

100

00

100

Plate 14 - Correlation Coefficients for Vertical Potentiometric Surface Variation (Plate 13)

Vertical Potentiometric Surface Variation - Correlation Coefficients

1.0

0.9

0.8

1.0

Plate 15 - Integrated Horizontal and Vertical Potentiometric Gradients

Plate 16 - Flow Patterns along Sampling Lines

END

0 5 - 0 6 - 9 | 6

FIN