# PROVINCE OF NOVA SCOTIA

## DEPARTMENT OF MINES
## Groundwater Section

Report 70-1

# PIEZOMETER NESTS AND THE GROUNDWATER FLOW SYSTEM
# near
# BERWICK, KINGS COUNTY, NOVA SCOTIA

by

Peter C. Trescott

HON. PERCY GAUM
MINISTER

J.P. NOWLAN, Ph.D.
DEPUTY MINISTER

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# PREFACE

The Nova Scotia Department of Mines initiated in 1964 an extensive program to evaluate the groundwater resources of the Province of Nova Scotia. The first detailed field investigation in this program was conducted in the Annapolis-Cornwallis Valley, and the results were published as Department of Mines Memoir 6. As part of this investigation, several piezometer nests were installed near Berwick to obtain data on the groundwater flow system and fluctuations in groundwater levels. The project was expanded in 1967 with the installation of more piezometers, and water-level measurements were continued until the end of October 1968. The results of this project, which are described in this report, are an important contribution to the understanding of the groundwater hydrology of the Annapolis-Cornwallis Valley. The author points out, however, that several facets of this project deserve additional study.

Most of the field work for this project was supported as a joint undertaking between the Canada Department of Forestry and Rural Development and the Province of Nova Scotia (ARDA project No. 22042). Recently the administration of the ARDA Act was transferred to the Canada Department of Regional Economic Expansion. Use of Dalhousie University's IBM/360 Model 50 computer was secured through the cooperation of the Geology Department.

John F. Jones
Chief, Groundwater Section
Nova Scotia Department of Mines

Halifax, April 1, 1970

# CONTENTS

## Illustrations

## Table

# PIEZOMETER NESTS AND THE GROUNDWATER FLOW SYSTEM NEAR BERWICK, KINGS COUNTY, NOVA SCOTIA

## ABSTRACT

Four piezometer nests were installed near Berwick in the Annapolis-Cornwallis Valley to monitor annual fluctuations in groundwater levels and to determine the variation in hydraulic head with depth at selected locations in the regional groundwater flow system. Groundwater levels in the flood plain adjacent to the Cornwallis River closely followed changes in the river stage. Except for periods of rising stage and flood crests, the river is effluent. Away from the river, the hydrographs of groundwater recession during the growing seasons of 1966-68 were similar each year. The water level at the end of the recession was a function of the date the recession started and the water level at the start of the recession. Groundwater recharge began in October and continued intermittently during the late fall, winter and spring.

Of the four piezometer nests, one is located in and another adjacent to an outwash-filled, glacial discharge channel in the recharge area and the other two are located in the regional discharge area which extends about 3,000 feet south of the Cornwallis River. The groundwater flow patterns predicted by the two-dimensional, steady-state digital models of the flow system are in general agreement with field observations. Groundwater samples collected from some of the piezometers installed in the bedrock contained more hardness and total dissolved solids with distance from the recharge area. In addition, the temperature of groundwater samples from the discharge area was 5°F greater than the temperature of groundwater samples from the recharge area. Both the chemical and physical properties of groundwater, therefore, may be useful in mapping groundwater flow systems in Nova Scotia.

# INTRODUCTION

## Purpose and Scope of the Investigation

In June 1966 four piezometer nests were installed near Berwick, Kings County, Nova Scotia to monitor water-level fluctuations and variation in hydraulic head[1] with depth. The initial piezometer records to April 1967 were presented and discussed by the writer in an earlier publication (see Trescott, 1968). In October 1967, several more piezometers were installed in three of the nests with the objective of determining the hydraulic head at two points in the surficial deposits and at two or more points in the underlying bedrock. In one nest two piezometers were constructed at the same depth by two different methods to see if the groundwater levels measured would be identical. Near the end of the period of record (June 1966 to October 31, 1968), 'slug' tests were conducted to determine formation transmissivity and piezometer response time, and groundwater samples were collected to see if the water's physical and chemical properties are related to its location in the flow system. In addition, the observed potential pattern is compared with that predicted by two-dimensional, steady-state digital models of the flow system.

## General Description of the Area

### Location and Access

The piezometer nests are located near west longitude 64°42' and north latitude 45°03' between Berwick and Waterville in Kings County (Fig. 1). Each of the nests is located within 40 feet of a good secondary road to facilitate daily water level measurements.

### Physiography and Drainage

The piezometer nests are located in the Triassic lowland — a linear, subsequent valley formed on easily eroded sandstones and shales of the Wolfville and Blomidon Formations. The lowland is flanked on the south by the northern scarp of the South Mountain highland which is formed on erosion-resistant early Pale-

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[1] The hydraulic head (the potential function used in this report) is the hydraulic potential (Hubbert, 1940) divided by the acceleration due to gravity; at any point in the saturated zone, the hydraulic head is equal to the elevation of the point above mean sea level (elevation head) plus the pressure head measured in a piezometer installed at that point.

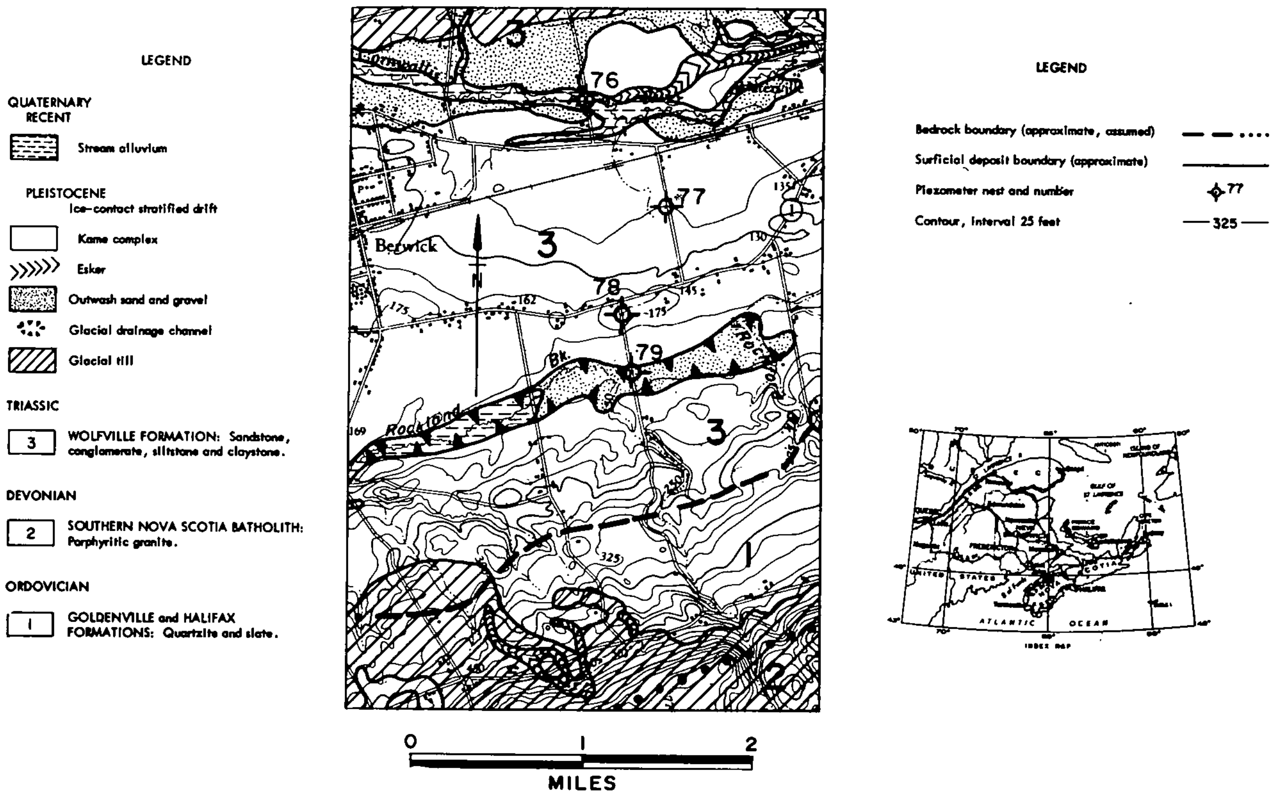

FIGURE 1. Location of the piezometer nests and geology of the area between Berwick and Waterville.

ozoic slates and quartzites and Devonian granite. The northern flank of the lowland is the scarp-slope of the North Mountain cuesta which is capped by Triassic basalts.

Preglacial bedrock topography in the lowland consists of a series of ridges and depressions paralleling the northeasterly strike of the bedrock. This topography was modified by Pleistocene glacial erosion and, in the area where the piezometers are located, by deposition of outwash deposits and ice-contact stratified drift (Trescott, 1968).

Piezometer nest 76 is located on the Cornwallis River flood plain at an elevation above mean sea level of 76 feet (see Fig. 1). Nest 77 is located one-half mile south of the Cornwallis River at an elevation of 103 feet on gently sloping land. The two piezometers of nest 78 are located at an elevation of 186 feet on the top of an elongate kame one mile south of the Cornwallis River. Nest 79 is located at an elevation of 153 feet nearly 1.5 miles south of the Cornwallis River in an outwash-filled, glacial discharge channel (outwash valley) adjacent to the South Mountain highland (Fig. 2). Note in figure 1 that nest 79 is in a section of the outwash valley that does not have a surface stream.

The pre-Pleistocene surface drainage of the area, as noted previously by the writer (Trescott, 1967), was altered by the glacial deposits. The headwaters of the Cornwallis River probably were the preglacial headwaters of the Annapolis River, and the outwash valley, now containing the headwaters of the Annapolis River was probably the site of the preglacial headwaters of the Cornwallis River. The preglacial Cornwallis River watershed, therefore, most likely included the sites of all four piezometer nests. Now, however, only nests 76 and 77 are in the Cornwallis River watershed; nest 78 is on the divide between watersheds, and nest 79 is in the Annapolis River watershed.

## Climate

Nova Scotia has a humid, temperate, continental climate modified by the Atlantic Ocean, which almost completely surrounds the province, and by the Gulf Stream which runs northeasterly parallel to the Atlantic coast. The proximity of the ocean tends to prevent extreme temperatures in the summer and winter and minimizes the number of severe atmospheric storms (N. S. Dept. of Trade and Industry, 1965).

The nearest climatic records are those for Garland on North Mountain north of Berwick. Although farther away, the records for Kentville 11 miles east of the piezometers and those for CFB Greenwood 12 miles west of the piezometers are more representative of climatic conditions in the Triassic lowland. Precipitation records from these two stations, therefore, have been averaged for inclusion on the piezometer hydrographs in Appendix A.

The 50-year weather records for Kentville, the station with the longest records in the area, give an indication of general climatic conditions in the lowland. Mean annual precipitation is 42 inches. Total snowfall for the winter months averages 85 inches. Precipitation is fairly well distributed during the year with slightly greater precipitation occurring during the fall and winter months than during the spring and summer months. The mean annual temperature is 43.6°F; the mean temperature of the coldest month (February) is 21.1°F, and of the warmest month (July) is 66.2°F. The average frost-free period at Kentville is 126 days (Canada Dept. of Agriculture, Research Station, Kentville, 1961).

FIGURE 2. Piezometer nest 79 in the outwash valley.

## Field Work

Most of the piezometers were installed in separate 4-inch diameter boreholes drilled with a rotary rig except for three multiple completions — piezometers 76 c and d, 77 c, d and e, and 78 a and b. The first piezometers were made of flexible, 1-inch diameter plastic pipe perforated in the bottom 3 feet with 1/8-inch diameter holes. Although flexible pipe is easier to work with in some respects, its tendency to bend and kink made installation difficult. Furthermore, piezometers made of flexible pipe tend to pinch off at the kinks if water pressure outside the piezometer is greater than that inside, making it difficult, if not impossible, to measure water levels, obtain water samples or conduct permeability tests. All later piezometers, therefore, were constructed of rigid 1-inch diameter plastic or black iron pipe.

After placing a piezometer in a borehole, water was pumped through it to clean out silt and fine sand that may have accumulated in the perforated section. The flow of water out of the borehole around the piezometer also kept fine-grained material from settling around the 'screen' while a gravel pack was placed. A cement seal was placed above the gravel pack by pumping cement grout down the hole through a grout pipe. During placement of the grout and while the grout set, the piezometer was kept tightly capped to prevent cement from filtering through the gravel pack and into the piezometer. (This will happan only if the cement can displace water in the piezometer.)

Depending on circumstances, the cement seal was continued to the surface, to the level of the next piezometer in the case of multiple completions, or for about 10 feet with the remainder of the hole being filled with drill cuttings. Drill cuttings were used exclusively to backfill some of the first piezometers. To see whether the lack of cement seals affected water levels in these piezometers, piezometer 79 e (with cement seal) was constructed at the same depth as 79 c (no cement seal). The differences in the hydrographs of these two piezometers are discussed in another section of this report.

During October 1968, 'slug' tests were conducted on all of the piezometers to determine the sensitivity of the piezometers and apparent formation transmissivity. Most of the slug tests were initiated by pouring a known volume of water into a piezometer. The water level decline was measured with an electric tape that was marked with water-soluble ink at a convenient measuring point and at suitable time intervals (as short as 5 seconds in formations with high transmissivity). After performing the slug tests, stagnant water was flushed out and water samples for chemical analysis were collected from most of the piezometers.

## Acknowledgments

The writer is indebted to Mr. J. L. Robinson of Berwick who measured the piezometer water levels once every day for a period of two and one-half years except during extremely bad weather. Dr. G. F. Pinder assisted the writer with the slug tests and collection of water samples.

# GEOLOGY

The Triassic Wolfville Formation consists of interbedded and lensing clean and silty sandstones, arenaceous siltstones, and claystones of continental origin. These beds dip gently to the northwest at 5 to 10 degrees and are overlain at the sites of all piezometer nests by unconsolidated surficial deposits (see logs, Appendix B). Along the Cornwallis River near nest 76, surficial deposits are composed of a few feet of coarse glacial outwash overlain by sandy alluvium that contains some lenses of silt, clay and organic matter. Stratified drift at the site of nest 77 consists mostly of interbedded sand, gravel and a few silt beds. The kame at the site of nest 78 was deposited on a low bedrock ridge and consists mostly of a cobble gravel with some interbedded fine gravel and coarse sand. Stratified drift in the outwash valley is composed of interbedded coarse sand and fine gravel except for a zone from 9 to 15 feet that is composed of interbedded clay, silt, fine sand and gravel.

## HYDROLOGY

### Permeability Tests and Piezometer Response Time

Data from the slug tests were used to plot graphs of $H/H_0$ versus t where H is the head at any time, t, after initiation of the slug test and $H_0$ is the initial head (see Fig. 3). These graphs can be matched to type curves to determine formation transmissivity (Cooper, Bredehoeft and Papadopulos, 1967) and they

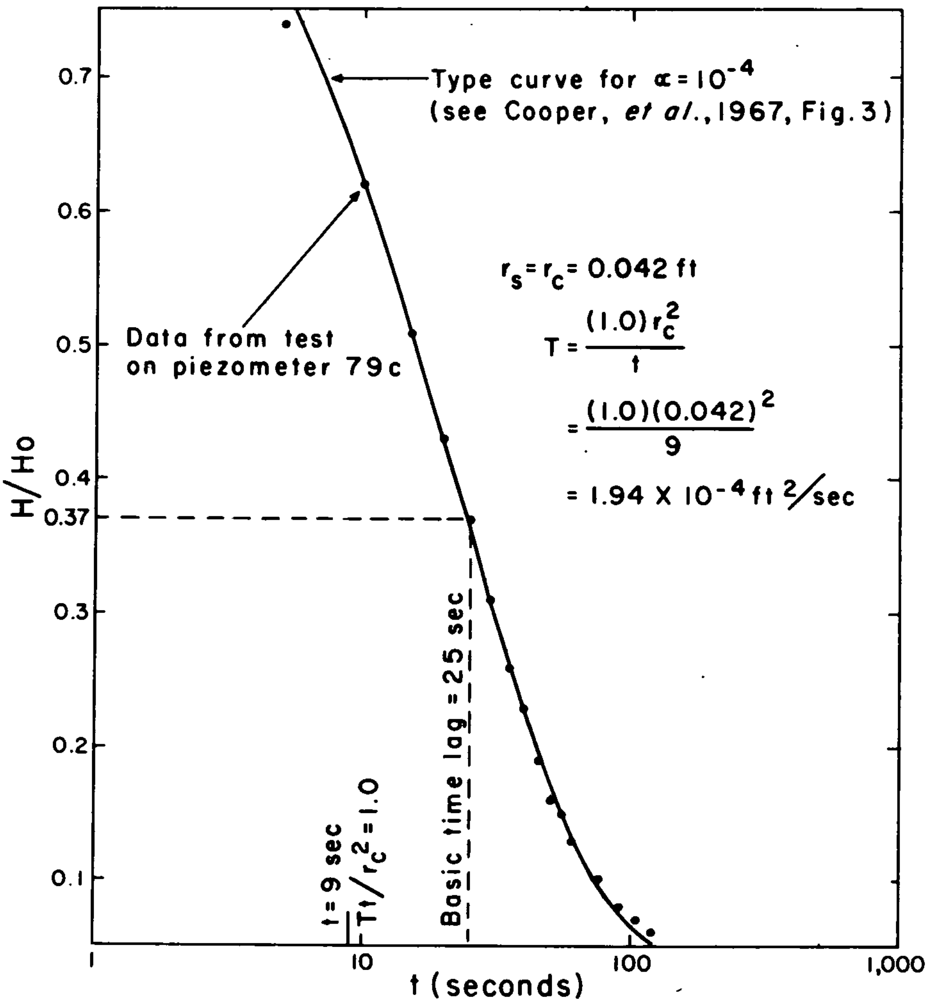

FIGURE 3. Determination of formation transmissivity and piezometer response time from slug-test data.

can also be used to determine the basic time lag, a measure of piezometer sensitivity (Hvorslev, 1951). The calculated transmissivity would be the true formation transmissivity if the piezometer screen were efficient. Perforated plastic pipe is not an efficient screen although it is generally adequate for the main purpose of the piezometers — measuring the pressure head at a point. Consequently a transmissivity value calculated by the method shown in figure 3 is considered to be equal to or less than the true formation transmissivity (assuming the proper type curve has been used) and is termed apparent formation transmissivity in this report.

When the pressure head in a piezometer is different from the formation water pressure, water flows into or out of the piezometer to equalize the pressure. The rate of flow depends on the dimensions of the piezometer, the nature of the piezometer screen, the formation permeability and the pressure difference. The basic time lag is defined as the time required for the pressure to equalize when the original rate of flow is maintained (Hvorslev, 1951, p. 10). Since the rate of flow decreases exponentially with time, the basic time lag of a piezometer is equal to a head ratio ($H/H_0$) of 0.37 (see example in Fig. 3). The time required for the head ratio to decrease to 0.10 is equal to 2.3 times the basic time lag and is a practical objective for field operations (Hvorslev, 1951, p. 37).

Most of the piezometers near Berwick have basic time lags of only a few seconds or minutes (see Table 1). These piezometers, therefore, respond rapidly to any change in hydraulic head. Two piezometers in nest 77 have basic time lags between 1 and 2 hours. Except for periods of rapid change in groundwater levels, the pressure head measured in these piezometers was probably within a few hundredths of a foot of the formation water pressure. Even the three piezometers with basic time lags between 5 and 22 hours seemed to respond as rapidly as other piezometers in the same nest to changes in hydraulic head. A small source of error in measuring those piezometers with a basic time lag of more than a few seconds is the volume of water displaced by the lead weight on the end of the steel tape (in 1-inch diameter piezometers, this weight raises the water level initially by 0.08 foot).

## Annual Groundwater-Level Fluctuations

Groundwater levels in the flood plain adjacent to the Cornwallis River respond rapidly to changes in the river stage (see Fig. 4 for identification of the piezometers in nest 76). Compare, for example, the groundwater hydrographs and the river-stage hydrograph in Appendix A for those periods when the river stage was measured[2]. The time lag between a change in river stage and a corre-

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[2] A yardstick was used temporarily to measure the river stage from November 1966 to February 1967; after October 1967 the river stage was measured in an iron pipe that was directly connected to the river.

Table 1. Information on the Piezometers

| Piezometer | Depth, in feet, below ground level to center of perforated section of pipe | Diameter in inches | Type of Pipe P = flexible plastic I = black iron | Cement grouted | Completed in | Basic time lag s = seconds, m = minutes, h = hours | Apparent formation transmissivity ft$^2$/sec |
|---|---|---|---|---|---|---|---|
| 76 | | | | | | | |
| a | 8 | 1 | P | no | alluvium | 3.2 s | $7.2 \times 10^{-4}$ |
| b | 26 | 1 | P | yes | bedrock | 3.5 s | $5.0 \times 10^{-5}$ |
| c | 20 | 1 | I | yes | alluvium | 1.8 m | $2.7 \times 10^{-5}$ |
| d | 57 | 1 | I | yes | bedrock | 22 h | $5.4 \times 10^{-8}$ |
| 77 | | | | | | | |
| a | 8 | 1 | P | no | stratified drift | 1.2 h | $7.2 \times 10^{-7}$ |
| b | 32 | 1 | P | no | bedrock | | |
| c | 17 | 1 | I | yes | stratified drift | 2.5 m | $2.2 \times 10^{-5}$ |
| d | 50 | 1 | P | yes | bedrock | 12.2 h | $1.0 \times 10^{-7}$ |
| e | 85 | 1 | P | yes | bedrock | 1.4 h | $8.6 \times 10^{-6}$ |
| 78 | | | | | | | |
| a | 47 | 1 | P | no | stratified drift | | |
| b | 67 | 1 | P | no | bedrock | | |
| 79 | | | | | | | |
| a | 8 | 1.25 | I | no | outwash | 5.3 h | $2.6 \times 10^{-7}$ |
| b | 21 | 1 | P | no | outwash | 3 s | $1.1 \times 10^{-3}$ |
| c | 44 | 1 | P | no | bedrock | 25 s | $1.9 \times 10^{-4}$ |
| d | 144 | 1 | P | no | bedrock | | |
| e | 43 | 1 | I | yes | bedrock | 1 m | $7.9 \times 10^{-5}$ |
| f | 58 | 1 | I | yes | bedrock | 12 h | $1.1 \times 10^{-7}$ |

FIGURE 4. Piezometer nest 76 with the Cornwallis River in the background.

sponding change in groundwater levels in adjacent alluvial deposits depends on aquifer diffusivity (Pinder, Bredehoeft and Cooper, 1969). Although the diffusivity of the sandy alluvium in the Cornwallis River flood plain may be an order of magnitude less than that of the glaciofluvial aquifer analyzed by Pinder, et al. (1969), it seems reasonable to assume from their observations (Pinder et al., 1969, p. 853) that the lag time within 12 feet of the Cornwallis River is only a few minutes.

The nearly instantaneous change in hydraulic head in the underlying artesian aquifers with change in river stage is a pressure response (see Harsh, 1969, for a similar example). The area affected by the variable load in the river increases with depth, and conversely, the relative change in pressure for any change in river stage decreases with depth. This is illustrated by the hydrographs for the storm of May 19-21, 1968 (Appendix A). During this storm, the hydrograph of piezometer 76 b (installed at a depth of 26 feet just below the bedrock surface) is similar to those of piezometers 76 a and c (installed in the alluvium). During the same storm, the water level in piezometer 76 d (installed 57 feet below the surface) rose only half as much. It could be argued that this was due to the relative insensitivity of piezometer 76 d (see Table 1), but the response of this piezometer during several storms in June 1968 when its water level rose as much as water levels in the shallower piezometers is evidence to the contrary. The increased response of piezometer 76 d during the June storms can be explained by noting that groundwater levels throughout the area increased much more during the June storms than during the storm in May (e.g. see hydrographs for piezometer nest 79). During the June storms, therefore, piezometer 76 d responded to the general increase in groundwater storage as well as to the changing stage of the Cornwallis River.

The hydrographs of the piezometers in nests 77 and 79 show the nature of groundwater recession and recovery during three years in which the precipitation distribution was different. The hydrographs of groundwater recession in the surficial deposits during the dry summers of 1966 and 1968 are similar. The recession in 1968, however, started a month later due to unusually heavy rains in June that raised groundwater levels by 2 feet. As a consequence, the lowest water levels in 1968 were nearly a foot above those in 1966. In 1967 the lowest water levels were about 2 feet above those in 1966 because of the greater groundwater storage at the end of May 1967. The 1967 recession hydrograph was more irregular due to relatively frequent precipitation but in general was similar to those of 1966 and 1968.

In all three years of record, significant groundwater recharge occurred only after several heavy rains in October at the end of the growing season. The growing season is normally terminated by the first fall frosts that occur from the middle of September to the middle of October (Canada Dept. of Agriculture, Research Station, Kentville, 1961). During the growing season, particularly July, August and September, a soil moisture deficit of 2 inches or more is common. Most of the 2.1 inches of rain that fell on September 1-3, 1967, for example, went to satisfy the soil moisture deficiency because the rains had little effect on groundwater levels.

Groundwater recharge from rain and melting snow continued intermittently throughout the late fall, winter and spring. Haupt (1967) observed that soil frost that develops during the winter may not reduce the permeability of the soil; in fact, some types of soil frost actually increase the soil infiltration capacity. It is apparent from the hydrographs of piezometer nests 77 and 79 that soil frost did not prevent groundwater recharge during the winter. The formation of soil frost from near-surface groundwater, however, may have caused some of the sharp declines in the water table during the winter months.

The recession of hydraulic head in the bedrock at the site of piezometer nest 77 was only about half as great as the recession of the water table in the overlying surficial deposits during the summer of 1968. Similarly, in the outwash valley, the hydrograph of piezometer 79 d shows that the long-term fluctuations in the hydraulic head at a depth of 144 feet below the surface are not as great as they are closer to the surface. The decline in hydraulic head in piezometer 79 d generally began a month after the start of the summer water-table recession, and recovery of the hydraulic head in the fall was much more gradual than recovery of the water table. Although a satisfactory slug test was not performed on this piezometer, the large, short-term fluctuations which were recorded at various times suggest that this piezometer is as sensitive as others installed in the bedrock in this nest.

Poor records and interference from nearby construction resulted in the termination of the measurement of piezometer nest 78 at the end of July 1967. As documented in Trescott (1968), piezometer 78 a was completed in sand and gravel at a point about midway between the annual high and low elevations of the water table. Thus it was dry about half the time. In 1966 all that was recorded in this piezometer was the rapid decay of the water table following recharge from October rains.

The hydraulic head at an elevation of 119 feet in the bedrock was measured in piezometer 78 b. The large, short-term fluctuations of the water level in this piezometer during the summer and fall of 1966 when the hydraulic head at the water table was apparently greater than that in the underlying bedrock were probably a result of the rapid rise and decay of the water table in the surficial deposits. This hypothesis is supported by the relatively smooth hydrograph of piezometer 78 b in the spring of 1967 when the hydraulic head in the bedrock was greater than that in the overlying surficial deposits. Note that the increase in hydraulic head of 9 feet from the summer of 1966 to the following spring in piezometer 78 b was greater than that recorded in any of the other piezometers. This is probably related to the relatively steep regional slope at the site of piezometer nest 78. At the site of piezometer nest 77 where the slope is less (about 70 feet per mile), the maximum range of the water table was 8 feet, and in the outwash valley where the slope is about 18 feet per mile, the maximum range of the water table was only 7 feet.

## Variation in Hydraulic Head with Depth

The hydrographs of the piezometers in nest 76 show that the hydraulic head in the Cornwallis River flood plain increases with depth most of the time — a condition normally expected in a regional discharge area. Only during the rising stage and at the crest of a flood did the gradient temporarily reverse as river water flowed into bank storage.

The vertical component of groundwater flow is upward at the site of nest 77 because the hydraulic head increases with depth during most of the year (cf. the hydrographs for the summer recession of 1968). The pattern of groundwater flow in the upper zone of the bedrock, however, seems to change with the season of the year since the hydraulic head at an elevation of 53 feet in the bedrock was nearly the same and sometimes less than that in the overlying surficial deposits during the winter and spring. In contrast, the direction of groundwater flow in the upper zone of the bedrock at the site of piezometer nest 78 was downward during the summer and fall of 1966 but was upward during the spring of 1967.

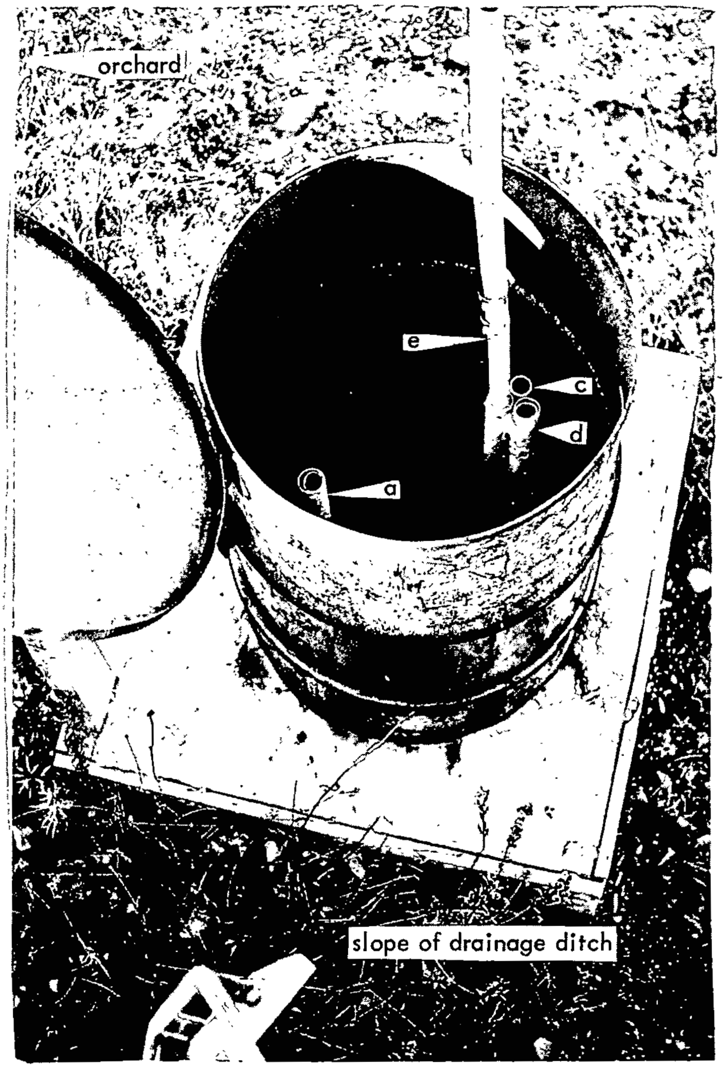


FIGURE 5. Piezometer nest 77 (note the extension used on 77 e when the water level is above the top of the barrel).

The water levels measured in piezometers 77 a and c in the surficial deposits may have been affected by the proximity of the road drainage ditch. The piezometers originally were located at the edge of an orchard about 15 feet from a shallow drainage ditch. In November 1967 the road was reconstructed and the bottom of the ditch was moved within 6 feet of the piezometer nest and deepened, increasing the period during which the ditch receives direct groundwater discharge (see Fig. 5). The observed increase in hydraulic head with depth, however, apparently was not artificially created because the water level in piezometer 77 c remained greater than that in piezometer 77 a during the late summer when the water table was several feet below the bottom of the ditch.

With the exception of short periods, particularly during the winter months, the hydraulic head at the site of piezometer nest 79 in the main body of outwash (from 15 to 31 feet below the surface) was less than the head above the surficial silt and clay beds and also less than the head in the upper zone of the bedrock. The main body of outwash, therefore, is a groundwater drain with flow predominantly westward down the outwash valley. It is evident from the hydrographs of piezometers 79 d, e and f, however, that the influence of the outwash valley on the flow pattern diminishes below an elevation of 110 feet and that the flow pattern in the bedrock varies with the season of the year and from year to year.

Piezometer 79 e, which had a cement seal, was installed in October 1967 about 8 feet from piezometer 79 c, which was backfilled with sand and gravel, to see if their water levels would be identical (see Fig. 2). The two piezometers are set at an elevation differing by 1 foot, but their perforations overlap the same zone. For the first month after piezometer 79 e was installed, the water levels of the two piezometers were nearly identical, but later the water levels differed significantly, particularly during the summer groundwater recession in 1968 when the water levels diverged and at the end of September were nearly a foot apart. The probably explanation for the different water levels is that a good hydraulic connection along the borehole of piezometer 79 c permitted most of the head difference between the outwash and the bottom of the borehole to be dissipated by vertical flow. Indeed, bridging of the sand and gravel, which was not tamped into place, may have prevented complete backfilling of the borehole. The close agreement of the hydrograph of piezometer 79 b (in the outwash) with that of 79 c, and the similarity of the chemical analyses of water samples from these piezometers (discussed in the next section) support this hypothesis. From this experience, it is concluded that piezometer boreholes should be backfilled with material having a permeability equal to or less than that of the formation. In fine-grained formations, cement seals or sand and bentonite seals described by Casagrande (1949) are recommended. Piezometers 78 b and 79 c are the only ones in which relatively permeable backfill material has permitted significant vertical flow along the borehole, resulting in inaccurate measurements of formation water pressure. The relative water levels observed in the other piezometers are reasonable when the stratigraphy and the location of the piezometers in the flow system are considered.

## Digital Models of the Flow System

### Introduction

The groundwater flow system from South Mountain to the Cornwallis River and along the outwash valley was studied by constructing two-dimensional, steady-state digital models. The models are based on theoretical work by Freeze and Witherspoon (1966) who used an explicit iterative technique to solve the finite-difference approximation of the flow equation on a digital computer. The computer program was written by Freeze (1967) and was modified by the writer for use on the IBM 360/50 computer at Dalhousie University, Halifax.

To determine the groundwater flow pattern along any vertical section through an inhomogeneous, anisotropic groundwater basin, the following conditions are assumed (see Freeze, 1967, p. 2):

(1) Groundwater flow in a basin can be represented by a two-dimensional cross-section taken perpendicular to the strike of the water-table surface.

(2) The vertical section is chosen to include the flow paths of all groundwater recharged and discharged along this section (i.e. no flow occurs across the lateral boundaries of the section which are located at the principal groundwater divide and at the center of the principal discharge area, and no flow occurs across a horizontal impermeable basement).

(3) All formations above the impermeable basement have some finite permeability, and permeability contrasts between adjacent formations can be estimated.

(4) The upper boundary of the flow system is the water table which does not fluctuate with time.

Freeze and Witherspoon (1966, pp. 642-643) discussed these assumptions.

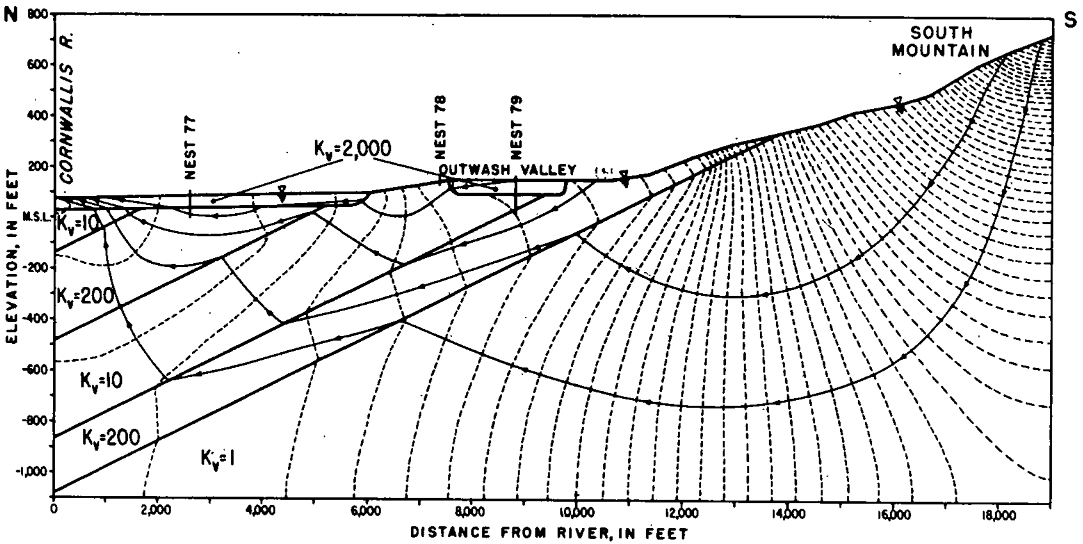
Input data for the digital model include the dimensions of the vertical section, the vertical and horizontal spacing of the finite set of nodes used to represent the section, the location and relative permeability of the various geologic units, the water-table configuration, the initial estimated values of hydraulic head from which a solution is obtained by iteration, and the plotting parameters. The program computes the value of the hydraulic head at each node and a plotting subroutine, modified for use with the Calcomp 565 plotter at Dalhousie University, produces a plot of equipotential lines.

## Regional Groundwater Flow Model

To study the regional groundwater flow near the piezometer nests, a vertical section extending from the crest of South Mountain to the Cornwallis River perpendicular to the strike of the Annapolis-Cornwallis Valley was chosen. The Annapolis-Cornwallis Valley was assumed to be the regional discharge area because North Mountain, a groundwater divide of the same order of magnitude as South Mountain, prevents underflow from the Valley to the Bay of Fundy along the more permeable Triassic sandstones. For the purpose of the model, the impermeable basement was assumed to be at an elevation of 1,100 feet below mean sea level, the estimated elevation of the Paleozoic-Triassic boundary beneath the Cornwallis River. Although groundwater flow undoubtedly occurs in the Paleozoic rocks below an elevation of - 1,100 feet, the potential pattern would be changed little by extending the model to include more of these rocks, particularly since the fracture permeability decreases with depth (see Freeze and Witherspoon, 1967, p. 628). The section chosen violates the assumptions of the mathematical model where it is not perpendicular to the strike of the water table. This is true in the outwash valley where the water table slopes more to the west than to the north. Flow along the outwash valley is considered in the second model.

The horizontal distance of 19,000 feet in the field was represented in the model by 26 nodes, and the vertical dimension of the section, extending from an elevation of - 1,100 feet to 750 feet, was represented by 74 nodes. The stratigraphy, which is complex and unknown in detail over most of the section, was of necessity simplified for the model. The distribution of geologic units in the model and the relative hydraulic conductivity values assigned to them on the basis of previous investigations (Trescott, 1968 and 1969a) are shown in figure 6. The elevation of the water table was determined from direct observation for the section from the Cornwallis River to the outwash valley. It was assumed to be close to the surface from the outwash valley to the crest of South Mountain.

The numerical problem was first solved assuming that all formations are isotropic, but as Freeze and Witherspoon (1966 and 1968) found in modeling their field examples, the resulting potential pattern is not in good agreement with field observations. Anisotropy was introduced by varying the ratio of $K_h$:$K_v$ where $K_h$ and $K_v$ are, respectively, the horizontal and vertical hydraulic conductivity. The axes of anisotropy were assumed to be coincident with the coordinate directions even though the axes of anisotropy are probably slightly skewed (e.g. parallel and perpendicular to the dip of the Triassic strata). The potential pattern obtained when $K_h$ was made equal to 25 $K_v$ was found to be reasonable and is illustrated in figure 6. The vertical exaggeration of 5:1 in figure 6 transforms the section to an equivalent isotropic medium in which flow lines can be drawn orthogonal to equipotential lines (see Maasland, 1957 or Freeze and Witherspoon 1967, p. 631).



LEGEND

| $K_v$ | |
|---|---|
| 2,000 | Glaciofluvial sand and gravel |
| 200 | Sandstone, clean |
| 10 | Sandstone, silty, and arenaceous shale |
| 1 | Granite, slate and quartzite |

(Note: $K_h = 25\ K_v$ in every formation)

| | |
|---|---|
| ——— | Geologic boundary |
| ▼ | Water table |
| - - - | Equipotential line, interval 10 feet |
| —•— | Direction of groundwater flow |

(Note: vertical exaggeration = 5:1)

G.McD.

FIGURE 6. Regional groundwater flow diagram.

The flow lines shown in figure 6 were inserted to illustrate the general pattern of flow and are not intended to be used for quantitative calculations. The four formations used to represent the Triassic strata are only a small fraction of the actual number of beds of varying hydraulic conductivity in the section, but they serve to show the effect of these beds on the flow system. Note in particular the refraction of groundwater flow along the relatively permeable Triassic sandstone strata.

In the model, as in the field, the outwash valley is a groundwater recharge area. The model, however, does not show the complex variation in hydraulic head with depth in the bedrock because of the assumptions of simplified stratigraphy and flow only in the plane of the diagram. At the site of piezometer nest 78, the actual variation in hydraulic head with depth in the bedrock is not known because only one piezometer was installed below the bedrock surface, but that predicted by the model appears to be reasonable.

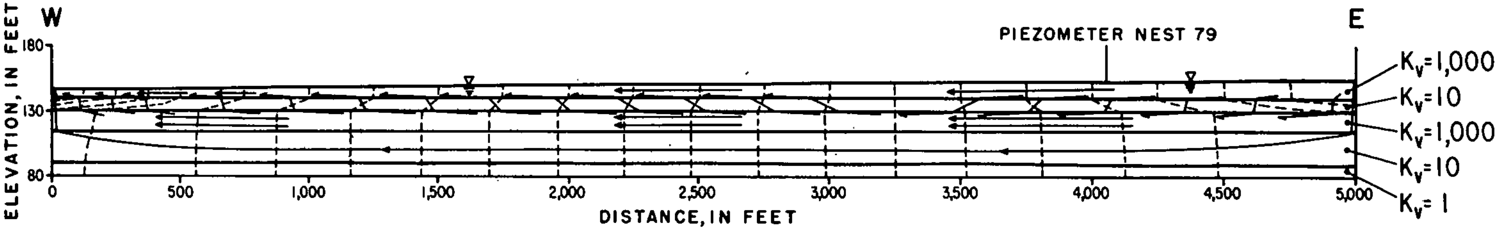
The groundwater discharge area in the model is limited to a zone within 3,000 feet of the Cornwallis River. The model, therefore, correctly predicts the upward component of the hydraulic gradient observed at the sites of piezometer nests 76 and 77 (nest 77 is about 2,600 feet from the Cornwallis River). The actual variation in hydraulic head with depth, of course, is different from that observed in the field because of the simplified stratigraphy used in the model.

## Groundwater Flow in the Outwash Valley

The water table slopes about 18 feet per mile to the west-southwest in the outwash valley (Trescott, 1968, p. 77). Although it also slopes to the north, flow in that direction is restricted by a low bedrock ridge. To model the component of groundwater flow along the outwash valley, a section 5,000 feet long and 70 feet deep was chosen. Nodal spacing was 500 feet in the horizontal dimension and 5 feet in the vertical dimension. Since the outwash valley parallels the strike of the Triassic rocks, the stratigraphy was assumed to be horizontal (see Fig. 7).

The eastern termination of the section is probably close to the groundwater divide between drainage westward to Rockland Brook and drainage eastward to Rochford Brook (Fig. 1). The western termination of the section is arbitrary because the outwash valley continues several miles to the west. The lower boundary of the section is at an elevation of 80 feet in a shale bed assigned a relative permeability of 1. Although this is not the lower limit of groundwater flow, it is a suitable limit for the purpose of this model.

As in the model of regional groundwater flow, the potential pattern in this model was not reasonable until $K_h$ was made greater than $K_v$. The loss of hydraulic head across the silt and clay beds in the model is similar to that observed in the field at the site of piezometer nest 79 for a ratio of $K_h : K_v = 25:1$.



## LEGEND

| $K_v$ | |
|---|---|
| 1,000 | Glaciofluvial sand and gravel |
| 10 | Sandstone (silty), arenaceous siltstone, and interbedded sand, silt and clay |
| 1 | Shale |

(Note: $K_h = 25 K_v$ in every formation)

—— Geologic boundary

▽ Water table

- - - Equipotential line, interval 0.5 foot

—◄— Direction of groundwater flow

(Note: vertical exaggeration = 5:1)

G.MCD.

FIGURE 7. Groundwater flow pattern in the outwash valley.

The resulting flow pattern is shown in figure 7 at a vertical exaggeration of 5:1. Flow lines are included to show the direction of groundwater flow and are drawn orthogonal to the equipotential lines.

Figure 7 illustrates that groundwater flow is concentrated in the sand and gravel aquifers. In the part of the section from 3,250 to 5,000 feet, including the site of piezometer nest 79, groundwater flows downward from the upper sand and gravel aquifer across the silt and clay beds to the lower aquifer. From about 1,000 feet west of piezometer nest 79 to the western terminus of the model, groundwater discharges upward across the silt and clay beds into the upper aquifer. The discharge area in the model therefore, is the same as that in the field because this section of the outwash valley contains Rockland Brook (see Fig. 1). The potential pattern in the bedrock, however, is not depicted correctly because only a few of the Triassic beds are included in the model and the model does not consider the potential pattern north and south of the outwash valley. Groundwater flow in this area could be studied best by constructing three-dimensional models such as the one in Freeze and Witherspoon (1966). Such a model would show, for example, that the outwash valley is a local discharge area west of piezometer nest 79 due to a groundwater divide on the north side of the valley west of piezometer nest 78.

# CHEMICAL QUALITY OF GROUNDWATER

## Sampling Procedure and Reliability of Samples

One of the objectives of this study was to determine if there is any relation between the chemical and physical quality of groundwater and its location in the groundwater flow system. Water samples were obtained from most of the piezometers with an air pump run by the compression of an automobile engine (see Trescott and Pinder, 1970, and Fig. 8). Although air pressure was used to obtain the sample shown in figure 8, most of the samples were obtained by the air-lift method. Consequently the dissolved gas content of the groundwater was altered in the process of obtaining the samples. Dissolved gases were not determined in the chemical analyses, but they affect other aspects of the chemical quality such as the pH and the amount of calcium bicarbonate in solution.

Shallow groundwaters near the Cornwallis River (from piezometers 76 a and c) are calcium bicarbonate in composition (see Fig. 9 and Appendix C). The distinguishing aspect of these samples is their relatively high content of dissolved iron (0.36 ppm in the sample from piezometer 76 a and 2.54 ppm in the sample from piezometer 76 c) and the 50 ppm sulphate in the sample from piezometer 76 a. It is possible that these aspects of the chemical quality were introduced during floods by infiltrating river water because the river receives the effluent from the Berwick sewage-disposal lagoon. It seems more likely, however, that the sulphate and iron are related to the decomposition of organic matter buried in the alluvial deposits.

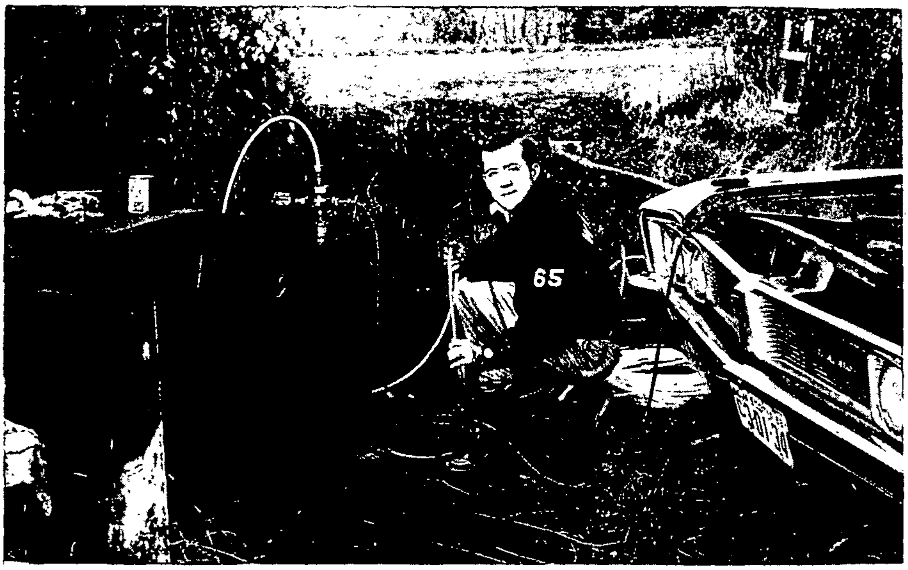


FIGURE 8. Pumping water from piezometer 76 d with air pressure.

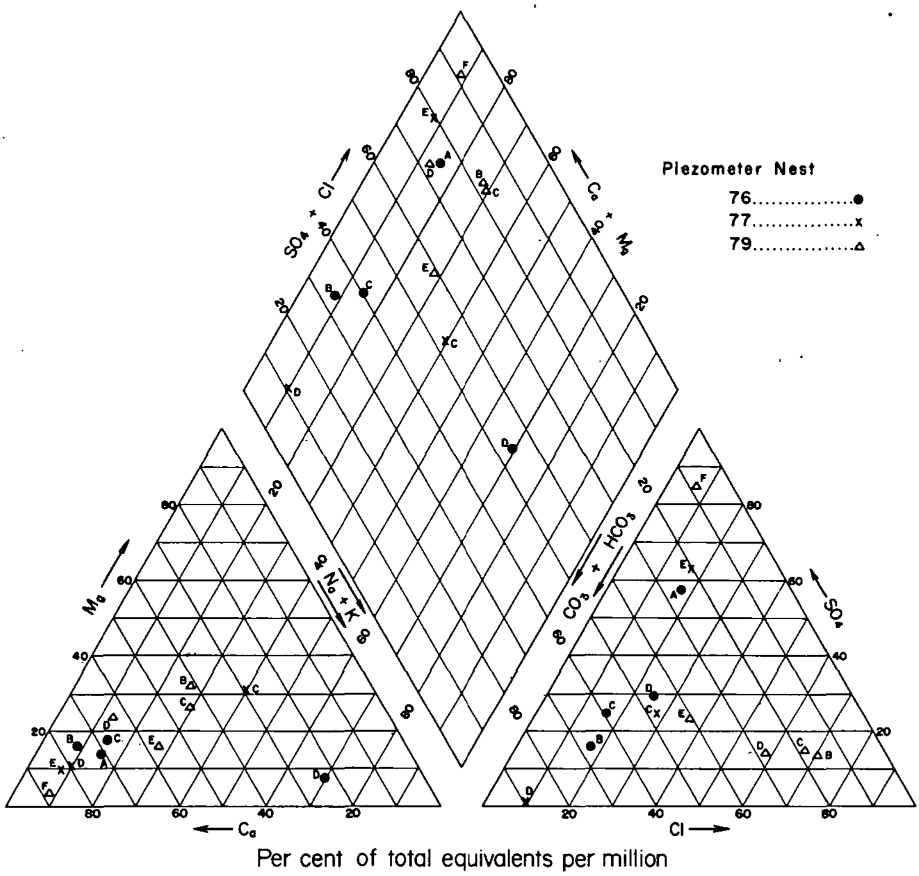


FIGURE 9. Trilinear plot of chemical analyses of water samples.

The sample from piezometer 76 d is probably not representative of the groundwater at a depth of 57 feet because it was not possible to flush out all of the stagnant water in this piezometer before taking a sample. The field pH value of 10+, for example, indicates that the sample was probably contaminated due to reaction of the cement seal with the surrounding groundwater. Water from the bedrock in this area should have a composition more like that from piezometers 76 b and 77 e.

The sample from piezometer 77 c in glacial outwash is a soft water containing few dissolved solids and is typical of the quality of groundwater found in shallow sand and gravel deposits in the Valley (Trescott, 1968). The sample from piezometer 77 d probably has been contaminated by solution of the cement seal because of the high pH and the unusually large amount of dissolved calcium carbonate and bicarbonate.

In comparing the chemistry of water samples from piezometer nest 79 in Appendix C and figure 9, it can be noted that the chemical quality of water from piezometer 79 c is nearly identical to that from piezometer 79 b but is significantly different from the quality of water from piezometer 79 e. This lends strong support to the contention that there is a good hydraulic connection (perhaps through an open hole) between the outwash and the bottom of the borehole containing piezometer 79 c. Furthermore, the samples from piezometers 79 b and c are the only ones that contain a significant amount of nitrate which has probably been leached from fertilizer spread on the soil

Compared to the samples from piezometers 79 d and e, the sample from piezometer 79 f contains a relatively large amount of calcium sulphate and has a high pH. This may be another case of contamination from the cement seal. The other possibility, however, is that the calcium sulphate has come from solution of a gypsum lens although gypsum lenses in Triassic rocks are normally confined to the Blomidon Formation (see Trescott, 1969a, p. 29).

## Relation of Groundwater Quality to the Flow System

Of the good (uncontaminated) samples of water from the bedrock, the two in the recharge area (from piezometers 79 d and e) contained about half the dissolved solids and hardness found in water samples from piezometers 77 e and 76 b in the discharge area. This is reasonable because groundwater in discharge areas has travelled a greater distance and has had more time to dissolve minerals from the porous media through which it has passed. The chemistry of many more groundwater samples from various parts of the flow system should be examined to determine whether this is a general relationship. Additional study is also necessary to establish whether there is a significant change in relative chemical composition (such as predicted by Chevotarev, 1955) with distance from the recharge area. The writer (Trescott, 1968 and 1969a) has shown that the chemical composition of groundwater in this area is related to the hydrostratigraph unit in which it is found. Consequently, such studies should be confined to areas where the groundwater flow system is in one hydrostratigraphic unit to eliminate variation due to different hydrostratigraphic units.

The most consistent difference in quality between samples from the recharge area and those from the discharge area is their temperature. The temperature of samples from the outwash valley recharge area was 47°F, 3°F greater than the mean annual air temperature but 5°F less than the temperature of waters from piezometer nests 76 and 77 in the discharge area. The increase in water temperature is probably an indication of the depth of circulation of the flow system. The possibility of mapping recharge and discharge areas by measuring the temperature of groundwater deserves further study.

# SUMMARY, RECOMMENDATIONS AND CONCLUSIONS

From the experience in installing and measuring the piezometers near Berwick, it is recommended that a piezometer be constructed of rigid pipe and that the screen be a commercial well point if one of the objectives of the study is to measure formation transmissivity. An efficient screen also improves piezometer sensitivity. Although more difficult, it is recommended that all of the piezometers in a nest be installed in the same borehole because (1) all of the water levels can be measured from a common measuring point, (2) the job of measuring the piezometers in the winter is made easier, and (3) the piezometers can be better protected from vandalism. Piezometers should be isolated in the zone where the pressure is being measured by sealing the borehole above the piezometer screen. Cement provides a good seal but may react with the surrounding groundwater and contaminate samples of water pumped from the piezometer for chemical analysis. If water samples are to be collected, a sand and clay seal is probably better.

The hydrographs of the piezometers illustrate groundwater depletion and recharge during three years, each of which had precipitation distribution significantly different from the others. The shape of the groundwater recession curve each year was similar, but the low water level at the end of the recession depended (1) on the amount of groundwater in storage at the start of the recession (cf. 1966 and 1967), and (2) on the time when the final recession started (June in 1966 and 1967, but July in 1968). Heavy rains in September had little effect on groundwater levels because of a soil moisture deficit of two or more inches during that month. Groundwater recharge each year began in October after frosts had terminated the growing season and rains had satisfied the soil moisture deficit. It continued intermittently during the winter (even when the soil was frozen) and spring.

The maximum range in the water table during the period of record was 8 feet in outwash deposits at the site of piezometer nest 77 where the slope is about 70 feet per mile, 7 feet in the outwash valley where the slope is about 18 feet per mile, and 6 feet in the alluvium adjacent to the Cornwallis River. The maximum annual change in hydraulic head in the Triassic rocks was generally less than the fluctuation of the water table in the overlying surficial deposits at the sites of piezometer nests 77 and 79. At the site of piezometer nest 78 where the slope of the water table is relatively steep, the hydraulic head in the bedrock increased 9 feet from the summer of 1966 to the spring of 1967. At the site of piezometer nest 76, the change in hydraulic head in the bedrock relative to a change in river stage decreases with depth.

Groundwater flow from South Mountain to the Cornwallis River and along the outwash valley was investigated with two-dimensional, steady-state digital models. The location of recharge and discharge areas in the models is in general agreement with field observations, but the actual variation in hydraulic head with depth is not predicted by the models because of the simplified stratigraphy and permeability distribution assumed in the models. Groundwater flow in the vicinity of the piezometer nests would be depicted best with a three-dimensional model because of the component of groundwater flow along the outwash valley at right angles to the regional flow system. The flow pattern is further complicated by the fact that the outwash valley is a recharge area at the site of piezometer nest 79, but is a local discharge area to the west.

For larger and more detailed models of the flow system, it is recommended that the digital model developed by Pinder and Bredehoeft (1968) be used to determine the potential distribution because (1) more detailed stratigraphy can be inserted in their model, (2) the hydraulic head values can be stored as single precision variables in their model, and (3) for large models, the numerical method they used requires less computer time than the one Freeze (1967) used (see Douglas and Peaceman, 1955).

The hardness and dissolved solids content of groundwater samples collected from piezometers in Triassic rocks increases with distance from the recharge area. In addition, the groundwater seems to have acquired a significant amount of heat in its passage through the regional flow system since the temperature of waters in the discharge area was 5°F greater than the temperature of waters in the recharge area. Both the change in water chemistry (including possible changes in dominant ions) and the change in temperature as groundwater passes through the flow system need further investigation.

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## APPENDIX C. CHEMICAL ANALYSES OF GROUNDWATER SAMPLES FROM THE PIEZOMETERS

| Index No. | Grid Location | Area | Depth of Well (feet) | Aquifer | Date Sampled | Analyses in parts per million (ppm): Ca | Mg | Na | Fe | Mn | $SO_4$ | Cl | $NO_3$ | Alkalinities: Phenol-pthalein as $CaCO_3$ | Alkalinities: Methyl Orange | Hardness | Specific Conductance (mhos x $10^{-5}$) | pH: Field | pH: Lab | Field Temp. °F | Colour | Turbidity | Ions in equivalents per million (epm): Cations: Ca | Cations: Mg | Cations: Na | Anions: $SO_4$ | Anions: Cl | Anions: $NO_3$ | SSP | SAR |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 76a | 21H2A39N | Berwick | 8 | River alluvium | Oct.23,68 | 36.1 | 3.9 | 9.1 | 0.36 | T | 50 | 11.5 | T | 0 | 46 | 106.0 | 30 |  | 7.6 | 52 | 30 | 19 | 1.80 | 0.32 | 0.40 | 1.04 | 0.32 |  | 16 | 0.39 |
| 76b | ″ | ″ | 26 | Triassic sandstone | Oct.23,68 | 51.5 | 5.6 | 6.5 | 1.10 | 1 | 17 | 12.4 | T | 6 | 130 | 151.6 | 38 | 8.6 | 8.1 | 52 | 5 | 90 | 2.57 | 0.44 | 0.28 | 0.35 | 0.35 |  | 9 | 0.23 |
| 76c | ″ | ″ | 20 | River alluvium | Oct.23,68 | 38.5 | 4.3 | 9.3 | 2.54 | T | 22 | 10.6 | T | 4 | 104 | 113.6 | 32 | 8.6 | 8.0 | 52 | 10 | 0 | 1.92 | 0.35 | 0.40 | 0.46 | 0.30 |  | 15 | 0.38 |
| 76d | ″ | ″ | 57 | Triassic sandstone | Oct.23,68 | 6.1 | 1.3 | 21.2 | 0.03 | T | 18 | 10.6 | T | 2 | 54 | 20.4 | 28 | 10+ | 8.0 | 52 | 10 | 0 | 0.30 | 0.11 | 0.92 | 0.37 | 0.30 |  | 69 | 2.03 |
| 77c | 21H2A39B | ″ | 17 | Glacial outwash | Oct.23,68 | 9.8 | 6.1 | 14.9 | 0.02 | T | 21 | 16.8 | T | 12 | 52 | 49.6 | 42 | 10 | 8.9 | 53 | 5 | 32 | 0.49 | 0.50 | 0.65 | 0.44 | 0.50 |  | 40 | 0.92 |
| 77d | ″ | ″ | 50 | Triassic sandstone | Oct.23,68 | 119.1 | 9.7 | 17.2 | 0.03 | T | 6 | 49.6 | T | 348 | 390 | 337.2 | 217 | 10+ | 11.8 | 52 | <5 | 0 | 5.94 | 0.80 | 0.75 | 0.12 | 1.40 |  | 10 | 0.41 |
| 77e | ″ | ″ | 85 | ″ | Oct.23,68 | 58.2 | 4.2 | 6.6 | 0.05 | T | 89 | 17.7 | T | 0 | 62 | 162.4 | 44 | 8.0 | 8.0 | 53 | <5 | 41 | 2.90 | 0.35 | 0.29 | 1.85 | 0.50 |  | 8 | 0.23 |
| 79b | 21H2A34C | ″ | 21 | Glacial outwash | Oct.23,68 | 16.0 | 7.2 | 12.1 | 0.50 | T | 9 | 34.6 | 4 | 0 | 22 | 69.6 | 30 | 5.5 | 7.2 | 47 | <5 | 26 | 0.80 | 0.59 | 0.53 | 0.19 | 0.98 | 0.065 | 27 | 0.63 |
| 79c | ″ | ″ | 44 | Triassic sandstone | Oct.23,68 | 18.3 | 6.7 | 13.8 | 0.03 | T | 9 | 30.1 | 8 | 0 | 24 | 73.2 | 30 | 5.6 | 7.0 | 47 | 5 | 38 | 0.91 | 0.55 | 0.60 | 0.19 | 0.85 | 0.129 | 29 | 0.70 |
| 79d | ″ | ″ | 144 | ″ | Oct.23,68 | 23.4 | 5.2 | 5.3 | 0.16 | T | 3 | 9.8 | T | 2 | 8 | 79.6 | 21 | 8.5 | 8.1 | 47 | 5 | 41 | 1.17 | 0.43 | 0.23 | 0.06 | 0.27 |  | 13 | 0.26 |
| 79e | ″ | ″ | 43 | ″ | Oct.23,68 | 18.3 | 2.2 | 9.6 | 1.43 | T | 15 | 17.7 | T | 0 | 56 | 54.8 | 22 | 7.0 | 7.6 | 47 | 10 | 27 | 0.91 | 0.18 | 0.40 | 0.31 | 0.50 |  | 28 | 0.54 |
| 79f | ″ | ″ | 58 | ″ | Oct.23,68 | 100.4 | 2.3 | 10.5 | 0.01 | T | 260 | 15.1 | T | 8 | 34 | 200 | 70 | 9.8 | 7.5 | 48 | <5 | 169 | 5.01 | 0.19 | 0.46 | 5.4 | 0.43 |  | 8 | 0.28 |

T = concentration < 0.01 ppm   SSP = soluble sodium percentage   SAR = sodium adsorption ratio