HYDROGEOLOGY OF THE WINTER RIVER BASIN

PRINCE EDWARD ISLAND

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ABSTRACT

A detailed study of the Winter River basin was conducted (1982-1987) to describe the physical and geochemical hydrogeology of its sedimentary red bed aquifer to determine the safe yield of existing well fields, assess the potential for new well field development, and give directions to well field protection. Field and laboratory studies addressed questions of fracture and matrix properties of the aquifer, distribution of hydraulic head and hydraulic conductivity with depth, and the role of surficial deposits. Evaluated were the effects of well field operation on water table position, groundwater-surface water interaction and hydrologic budget. Inorganic and environmental isotope geochemistry aided interpretation of the groundwater flow system.

The aquifer appears to behave as a classical unconfined flow system having local, intermediate and regional components. The active groundwater flow system is fully contained within the surface water drainage basin. Groundwater withdrawals are reducing baseflow to streams by 54 to 70% in the upper portion of the basin, but pumping does not exceed annual recharge. The well fields have a stable average annual water level. Good potential exists for development of future supply in the watershed but withdrawals should be limited to 50% of average annual recharge. Groundwater protection zones are strongly recommended.

1. INTRODUCTION

1.1 Background and Objectives

The province of Prince Edward Island relies almost exclusively on groundwater for domestic, municipal and industrial water supply. Charlottetown, the capital city, and several surrounding municipalities obtain all or a portion of their water supply from well fields at Brackley and Union in the Winter River basin, north of the city (Figure 1).

In the 1970s, the Charlottetown Water Commission (CWC) and the Water Resources Branch of the provincial Department of the Environment expressed concern about the future planning and management of these groundwater supplies. Questions were raised about the capacity of the existing well fields, their effects on streamflow and the water budget, their effects on other wells in the area, the availability of additional water supply, and the risk to groundwater quality posed by encroaching development.

In 1976, Environment Canada conducted a planning study [1] which documented the existing situation and defined several water management issues as perceived at that time. In 1978, Callan [2] evaluated existing yield test data from production wells at Union and Brackley well fields.

The current study of the hydrogeology of the Winter River basin began in 1981-82 as a joint program of the Water Resources Branch, Prince Edward Island Department of the Environment, (then the Department of Community & Cultural Affairs) the Charlottetown Water Commission, the Department of Earth Sciences, Memorial University of Newfoundland, and the Water Planning and Management Branch (Atlantic) of Environment Canada. Over the following five field seasons, a series of projects was carried out to define the various aspects of basin hydrogeology and to address the water management issues raised. The specific objectives of the program were:

(1) to determine the safe yield of the well fields at Brackley and Union,

(2) to define the potential for future water supply development in the Winter River basin,

(3) to provide direction on the need to protect groundwater quality, and

(4) to gain a better understanding of the hydrogeology of the red bed aquifer and thus improve the capability of water resource agencies in the province to make informed water management decisions.

1.2 Acknowledgements

The Winter River Basin Study was conducted through a work-shared agreement between the Province of Prince Edward Island, Environment Canada (Inland Waters Directorate, Atlantic) and the Charlottetown Water Commission, with the Department of Earth Sciences, Memorial University of Newfoundland, involved in the design and implementation of a number of projects.

A study of this magnitude required the committment and involvement of many people from each of the associated agencies: Don Jardine, Richard Gaudet and Gordon Jenkins of the provincial Water Resources Branch; Terry Hennigar, John Gibb and Frank Cruickshanks of Environment Canada; Walter Cox, Chairman of the Charlottetown Water Commission and Reagh Clark, General Manager; Dr. John Gale and Dr. John Welhan, Memorial University of Newfoundland; and the many summer students who worked on the various projects.

I would like to thank Sid MacDonald for his drafting expertise, Stan Vass for editorial assistance and Edna Sprake, Trudy Gordon and Donna Bradley for word processing.

Finally, I would like to express my appreciation to Bill Howard, Executive Director; Ken DesRoches, Deputy Minister; and Gilbert R. Clements, Minister of the Environment, for allowing me leave from regular duties to complete this report.

2. PHYSIOGRAPHY

2.1 Location and Topography

The Winter River basin is located in central Prince Edward Island, north of the city of Charlottetown (Figure 1). The watershed includes portions of the municipalities of Winsloe, Sherwood, East Royalty, Brackley, Union Road, York and several other unincorporated communities. From headwater tributaries in the Brackley-Winsloe region, the river drains an area of about 63 km^2 of Queens County and flows northeasterly to the Gulf of St. Lawrence through its estuaries in Winter Bay and Tracadie Bay.

The topography of the basin consists of rolling hills with slopes up to 8%. Average slopes are 3% to 5%. Elevations range from sea level in the tidal portion of the river to 60m in the Winsloe area. The basin is about 13 km long and averages 5 km in width. The main stem of the Winter River is about 21 km long, with an average gradient of 2 m/km. The lower 4.3 km of the main stem, from Pleasant Grove to Corran Ban bridge, are tidal. The basin is drained by a relatively simple system of streams of the 3rd order, with a bifurcation ratio of 5, characteristic of watersheds in which geological features do not distort the drainage pattern [1]. There are small dams located at Officers Pond, Hardy's Pond, York, and Brackley well field.

2.2 Land Use

The Winter River watershed is a predominantly rural area consisting of 65-70% agricultural land, 25% forested land, and less than 10% built up areas. The largest commercial area is the Charlottetown Airport in the southwest corner of the watershed (Figure 1). Agricultural land use is largely mixed farming, with 45% of the land in crop production (mostly mixed grain and hay), 20% in pasture and 20% of farm units in woodland. Potatoes are a very small component of farm land use. The forested land, primarily located in the northeastern portion of the basin and along the river, consists mostly of softwood species.

The watershed is highly productive of aquatic furbearers and waterfowl, particularly in the Officers Pond and Hardy's Pond area. A productive brook trout population provides an important sports fishery in both open reaches of the river and the various dam locations. The productivity of the trout population in Prince Edward Island rivers is, in general, the result of both ample nutrient input and the moderating effect of groundwater baseflow on water quality, water temperatures, and maintenance flow.

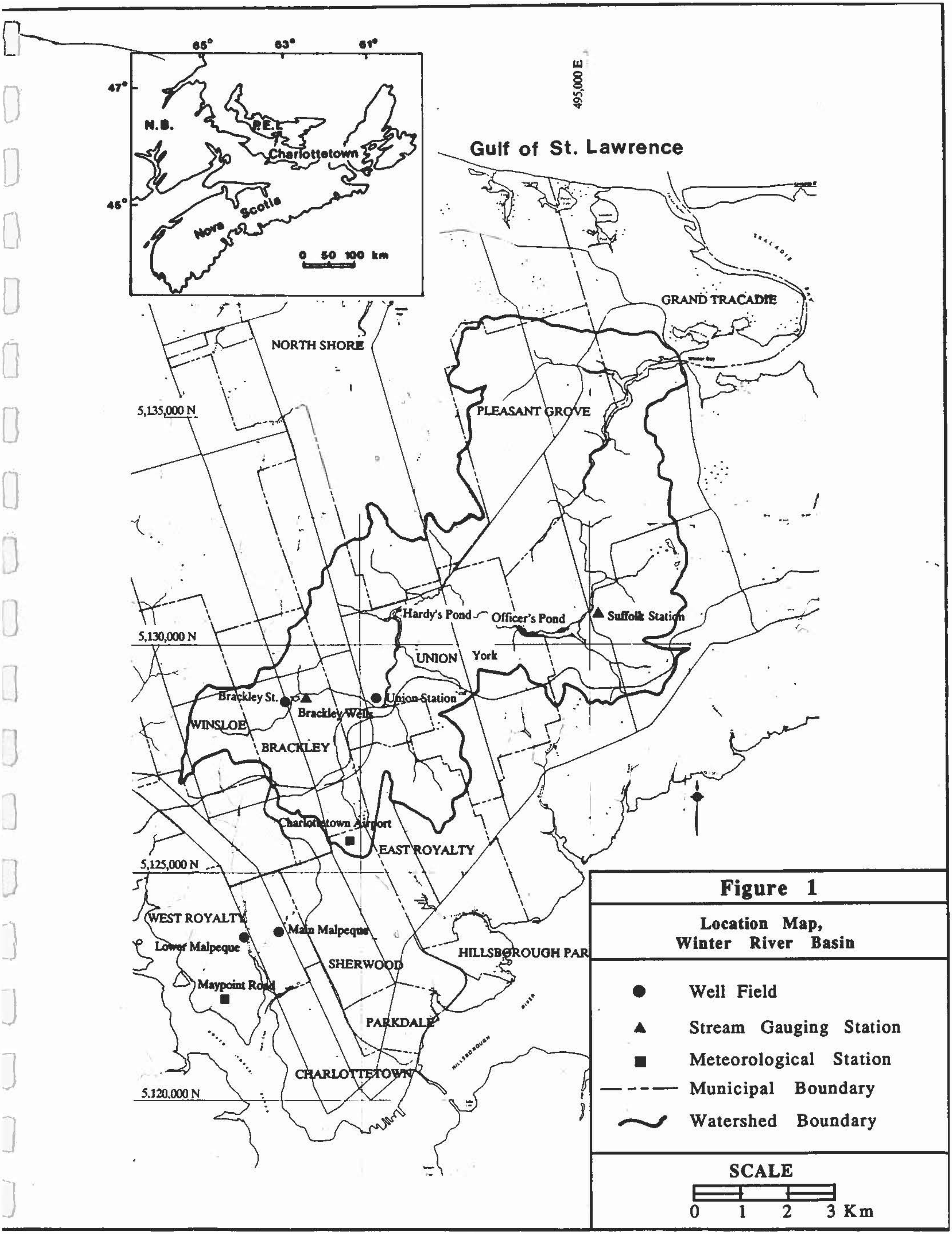


Figure 1

Location Map,
Winter River Basin

Commercial and industrial development in the watershed has not been extensive, although several small enterprises do exist. Ribbon development is the characteristic residential development pattern, but a number of small subdivisions have been developed in the Brackley, Union and York areas. The population living within the watershed is estimated at 800 to 1000 people, with residential and commercial growth pressures felt particularly in the Brackley, Sherwood and East Royalty areas within and near the southwestern margin of the watershed. The municipalities of Sherwood, East Royalty, Brackley and Winsloe have adopted official zoning plans for their areas.

2.3 Climate and Streamflow Characteristics

The climate of Prince Edward Island, including the Winter River basin, is described as humid-continental, with long and fairly cold winters and warm summers. Table 1 summarizes precipitation and temperature data collected at the Charlottetown Airport Meteorological Station (Figure 1). Mean annual precipitation for the period 1951-1980 was 1169 mm with most precipitation occuring in November and December. Mean annual temperature is about 5.4°C. Figure 2 shows the variation in average annual precipitation at this location for the period 1941 to 1988.

Streamflow data for the Winter River have been collected at Water Survey of Canada stream gauging stations located at Suffolk (01CC002) and Brackley well field (01CC003) (Figure 1) since 1967 and 1968 respectively. The drainage area for the Brackley gauging station sub-watershed is 4.92 km^2 and for Suffolk 37.5 km^2. Figure 3 shows the mean monthly basin yield at those stations for the period of record to 1982. Basin yield at the Brackley gauging station is lower in the summer months, and on an annual basis, than at Suffolk. The daily flow duration curve [3] for the Suffolk gauging station is presented in Figure 4. Further discussion of streamflow characteristics as they relate to the hydrologic budget for the watershed is contained in Section 5.

Table 1. Historical Precipitation Data: Charlottetown 'A' Station, 30 year norm (1951-1980).

Period	Rainfall (mm)	Snowfall (m)	Total Precipitation (mm)	Average Daily Temperature (C°)
January	42.7	76.8	116.8	-7.1
February	32.8	65.8	97.4	-7.5
March	31.8	61.6	95.3	-3.1
April	53.9	27.3	81.8	2.3
May	81.3	2.1	83.6	8.5
June	79.9	0	79.9	14.5
July	84.3	0	84.3	18.3
August	88.1	0	88.1	17.8
September	86.3	0	86.3	13.5
October	103.8	2.6	106.4	8.1
November	97.4	21.6	120.5	2.9
December	58.8	72.8	129	-3.9
Year	841.1	330.6	1169.4	5.4

Source: Environment Canada, Atmospheric Environment Service

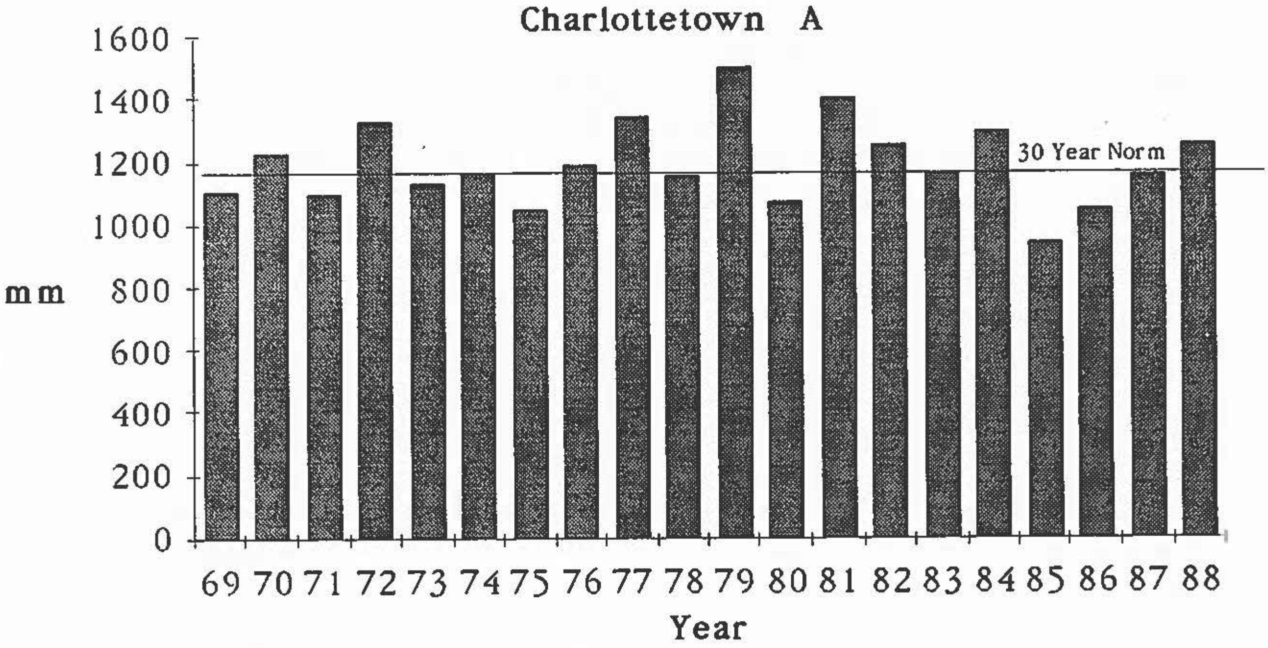


Figure 2. Average annual precipitation, Charlottetown A meteorological station, 1969 - 88.

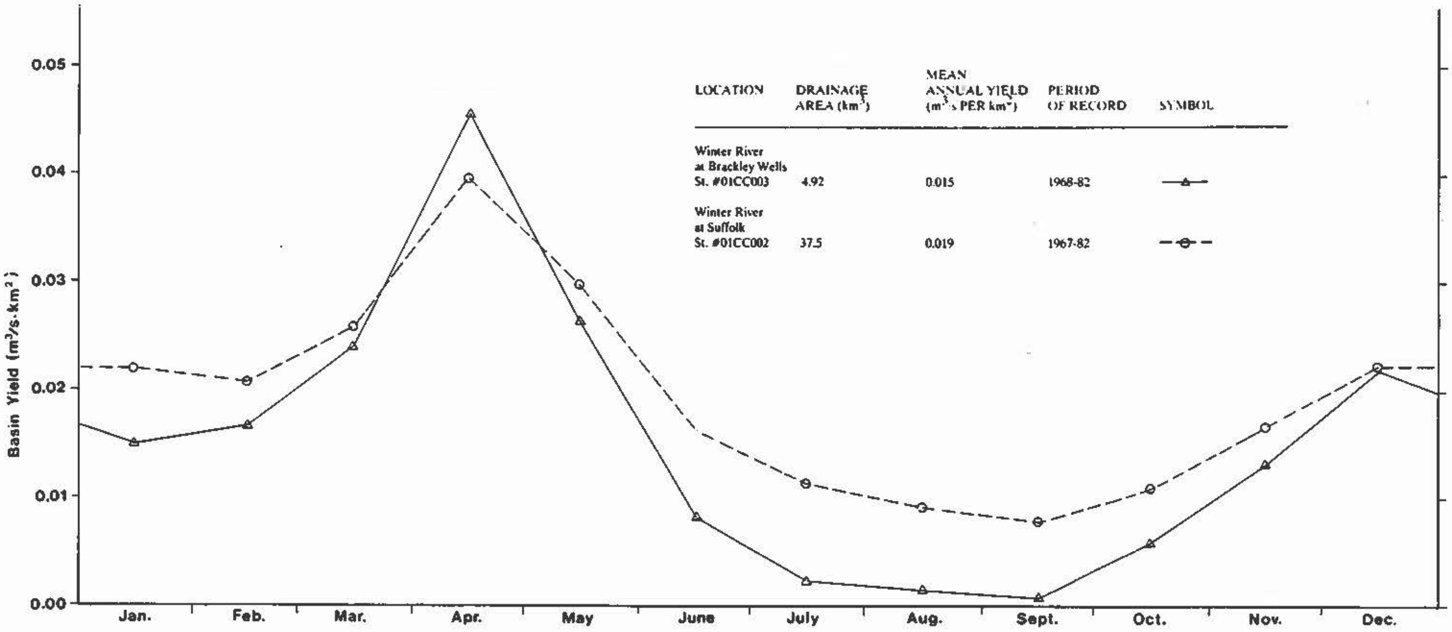


Figure 3. Mean monthly basin yield, Brackley and Suffolk gauging stations.

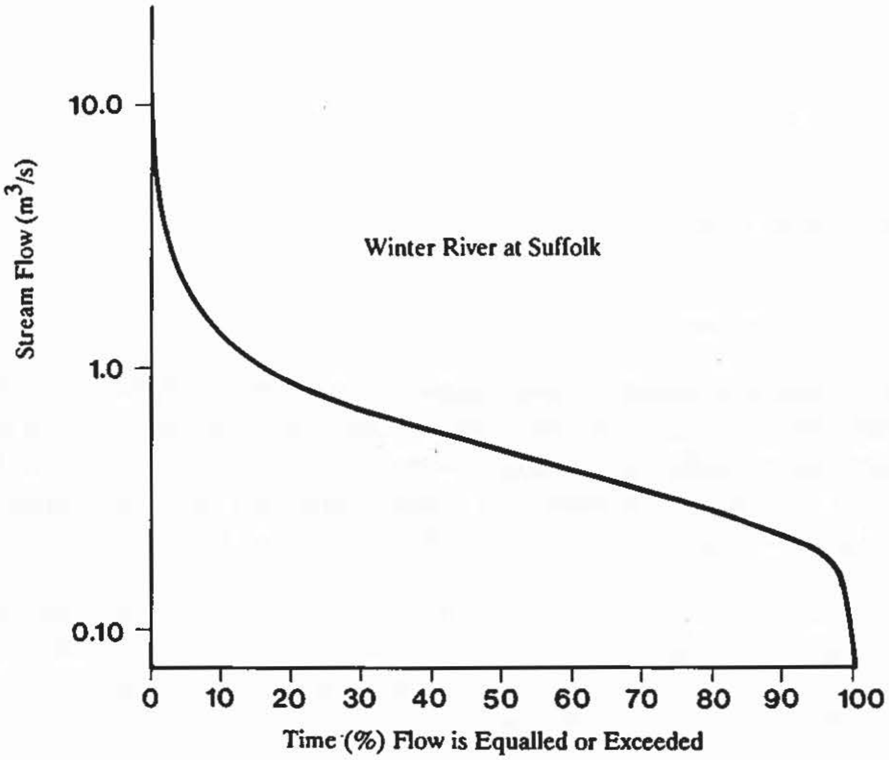


Figure 4. Daily flow duration curve, Winter River at Suffolk.

3. GEOLOGICAL SETTING

3.1 Bedrock Geology

3.1.1 Previous Work

Prince Edward Island is a cresent-shaped cuesta of continental red beds, Upper Pennsylvanian to Middle Permian in age, dipping to the northeast at about one to three degrees [4]. The constituent mineral grains of the bedrock were carried by streams and rivers from highlands in present day New Brunswick and Nova Scotia and deposited under oxidizing conditions in the low-lying area which is now Prince Edward Island [5].

The red beds, composed of varying amounts of sandstone, siltstone, claystone, intraformational breccias and conglomerates, exhibit rapid lateral and vertical facies changes and strong cross-bedding features. There are no recognizable marker beds and little attempt has been made to subdivide the several thousand metres of red beds into mapable units [4].

The most recent and complete review of the bedrock geology of Prince Edward Island has been conducted by van de Poll [4]. He mapped the red bed units as an upwards-fining series of cyclic deposits containing four 'megacycles'. Figure 5 is derived from van de Poll's report and shows the location of the Winter River basin with respect to this assessment of Prince Edward Island geology. The basin is underlain by portions of Megacyclic Sequences III and IV of the Lower Permian Pictou group. These sequences are described by van de Poll as consisting of conglomerate, sandstone and siltstone red beds. Exposures of conglomerates are limited to a number of gravel pits in the Bedford - York area.

A 3400 m petroleum exploration well (Hudson's Bay-Fina *et al-* Green Gables #1) was drilled in 1972 near Rustico Harbour, about 15 km from the Winter River basin. It encountered over 850 m of Pictou group red beds, mainly sandstone, about 1000 m of Pictou group gray sandstone, shale and coaly fragments, and 1500 m of Pre-Pictou sandstone, shale and evaporites [4].

Prior to this current study, several investigations provided information on the bedrock geology of the Winter River basin. These include geological and geophysical logging of municipal water supply wells at Union and Brackley well fields [2], [6], well drillers' logs from domestic water wells and a study of the impact of Charlottetown Airport redevelopment on water resources in the area [7]. These projects, conducted mostly in the southwestern portion of the basin, have indicated that the bedrock is primarily fine- to medium-grained sandstone (80 - 85%) and mudstone (siltstone and claystone). The sandstone is highly fractured in surface exposures with bed thickness of a few centimetres to a few metres. Vertical to sub-vertical fractures occur as well as fractures parallel to bedding planes.

3.1.2 Present Study

Information on bedrock geology in the Winter River basin was obtained in this study from a series of four diamond coreholes drilled at Union well field (Figure 6) to depths of about 60 m to 75 m [8], [9], and from seven 150 m boreholes drilled at various locations in the basin (Figure 7). At the Union station, about 80 percent of the bedrock penetrated is composed of red-brown, argillaceous, fine- to medium-grained, slightly friable arkosic sandstone. The remainder is siltstone and claystone. Claystone occurs both as a fairly competent silty claystone and a greasy, plastic claystone which tends to squeeze into boreholes after drilling. Claystone and siltstone thicknesses do not exceed one metre at the Union site, and their occurrence is usually limited to thin (< 5 cm) lenses in the predominant sandstone.

Figure 8 shows geological logs (expressed as percent sandstone) for two metre depth intervals, along with geophysical logs of each corehole. The geophysical logs illustrate the rapid vertical lithological variations which occur. The more argillaceous siltstone and claystone are indicated by the lower single point resistance and higher natural gamma responses compared to the sandstones. Comparison of these corehole logs shows a limited degree of horizontal lithological continuity even though the distance between the coreholes at this site is less than 100 m.

Geological and geophysical logs for the seven 150 m boreholes are provided in Appendix 1. The particular locations were chosen based on geographic coverage, probable position in

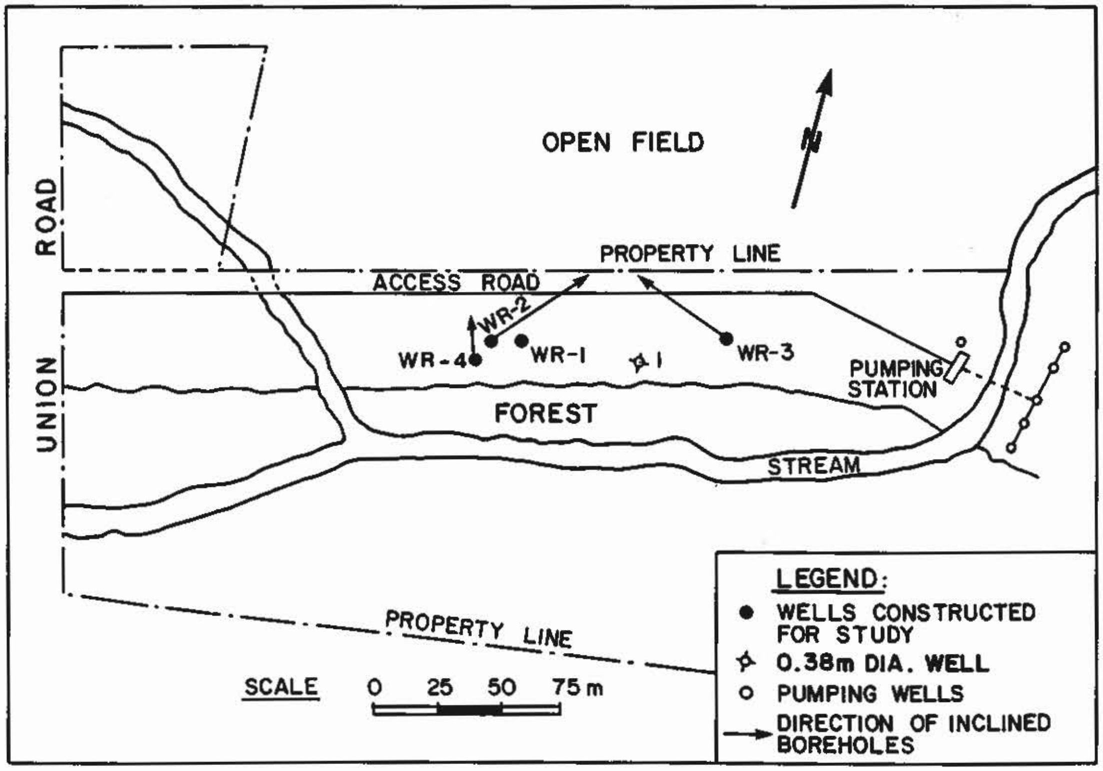


Figure 6. Location map, Union well field test site.

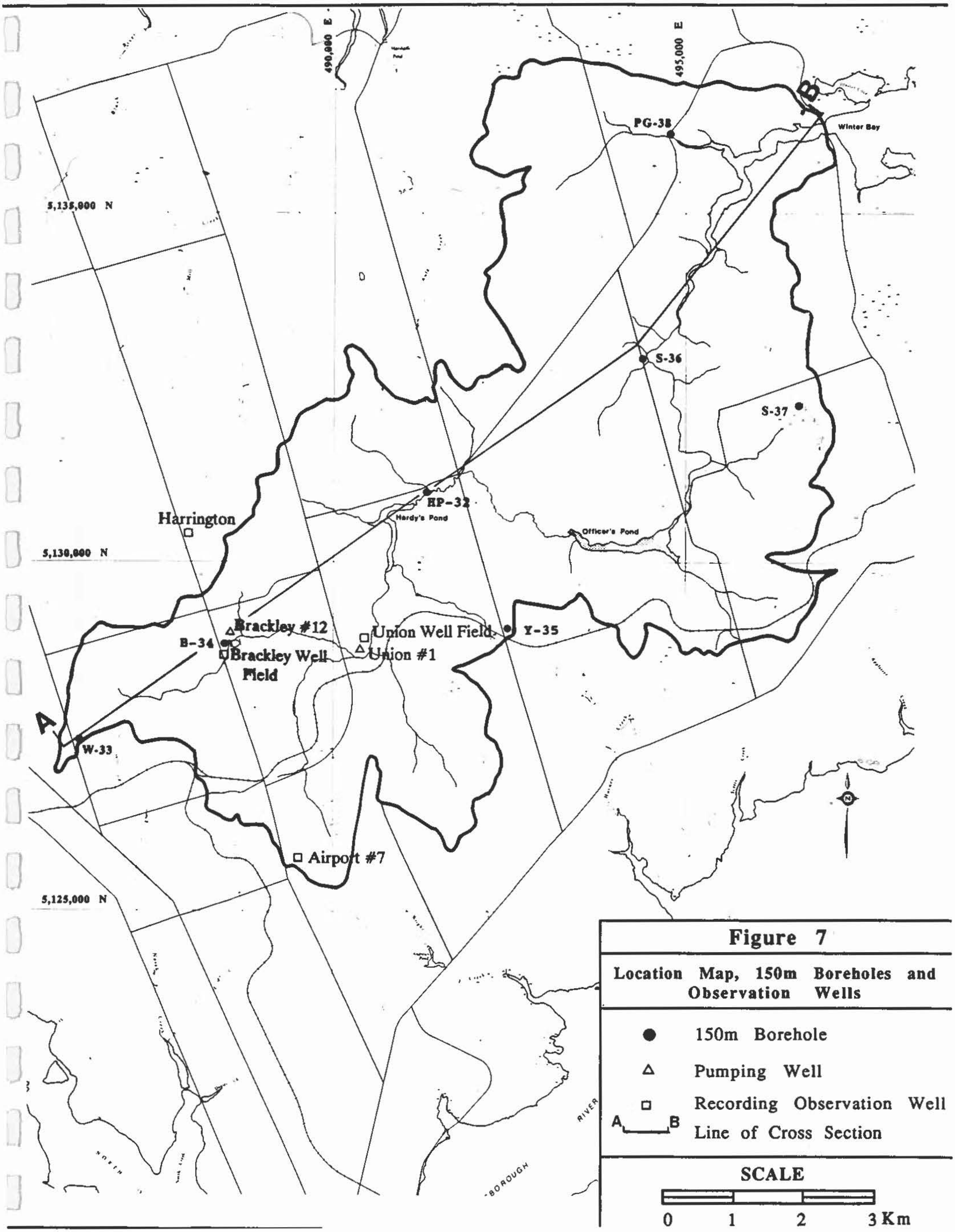


Figure 7

Location Map, 150m Boreholes and Observation Wells

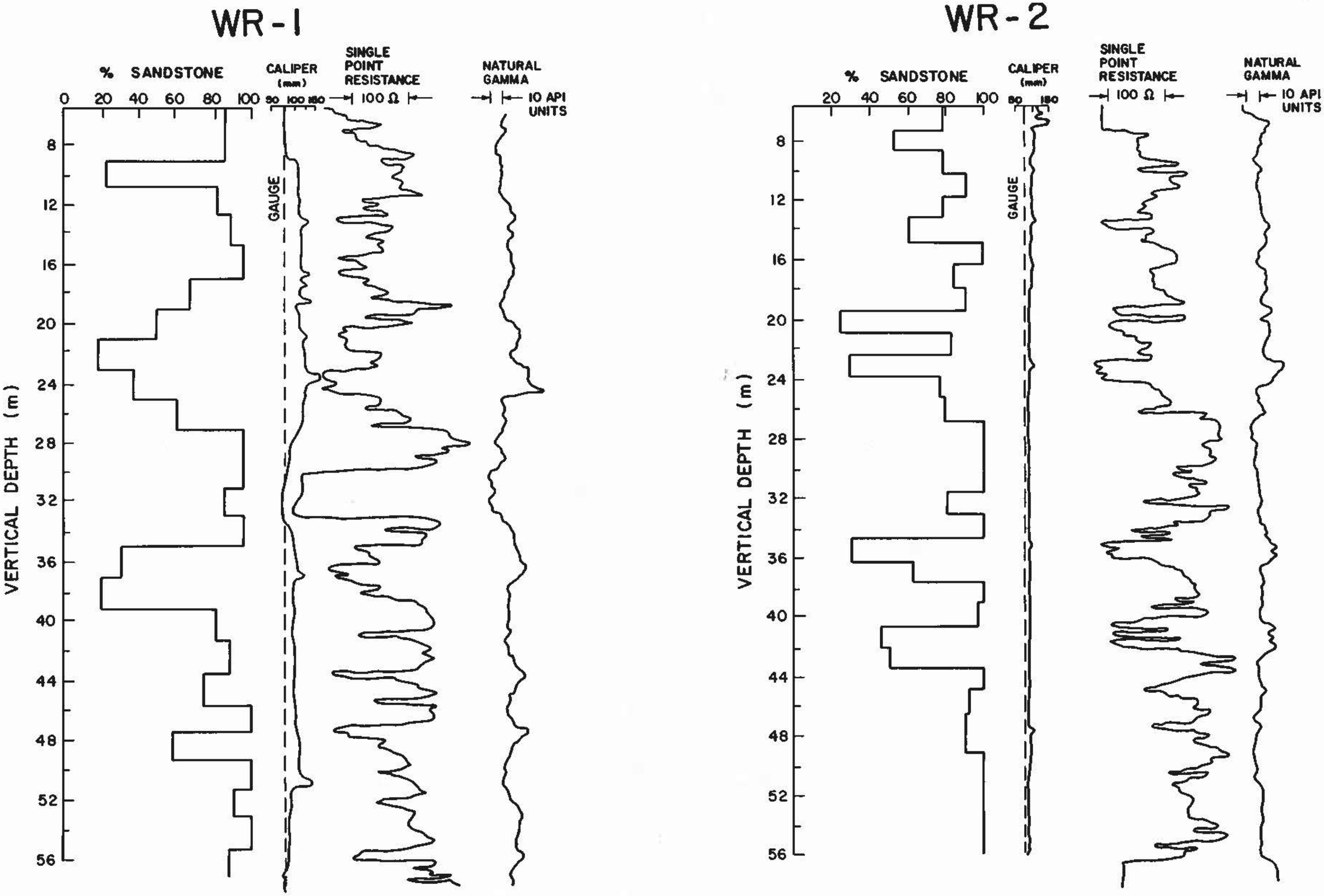


Figure 8. Lithological and geophysical logs, Union boreholes [8,9].

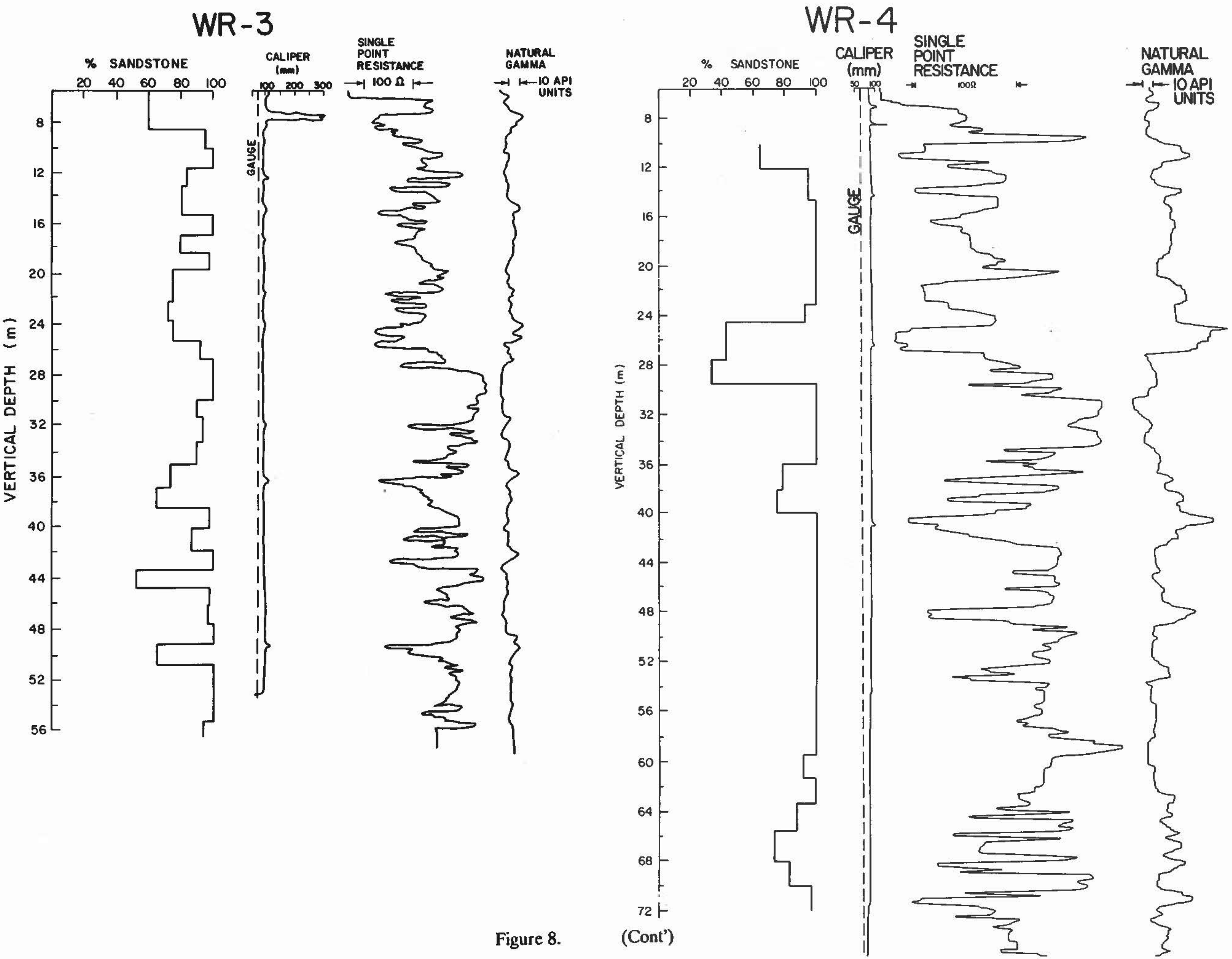


Figure 8. (Cont')

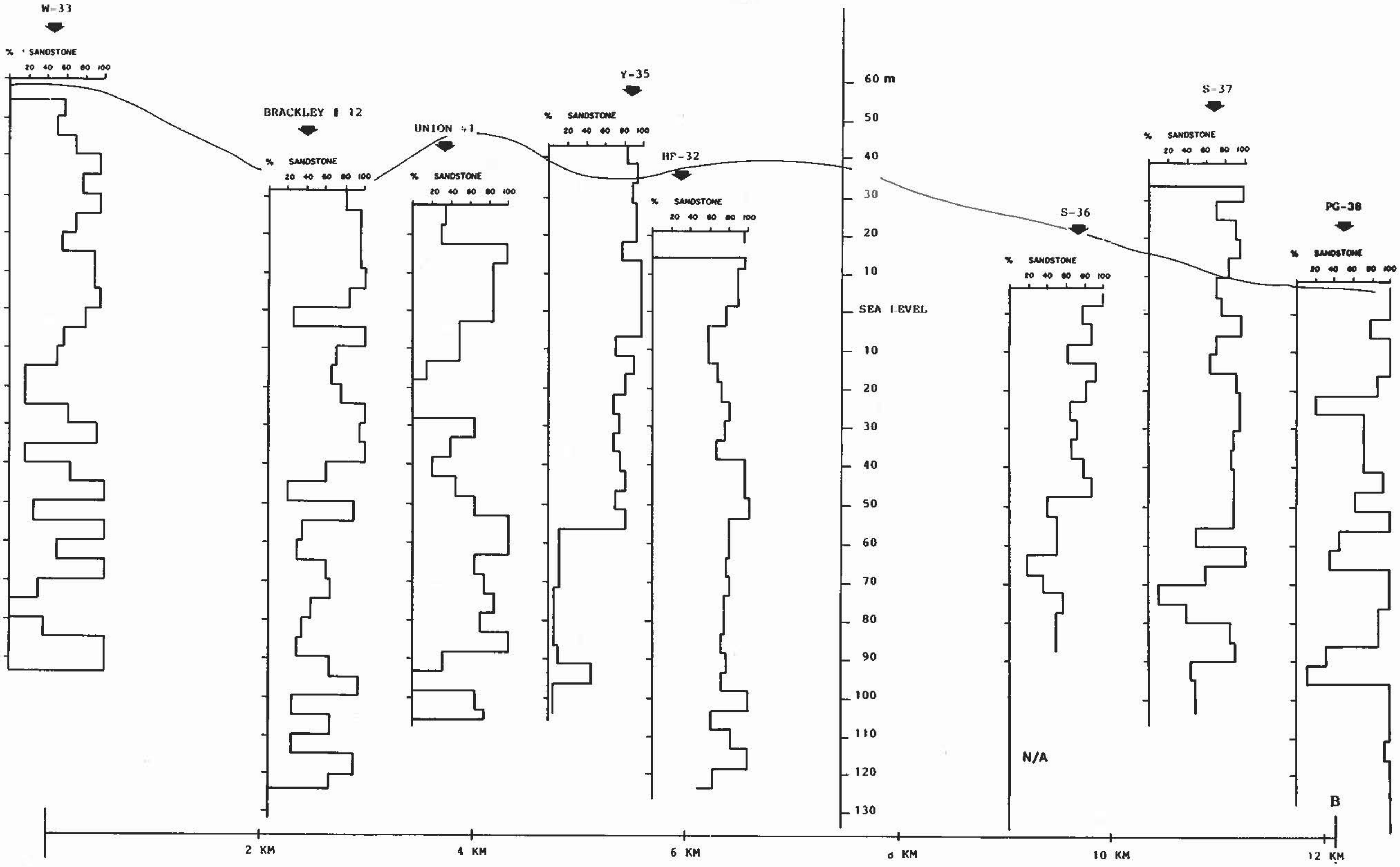


Figure 9. Cross section A-B (Figure 6) showing general geology of deep boreholes.

the groundwater flow system, and site accessibility. Boreholes W-33, Y-35, and S-37 are located on topographic highs (maximum elevation 60 m at W-33) near the watershed divide, while HP-32, BP-34, S-36, and PG-38 are located near the river. Each borehole was drilled using cable tool or air-rotary drilling techniques. Approximately 10 m of 12.5 cm steel surface casing was installed in each. The borehole diameters decreased from 12.5 to 10 cm after about 100 m due to a change in drill size.

As detailed in Appendix 1, and summarized in the cross section in Figure 9, fine-grained sandstone predominates at all borehole locations. Claystone generally occurs as thin (less than one metre) layers or lenses. Several boreholes have intervals where siltstone is the predominant rock type, shown as low 'percent sandstone' in Figure 9. This cross-section runs southwest - northeast through the basin (Figure 7) and includes logs of Brackley #12 and Union #1 which are municipal supply wells at Brackley and Union well fields. Boreholes off the line of section have been superimposed for completeness. The line of section is approximately parallel to the strike of the beds suggested by van de Poll [4].

In the Prince Edward Island red bed deposits, continuity of lithological units is always difficult to establish, even over short distances. Assuming that cross section A-B is parallel to the strike of the beds, one should be able to detect any obvious zones of similar lithology in the zone 0 - 80 m below sea level which is common to all boreholes (Figure 9). Such a correlation is not apparent, nor is any cyclic change in lithology with depth noted.

3.2 Surficial Geology

3.2.1 Previous Work

The Permo-Pennsylvanian bedrock of Prince Edward Island is almost everywhere covered by a layer of unconsolidated glacial material from a few centimetres to several metres in thickness [5]. These deposits are generally derived directly or indirectly from local bedrock sources and comprise both unsorted, ground-up bedrock usually referred to as till, and water-worked glaciofluvial and glaciomarine deposits.

The surficial geology of the Winter River basin area has been mapped by Crowl and Frankel as part of their study of the surficial geology of Central Prince Edward Island [10]. They describe two main types of deposits in the basin: glacial tills (ground moraine and ablation till) and glaciofluvial deposits. Figure 10 shows their assessment of the glacial deposits in the area. The southwestern portion of the basin is predominated by clay-sand and clay-silt till, with a small area of ablation till near the Charlottetown airport. The northeastern half of the basin is characterized by sandy glaciofluvial deposits, and several large eskers have been identified.

3.2.2 Present Study

To investigate the role of glacial deposits in the hydrogeology of the basin, particularly the southwestern portion, 31 boreholes were drilled at locations shown on Figure 11, using an air-rotary drilling rig. Boreholes were generally between 5 m and 8 m deep, and about 15 cm in diameter. Boreholes at locations 8-U, 10-U, 11-U and 12-U were drilled to depths of about 20 m.

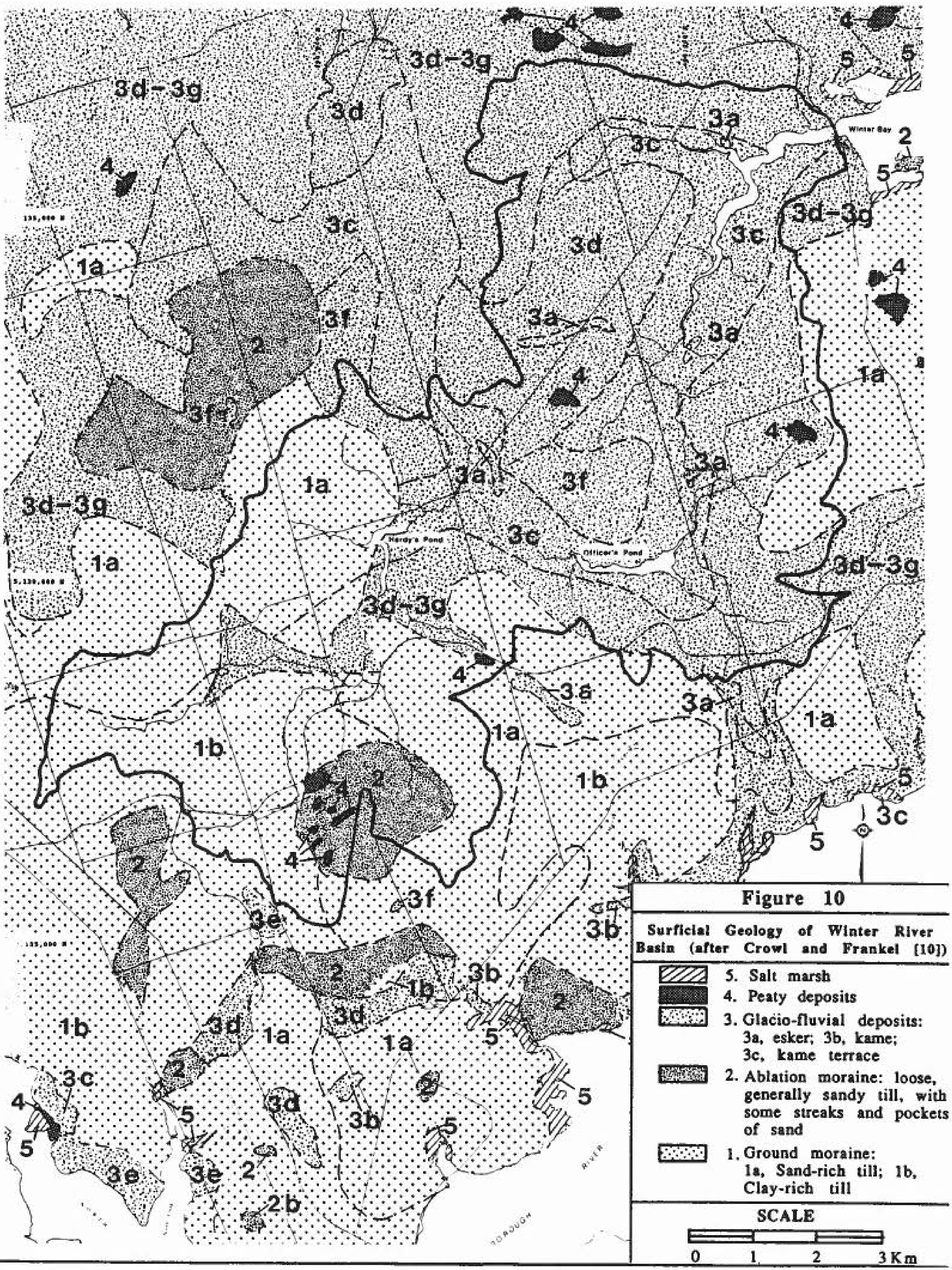


Figure 10

Surficial Geology of Winter River Basin (after Crowl and Frankel [10])

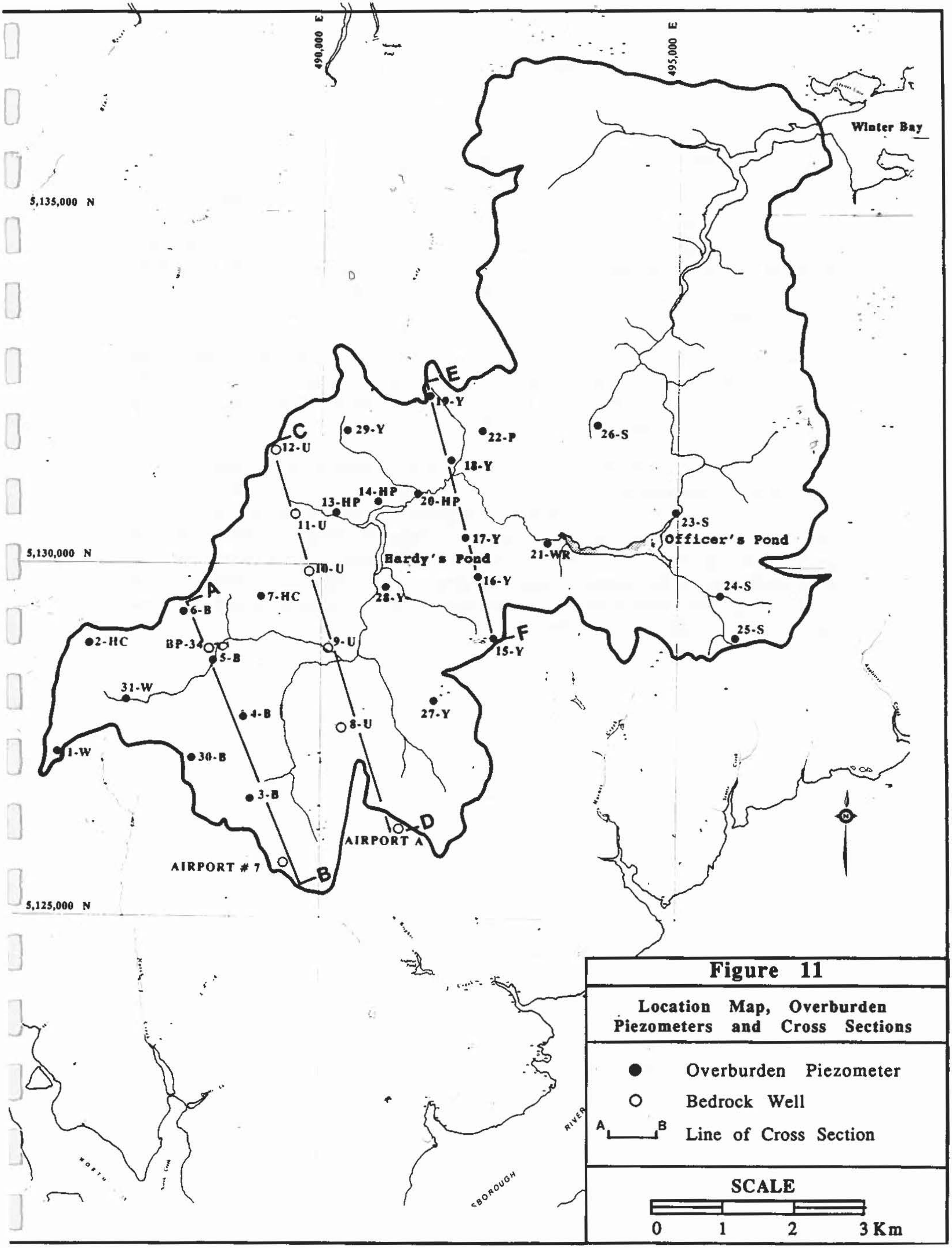


Figure 11

Location Map, Overburden Piezometers and Cross Sections

In each borehole, a split-spoon sampler was used to obtain overburden samples at depth intervals of about one metre. The samples were retained for detailed grain-size analyses. Drilling and sampling normally continued until bedrock was encountered. Water seepage, water table elevation, and depth to bedrock were recorded, along with a detailed geological log. This information is presented in Appendix 2.

The description of the overburden materials provided by the above work largely supported the work of Crowl and Frankel. However, the clay content of the tills is less than their classification might suggest. Silty-sand to sand phase till predominates over the southwestern portion of the basin, with several boreholes near the river (18-Y, 20-HP, 22-P, 23-S, 28-Y) encountering water-worked sandy glaciofluvial material. Only one borehole (1-W) intersected clay-sand or clay-silt till, a thin layer overlying silty-sand phase till.

The results of grain size analyses on split-spoon samples are presented in Table 2 and Figure 12. The material has a highly variable 'gravel' size component, usually comprised of angular sandstone fragments which form from 10% to 50% of the sample. The silt-clay fraction is normally less than 20% and clay less than 5%.

The thickness of the overburden (depth to bedrock below ground surface) ranges from two metres to more than eight metres, averaging about 4.5 m. Figure 13 shows the overburden thickness as a function of geodetic elevation at each borehole location. Data from several of the 150 m bedrock boreholes (Section 3.1.2) are also included. While it is apparent that one can expect at least two metres of overburden at most locations, the probability of encountering thicker overburden deposits is somewhat greater at lower elevations. This is probably because glacial action deposited the thicker sequences of till and glaciofluvial material at the lower elevations along the river valley.

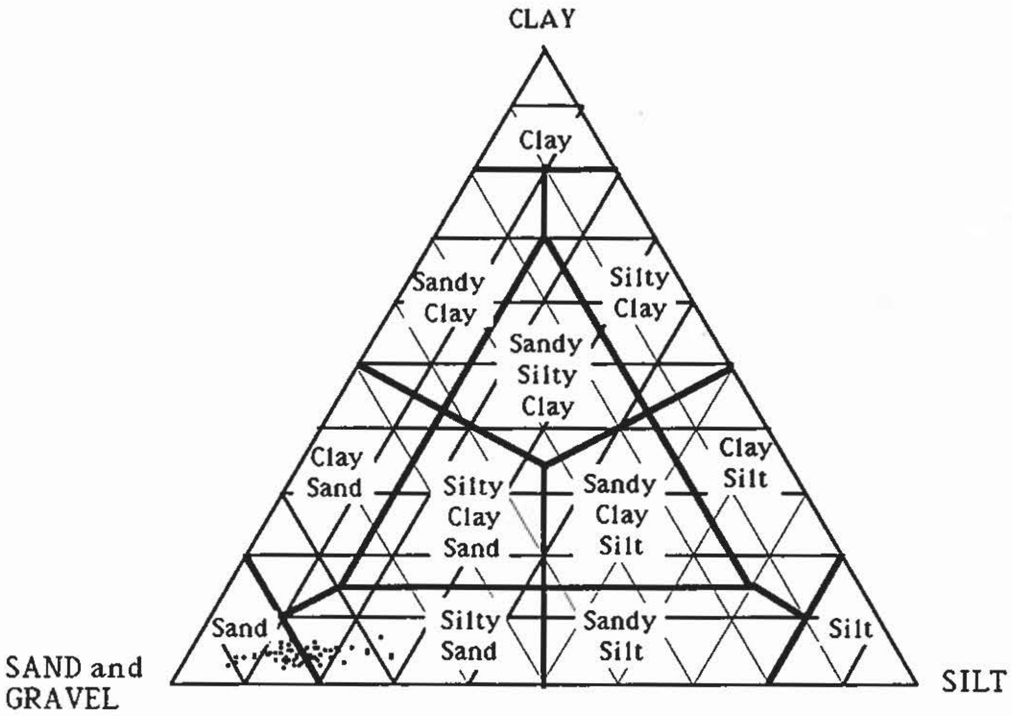


Figure 12. Trilinear plot of overburden grain size analyses.

Table 2. Grain Size Analyses.

Hole #	Depth (m)	% Gravel	% Sand	% Silt	% Clay	K(m/s)
1W	0.9-1.5	16.0	57.0	21.0	6.0	8.3E-08
2HC	0.9-1.4	13.0	64.0	19.5	3.5	3.8E-07
2HC	2.9-3.5	22.0	61.0	15.0	2.0	1.3E-06
2HC	4.6-5.2	41.0	46.0	9.5	3.5	1.1E-06
3B	0.9-1.5	38.0	53.0	8.0	1.0	1.3E-05
3B	3.4-3.7	27.5	57.0	13.5	2.0	2.3E-06
4B	0.9-1.5	39.5	48.0	10.0	2.5	4.3E-06
5B	0.9-1.5	56.0	34.0	8.5	1.5	1.1E-05
5B	2.7-3.1	28.0	57.0	12.0	3.0	2.3E-06
5B	4.6-5.2	51.0	25.0	22.0	2.0	2.4E-06
6B	0.9-1.5	27.5	62.0	9.5	1.0	6.7E-06
6B	2.7-3.1	10.0	71.0	18.5	0.5	2.7E-06
7HC	0.9-1.5	11.5	70.5	15.5	2.5	4.6E-07
7HC	2.7-3.4	17.0	66.5	14.0	2.5	2.6E-06
7HC	4.6-5.1	13.0	72.0	13.5	1.5	3.2E-06
8U	2.4-3.1	9.0	68.5	19.0	3.5	2.7E-07
8U	4.3-4.6	24.0	58.0	14.0	4.0	6.2E-07
9U	0.9-1.5	44.0	44.0	10.0	2.0	7.2E-06
9U	2.7-3.1	-	-	-	-	6.7E-06
10U	0.9-1.5	44.0	47.0	8.0	1.0	1.2E-05
10U	2.7-3.1	33.5	55.5	9.0	2.0	7.2E-06
10U	4.6-5.2	36.0	51.0	11.0	2.0	4.3E-06
11U	0.9-1.5	26.0	60.0	12.0	2.0	2.0E-06
11U	2.7-3.4	34.0	56.0	8.5	1.5	2.4E-06
12U	0.9-1.5	29.0	55.5	12.5	3.0	1.4E-06
12U	2.7-3.4	26.5	60.0	11.5	2.0	2.4E-06
13HP	0.9-1.5	29.5	61.0	7.5	2.0	1.1E-05
13HP	2.7-3.4	18.0	63.0	15.0	4.0	4.6E-07
13HP	4.6-5.3	23.0	62.0	11.5	3.5	6.2E-07
14HP	0.9-1.5	10.5	70.0	17.5	2.0	6.2E-07
14HP	3.1-3.7	18.0	65.5	12.5	4.0	6.2E-07
15Y	0.9-1.4	12.0	66.5	19.5	2.0	7.8E-07
15Y	2.7-3.4	8.5	62.0	25.0	4.5	1.5E-07
15Y	4.6-5.2	18.0	63.0	15.0	4.0	5.4E-07
16Y	0.9-1.2	17.0	65.0	13.5	4.5	2.7E-07
16Y	3.1-3.5	7.5	71.5	17.5	3.5	6.2E-07
17Y	0.9-1.5	9.0	73.5	14.5	3.0	4.6E-07
17Y	2.7-3.4	5.0	80.0	13.0	2.0	3.2E-06
18Y	0.9-1.5	8.0	72.0	16.5	3.5	1.5E-06
18Y	2.9-3.5	12.0	72.0	13.5	2.5	2.1E-06
18Y	4.6-5.2	15.5	68.0	15.0	1.5	2.7E-06
19Y	0.9-1.5	14.0	67.5	15.5	3.0	6.2E-07
19Y	2.7-3.4	14.0	67.0	16.0	3.0	6.2E-07
19Y	4.9-5.5	23.5	56.5	16.0	4.0	1.1E-06
20HP	0.9-1.5	17.0	56.0	23.0	4.0	2.4E-07
20HP	2.9-3.5	23.0	55.0	18.5	3.5	3.8E-07
20HP	4.9-5.5	16.0	66.0	13.5	4.5	9.7E-06
21WR	0.9-1.5	19.0	65.0	14.0	2.0	2.4E-06
21WR	2.7-3.4	18.5	49.5	28.5	3.5	7.0E-07
22P	0.9-1.8	22.0	62.0	14.5	1.5	1.2E-06
22P	2.7-3.7	20.5	60.5	17.0	2.0	1.6E-06
23S	0.9-1.5	15.5	69.0	14.5	1.0	5.4E-06
23S	2.7-3.4	17.0	67.0	14.5	1.5	2.0E-06
23S	4.6-5.2	19.0	61.5	17.0	2.5	2.7E-07
24S	0.9-1.5	22.0	57.0	17.0	4.0	3.5E-07
24S	2.7-3.4	25.0	52.5	16.5	6.0	6.7E-08
24S	4.6-5.2	16.0	67.0	13.0	4.0	6.2E-07
25S	0.9-1.5	12.0	73.0	13.0	2.0	2.0E-06
25S	2.7-3.4	16.0	75.5	8.0	0.5	1.3E-05
26S	0.9-1.5	21.0	60.0	14.5	4.5	5.4E-07
26S	2.7-3.2	12.0	71.5	14.5	2.0	1.6E-06
27Y	0.9-1.2	3.0	64.5	27.5	5.0	9.7E-08
27Y	2.7-3.4	30.0	53.0	14.0	3.0	6.2E-07
27Y	6.1-6.5	21.0	61.0	14.5	3.5	4.8E-07
28Y	0.9-1.8	19.0	58.0	20.0	3.0	4.3E-07
28Y	2.7-3.5	42.0	42.0	12.0	4.0	6.2E-07
29Y	0.9-1.5	25.0	58.0	12.0	5.0	2.7E-07
29Y	2.7-3.0	11.0	72.0	15.0	2.0	1.8E-06
30B	0.9-1.2	31.0	53.0	14.0	2.0	2.0E-06
30B	2.7-3.4	18.0	70.0	10.0	2.0	6.7E-06
30B	4.6-4.9	17.5	68.5	11.5	2.5	3.2E-06
31W	0.9-1.5	11.0	70.0	15.5	3.5	3.2E-06
31W	2.7-3.5	22.0	62.0	13.0	3.0	5.4E-07
31W	4.6-5.2	26.0	47.5	23.5	3.0	6.2E-07
20HP	7.3-7.6	0.5	87.5	11.0	1.0	
22P	4.6-5.5	23.0	58.0	17.0	2.0	

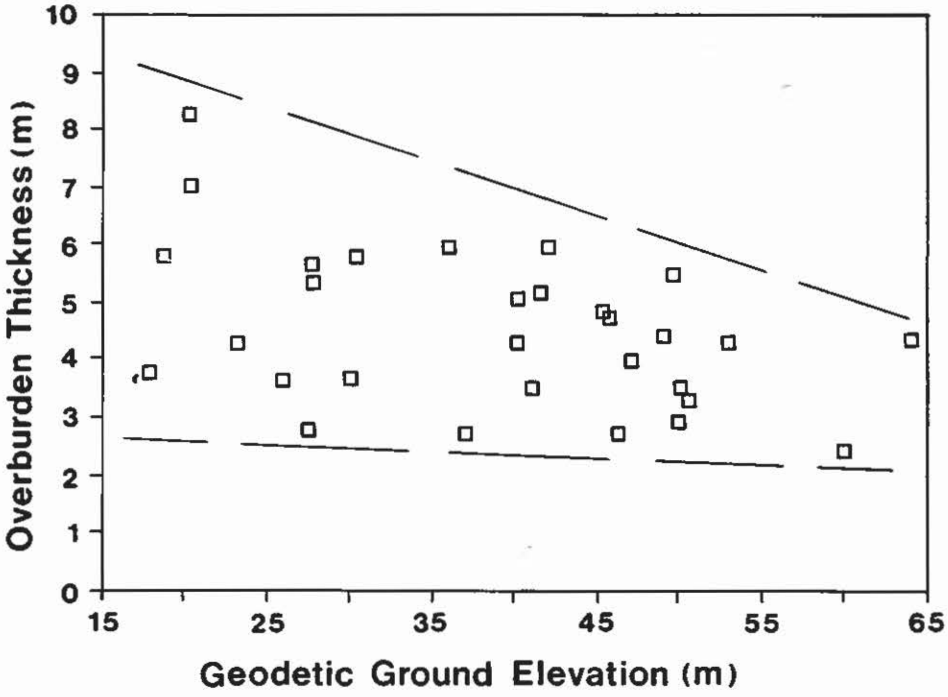


Figure 13. Overburden thickness as a function of geodetic elevation.

4. PHYSICAL HYDROGEOLOGY

4.1 Surficial Deposits

4.1.1 Field Methods

Information from the 31 boreholes described in the previous section was used to define the hydrogeological characteristics of the surficial deposits. After the completion of drilling, boreholes were normally filled with drill cuttings and bentonite to just above the overburden - bedrock contact. A piezometer was installed consisting of a 5 cm I.D. PVC pipe with the bottom three meters perforated and wrapped with fiber glass screen (Figure 14). A gravel pack (0.3 - 1.8 cm diameter Nova Scotia washed blue gravel) was placed in the annular space to completely cover the perforated section of the piezometer. A 0.5 m - 1.0 m bentonite seal was placed over the gravel pack, followed by drill cuttings and soil material.

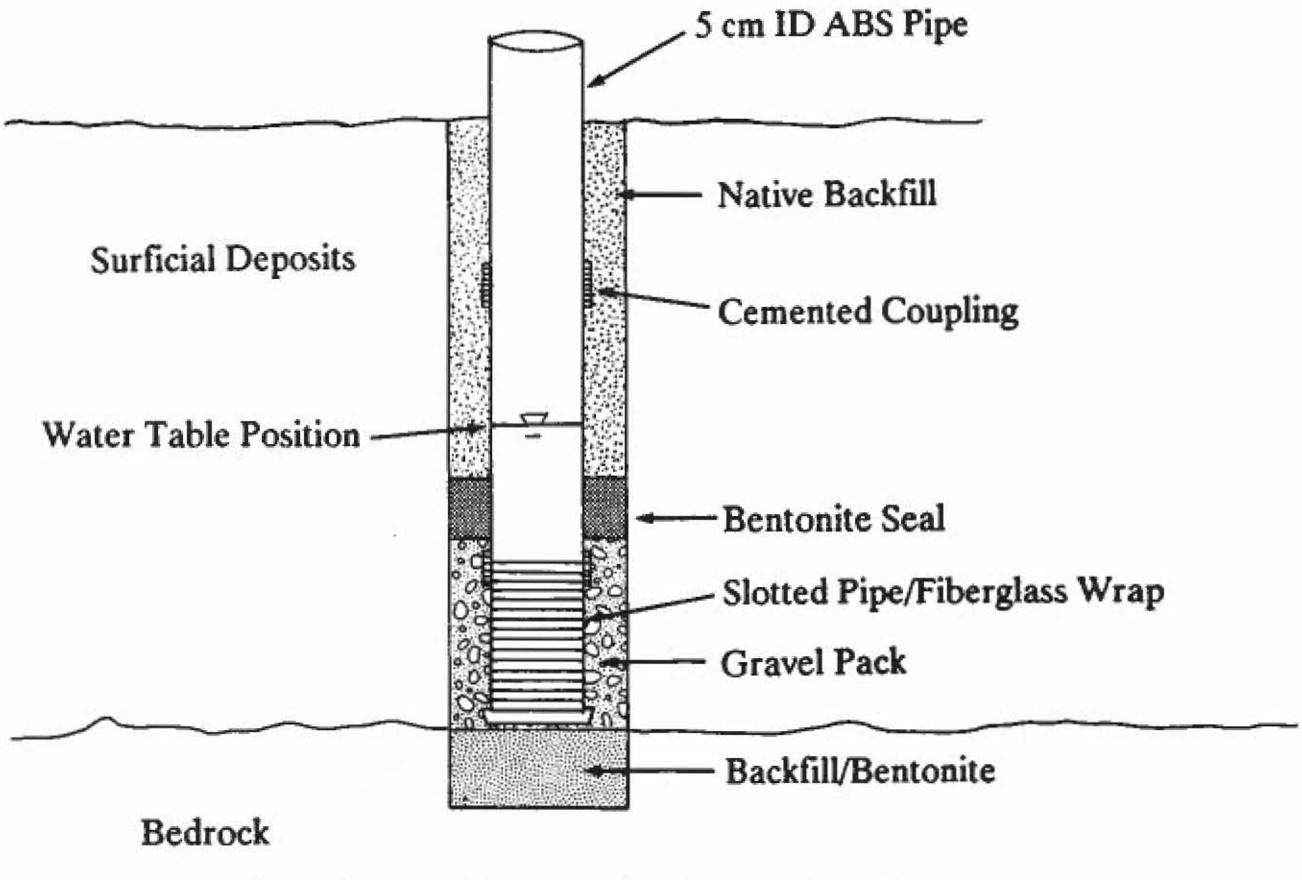


Figure 14. Typical overburden piezometer installation.

The borehole logs in Appendix 2 give piezometer construction details for each borehole. Piezometers at locations 8-U, 10-U, 11-U, and 12-U (Figure 11) were completed in bedrock. Piezometers 21-WR and 14-HP were damaged beyond use by vandals. Conventional slug tests were conducted on a number of piezometers to determine the in situ hydraulic conductivity of the overburden. Only four boreholes were tested in this manner because of insufficient depth of water in the piezometers, or dry holes. Slug tests in the four piezometers were conducted as falling head tests using a closed PVC pipe as a slug, causing an initial water level rise of 0.7 m in the piezometers. Response was measured using a conventional water level tape.

4.1.2 Hydraulic Conductivity Characteristics

Using the grain-size distribution curves for each sample and an empirical relationship between permeability and grain size, it is possible to provide a useful estimation of the hydraulic conductivity of surficial deposits.

A review of applicable relationships [11] indicates that the Kozeny-Carmen equation [12] may be most applicable for sandy tills of Prince Edward Island.

The relationship takes the form:

$$K = \left(\frac{\rho g}{\mu}\right)\left[\frac{n^3}{(1-n^2)}\right]\left(\frac{d_m^2}{180}\right)$$

where ρ - is the fluid density, g is the gravitational constant, μ - is the fluid viscosity, n is the porosity of the soil material and d_m is a representative grain size. Although porosity (n) was not measured on these samples, it can be safely estimated to range from 20% - 35%. A value of 30% has been used in these calculations. The representative grain size (d_m) has been chosen at d_{10}, or the grain size at which 10% by weight of the particles are finer and 90% are coarser. The silt-clay fraction of a till should have the most influence on its hydraulic conductivity.

Table 2 shows the resulting estimated hydraulic conductivity value for each overburden sample. Due to possible variations in sample porosity, these values should be considered estimates to within one half an order of magnitude. The values range from a low of 6.7×10^{-8} m/s to a high of 1.3×10^{-5} m/s with an average value of 2.6×10^{-6} m/s. A histogram of these values, shown in Figure 15, suggests that this glacial till has a relatively high hydraulic conductivity for this type of geological deposit.

Slug tests were carried out on piezometers 14-HP, 18-Y, 20-HP, and 22-P, and analyzed using the Hvorslev method [13], case G; so that:

$$K_h = \frac{d^2 \cdot \ln\left(\frac{2mL}{D}\right)}{8LT}$$

where:

d - standpipe diameter - 0.05 m
D - effective well diameter - 0.15 m
L - screen (gravel pack) length - 3 m
m - $(K_h/K_v)^{1/2}$ - 1
T - basic time lag .

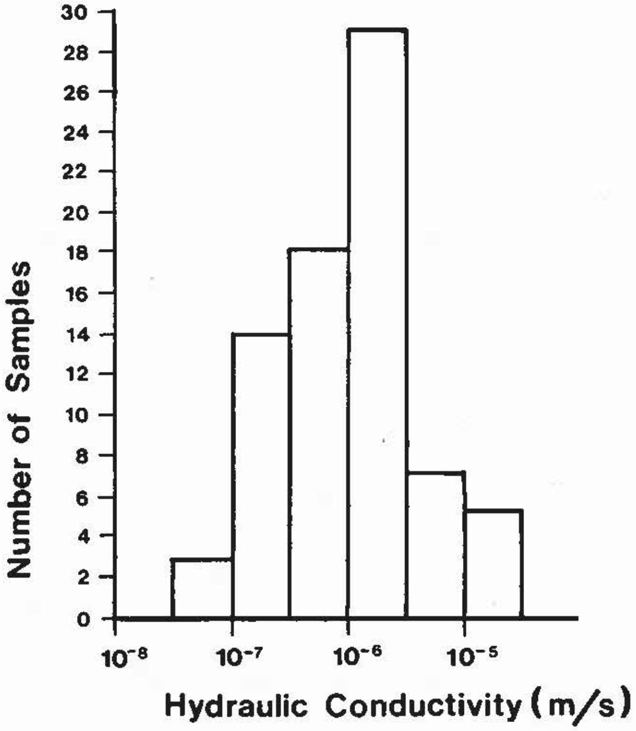


Figure 15. Histogram of overburden hydraulic conductivity as determined by grain size analyses.

Plotting the results of each slug test on semi-log paper and determining the basic time lag (T) provides a field estimate of hydraulic conductivity. The results, shown in Table 3, indicate values in the 10^{-7} to 10^{-5} m/s range, lower than the most frequent results from estimates based on grain size analyses.

Two factors should be noted with regard to the slug tests. These four piezometers could be tested because there was sufficient depth of water in each. This was probably because of their location in the basin, at relatively low elevations along the river, where the water table is near surface. As well, the water table may have been higher due to relatively lower permeability in the overburden at these locations. This leaves some question as to how representative these slug test results are.

Normally, one might expect higher hydraulic conductivity values in the field tests as compared to lab permeability tests because of the dual permeability in the till: the primary intergranular spaces, as well as the secondary permeability caused by rock fragment-to-soil contacts and preferential flow channels or fractures. However, these secondary features may have been destroyed by the drilling and piezometer installation.

Table 3. Results of Overburden Slug Tests.

Location	Hydraulic Conductivity (m/s)
14-HP	5.4E-07
18-Y	<10E-07
20-HP	8.5E-06
22-P	5.8E-06

4.1.3 Water Table Position and Flow Dynamics

Manual water level measurements were made several times per year from 1982 to 1986 in each overburden piezometer. In addition, bedrock piezometers at locations 8-U, 11-U, and 12-U and overburden piezometer 9-U were instrumented with continuous-record water level recorders from 1982 to 1988. Five-year summary hydrographs of water table fluctuations are presented in Appendix 3. All, with the exception of the bedrock piezometer graphs and 9-U, represent interpolations between point measurements.

Twelve of the overburden piezometers were always dry, and three others were dry during periods of low water table. Thirteen others consistently showed the water table to be in the overburden at those locations. The majority of these, specifically 5-B, 9-U, 14-HP, 18-Y, 20-HP, 22-P, 24-S, 28-Y and 31-W are in topographically low areas. Piezometers 1-W, 3-B and 15-Y are in higher areas, and the high water table at those locations appears to be due to the relatively lower permeability of the overburden or underlying bedrock.

Figure 16 shows three cross-sections, running north-south and approximately perpendicular to the river (Figure 11), which illustrate the overburden-bedrock-water table relationships in the basin. At higher elevations the water table is well below the overburden-bedrock contact. Moving down-gradient toward the river, the overburden is somewhat thicker, and the water table crosses the overburden-bedrock contact, until it meets ground surface at the river.

A substantial baseflow component of streamflow can be expected to result from both horizontal groundwater flow and discharge through the overburden as well as upward discharge of groundwater from the bedrock through the overburden in close proximity to the river.

Figure 17 shows representative hydrographs from various overburden piezometer locations in the watershed, along with the continuous hydrographs from 9-U and 11-U. All locations demonstrate the seasonal response to climatic events typical for Prince Edward Island - a major spring recharge event, followed by summer decline of the water table, a smaller fall recharge event (sometimes almost non-existent, as in 1984 and 1985) and finally a decline in the water table through winter, prior to the next spring recharge event. Recharge events during the December-March period are common, a result of winter thaws, rain and snowmelt. Depending on the frost conditions in the soil, these recharge events can be very significant.

Piezometers 3-B and 31-W are located in the headwaters of the basin (Figure 11). In Figure 17, both show seasonal variations in water table elevation of over two metres. In contrast, location 18-Y and 20-HP are indicative of water table response in areas of high water table, near discharge areas. Seasonal fluctuations are about one metre. Bedrock piezometer 11-U, located in an upland portion of the basin, shows natural water level variations of over four metres. This suggests that the undrained porosity of the bedrock is less than that of the overburden. The timing and pattern of the response is almost identical in the bedrock and in the overburden piezometers. These hydrographs reveal that the permeability of the surficial deposits allows rapid water table response to recharge events either in the overburden or in the bedrock, as the overburden rapidly transmits recharge to the bedrock.

Piezometers 5-B and 9-U are within the influence of the Brackley and Union well fields, respectively. The well fields each pump, on average, about 75 L/s. Hydrographs from these

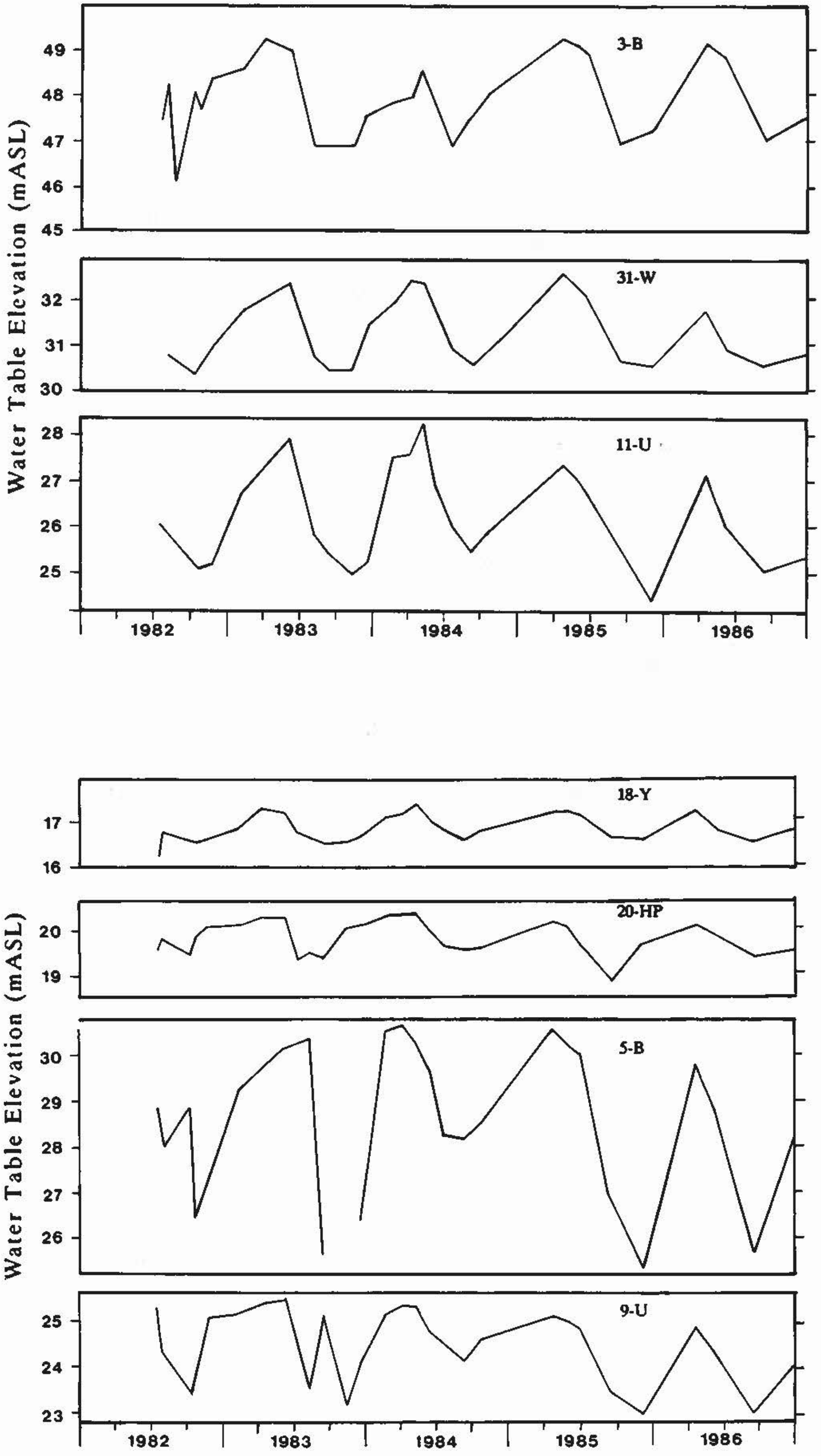


Figure 17. Representative groundwater hydrographs.

locations show that, although the pumping wells are bedrock wells, the overburden piezometers respond quickly to pumping/non-pumping cycles. This reflects the very good hydraulic connection between the overburden and bedrock. These piezometers display a much larger range in water table position (over 5 metres for 5-B) than at 18-Y and 20-HP which are also in close proximity to discharge areas along streams.

Well field pumping creates a much larger decline in the water table near the well fields during the summer months than would normally occur. The magnitude of the effect can be noted in the July-August, 1983 portion of the hydrographs, when pumping was increased substantially at Brackley and decreased at Union. However, there is no evidence of a continuing decline of the water table. This will be discussed further in Section 4.2.

These results show that pumping of the bedrock aquifer at the well fields can influence hydraulic gradients in the overburden. The evidence for baseflow reduction and induced recharge will also be evaluated in later sections.

4.2 Hydrogeology of the Red Bed Aquifer

4.2.1. Introduction

All sedimentary and crystalline rocks, and even some clays and tills contain fractures. In a given rock mass there may be a number of different fracture sets and in each set the fracture spacings may be fractions of a metre to hundreds of metres, depending on the rock type and tectonic environment. From one rock type to another, the fractures, used here collectively to describe joints, bedding plane separations, faults and solution cavities, will have different surface characteristics and different degrees of interconnection. The fractures impart a secondary porosity and hydraulic conductivity to the rock mass which, along with the primary, or intergranular hydraulic conductivity, determine the hydraulic behaviour of the system.

In general, fractures form a small percentage of the total porosity in an aquifer and hence the bulk of the fluid is stored in the intact rock blocks. Individual fractures may have apertures, or openings, that are many times larger than the average pore space in the matrix. When fractures are idealized as parallel plate conduits, the hydraulic conductivity is a function of the aperture squared [14]. In a fractured rock aquifer having appreciable matrix porosity, i.e. a fractured porous aquifer [15, 16] (Figure 18), most of the fluid is stored in the rock blocks, but the fractures represent the primary flow paths. The hydraulic conductivity of the fracture system depends on the fracture spacing, interconnection and aperture distribution. The Prince Edward Island red bed aquifer is an excellent example of a fractured porous aquifer. Ultimately, the relative importance of the fracture system to the total rock mass hydraulic conductivity depends on the ratio of fracture to intergranular hydraulic conductivity [16].

Hydrogeological studies are often required to answer questions relating to movement of fluids through soils and aquifers, i.e. the volumetric flow rate and velocity of groundwater, rates of contaminant migration, hydraulic response to pumping and susceptibility to contamination. In fractured porous aquifers, such questions are complicated by the dual nature of porosity and permeability and the variable degree of interaction between fractures and matrix. It has, therefore, been important in this study to build a fundamental understanding of the hydrogeological properies of the red bed aquifer system. Several research

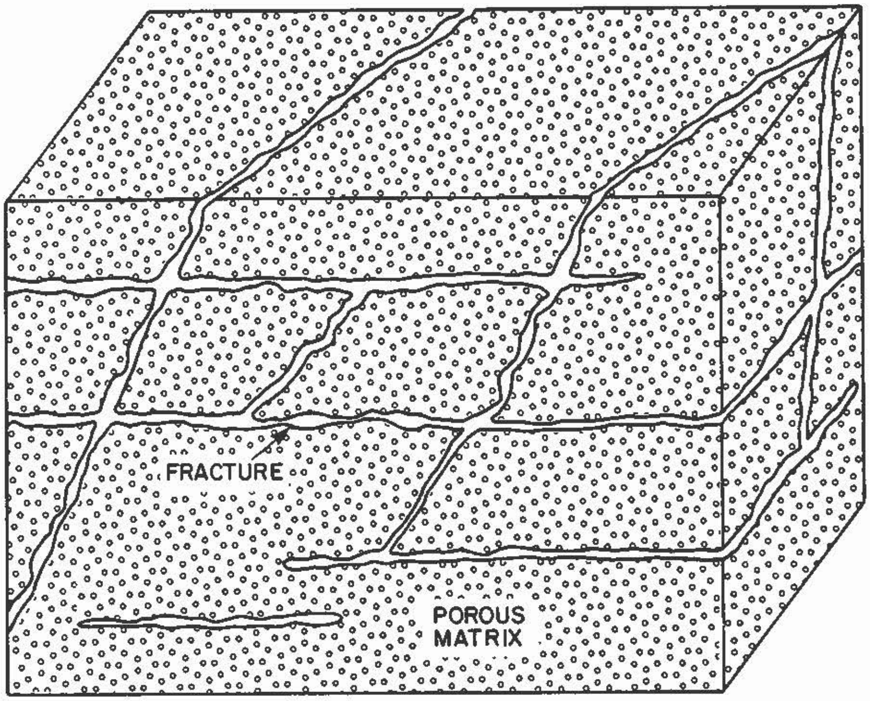


Figure 18. Conceptual model of a fractured porous aquifer.

projects were carried out which focus on the characteristics of the bedrock aquifer and provide a framework for addressing a variety of groundwater management issues. Following a review of previous work on bedrock hydrogeology in Prince Edward Island, the results of these projects will be discussed in the context of their contribution toward understanding the characteristics of the aquifer system.

4.2.2. Previous Work

The earliest study of the groundwater resources of Prince Edward Island was conducted by Brandon [17], collecting information on well yields, groundwater level variations, streamflow and water chemistry. He concluded that the movement of groundwater was permitted by both intergranular and fracture flow in the bedrock, and that groundwater is effluent to rivers. Carr [18] calculated an average hydraulic conductivity of 1.9×10^{-5} m/s from the results of thirty-two pumping tests throughout Prince Edward Island. He compared this to a maximum value of intergranular hydraulic conductivity of 1.1×10^{-6} m/s measured in thirteen core samples. The difference was attributed to a predominance of fracture flow conditions. Average sandstone porosities of 23.2 per cent and 17.7 per cent have been reported by Brandon [17] and Carr [19] respectively. Carr and van der Kamp [20] report a typical value of storativity of 10^{-4} based on pumping test data, and a specific storage value of about $2 \times 10^{-6} m^{-1}$, calculated using the tidal method. Fracture characteristics along parts of the south shore of Prince Edward Island were studied by Parsons [21]. Using a parallel plate model for the fractures, he calculated hydraulic conductivities in the range of 7×10^{-7} m/s to 7×10^{-5} m/s.

In the Winter River basin, previous studies have been confined to well yield test evaluations [22, 23] and environmental impact assessments such as the Charlottetown Airport project [24]. A planning report was prepared by Environment Canada [1] in 1977 which documented existing information from the watershed and outlined various water resource management issues. Callan [2] determined aquifer properties at Union and Brackley well fields on the basis of conventional analyses of several pumping tests. The results (Table 4) suggest that both hydraulic conductivity and specific storage are lower at depth.

Table 4. **Aquifer Properties at Well Fields in the Winter River Basin [2].**

Location	Depth Interval (m)	K(m/s)	S_s (m^{-1})
Brackley Well Field	0-12	1.5E-03	4.4E-05
Brackley Well Field	0-150	6.9E-05	2.5E-05
Union Well Field	0-25	1.4E-03	2.4E-05
Union Well Field	25-131	3.7E-05	1.7E-05

4.2.3. Fracture and Matrix Properties

A field and laboratory study has more recently been carried out [8] as part of this overall program to determine the relative contributions of fracture and intergranular permeability at the Union well field test site.

The field study included diamond coring one vertical and three inclined boreholes 60 m to 75 m in depth. A map of the study site and the corehole locations is shown in Figure 6 (Section 3.1.2). Geological and geophysical logging of each corehole was carried out. Reconstruction of cores from the inclined boreholes allowed determination of fracture frequency and fracture geometry. The results are presented in Figure 19 and Figure 20.

Horizontal bedding plane fractures comprised 82% of all natural fractures, and subvertical fractures were infrequent below about 35 m. In Figure 20, poles to fractures encountered in coreholes WR-2, WR-3, and WR-4 are plotted and contoured on lower hemisphere, equal area stereonets. A nearly vertical set, striking northwest-southeast was intersected by corehole WR-2 and possibly by WR-4. This set includes about 10% of fractures encountered in WR-2 and appears to correspond with a set of similar attitude observed in outcrops in the Winter River basin [25].

At the test site, the average spacing of the horizontal bedding plane fractures decreases from 0.1 m in the upper 35 m to 0.5 m below. The vertical set has an average spacing of 0.6 m in the upper 35 m and 4.9 m below (Figure 19). Using a borehole periscope, apparent fracture apertures in the upper 20 m of bedrock were estimated. The aperture distribution (Figure 21) was found to be log-normal, with a mean of 1.6 mm, a mode (most frequent value) of 0.5 mm and a maximum of about 30 mm.

Separation of the relative contributions of fracture and matrix hydraulic conductivity was accomplished by field measurements of in situ hydraulic conductivity and laboratory measurements of intergranular permeability. The field profiles of hydraulic conductivity were obtained using constant head injection tests on two metre borehole intervals, isolated by a pneumatic packer assembly (Figure 22). Injection tests were conducted under laminar and turbulent flow conditions, turbulent flow predominating in high permeability, high flow rate test intervals.

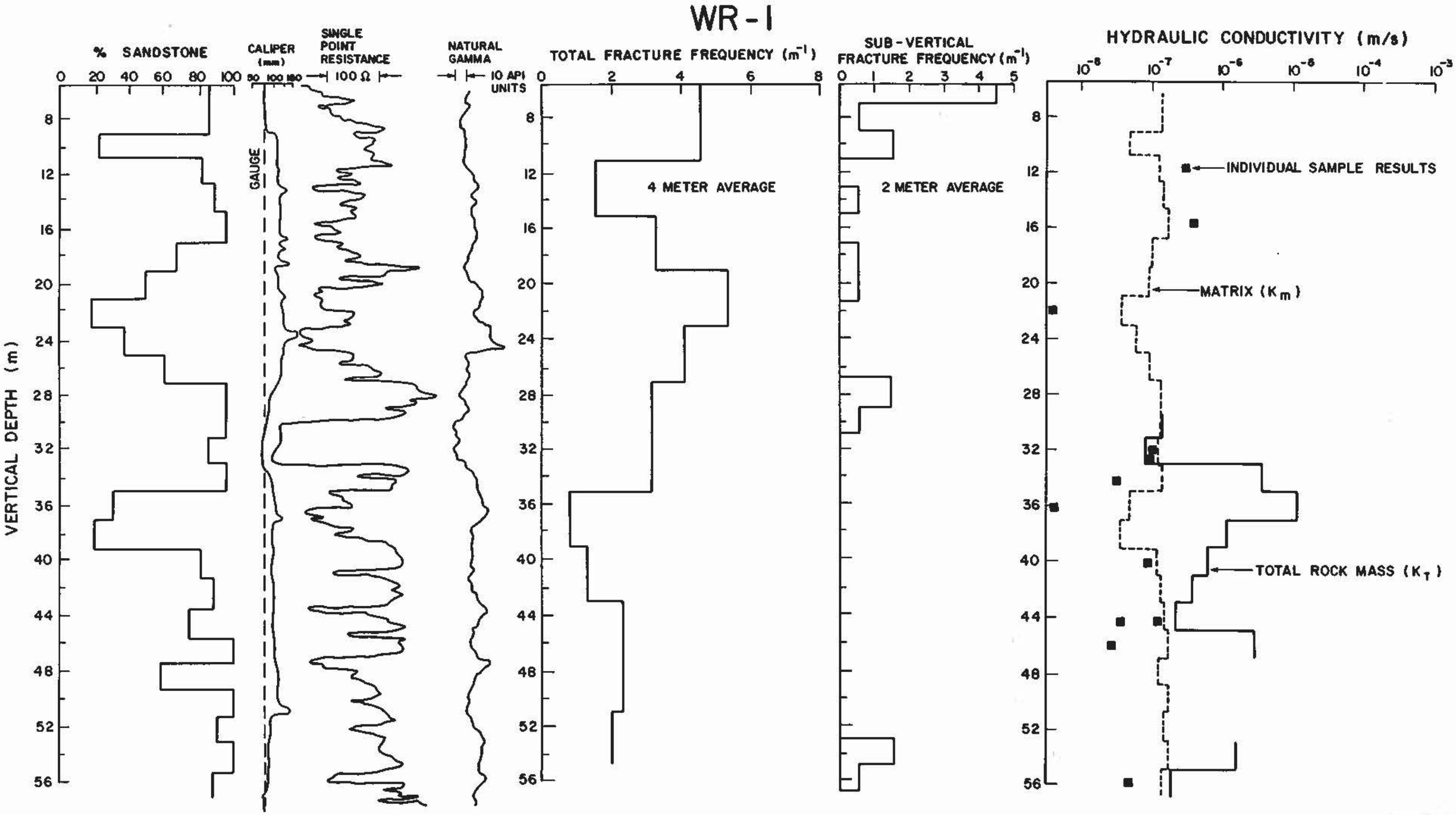


Figure 19. Profiles of geology, fracture frequency and hydraulic conductivity, Union coreholes [8 , 9].

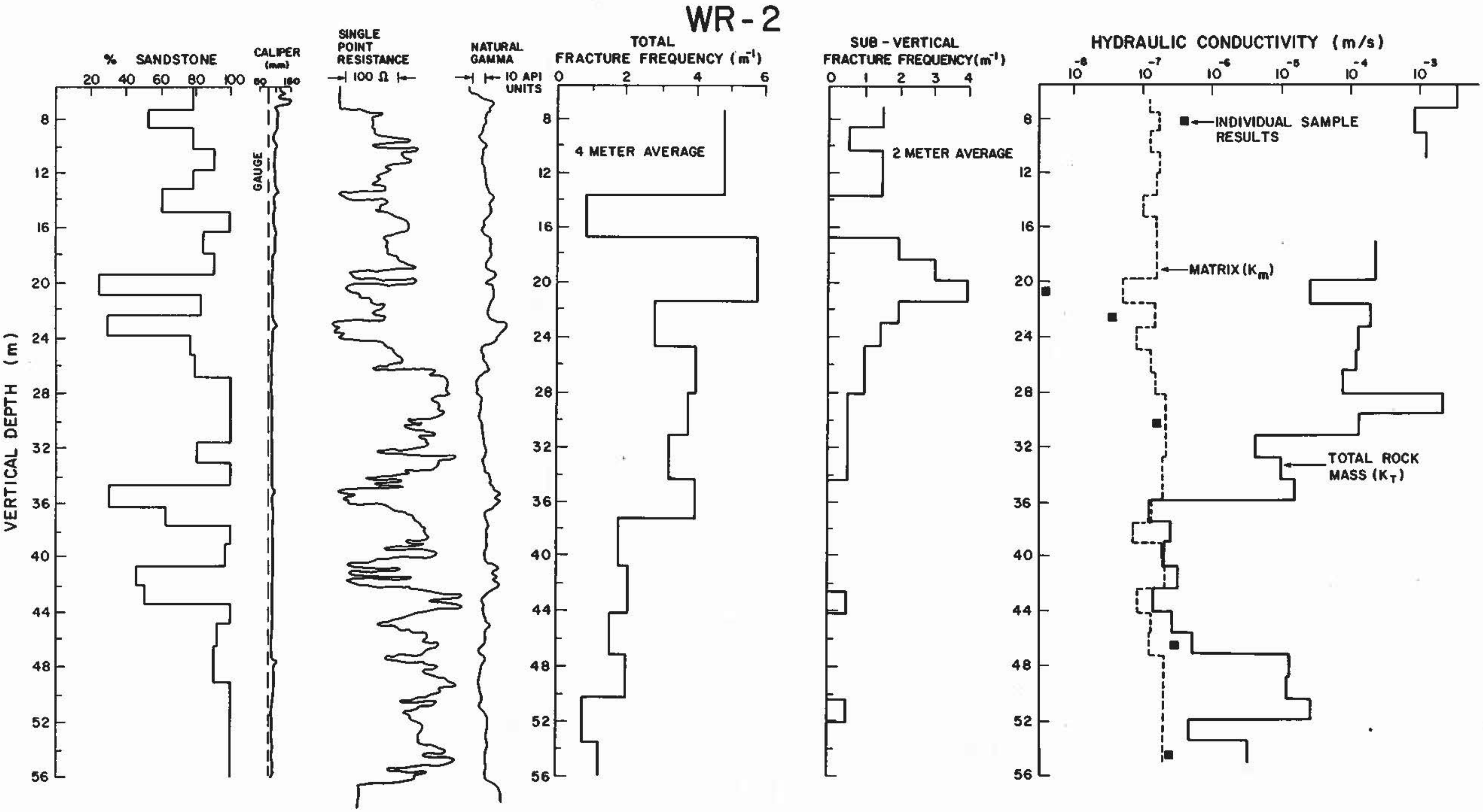
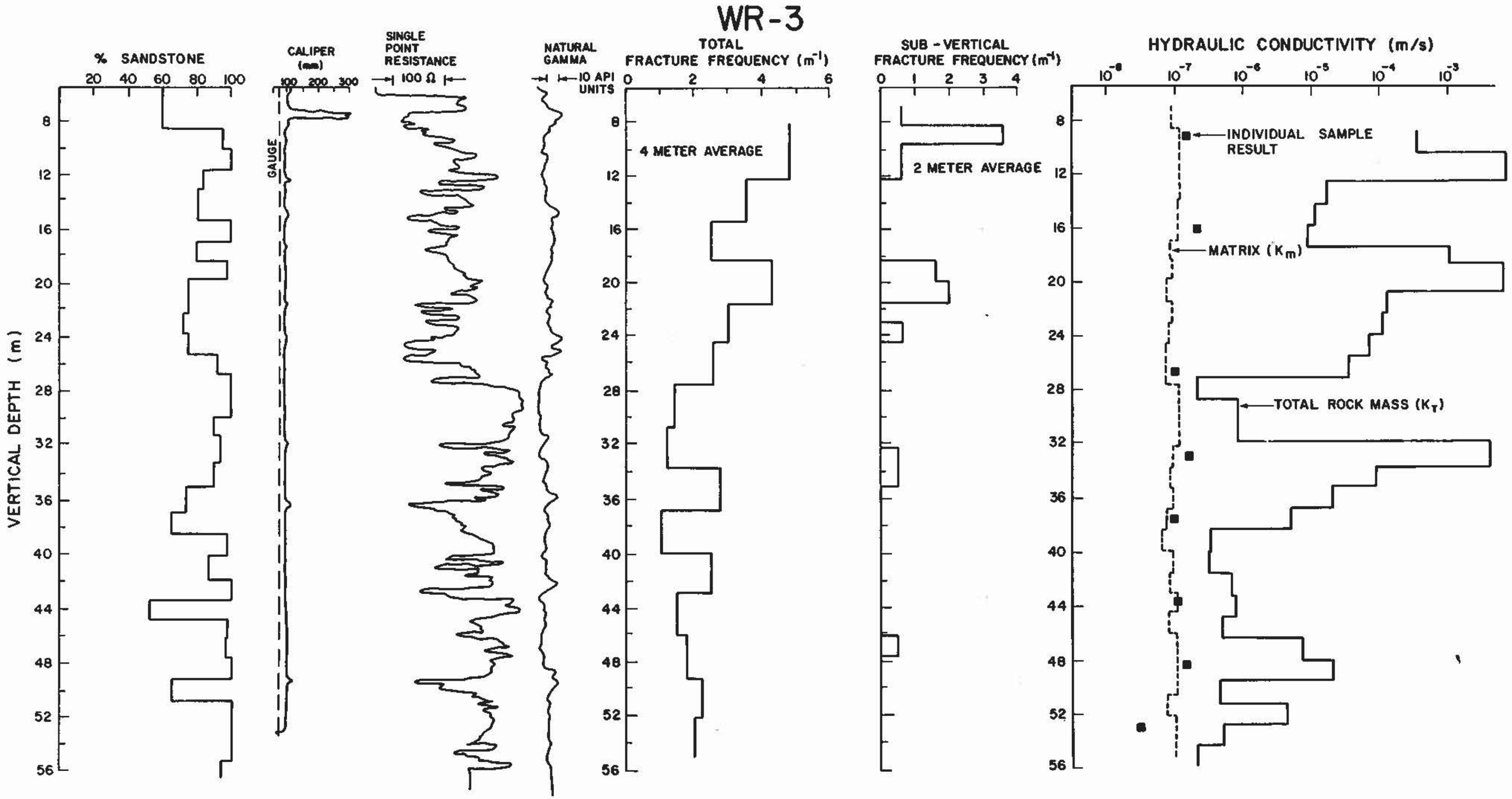


Figure 19. (Cont')



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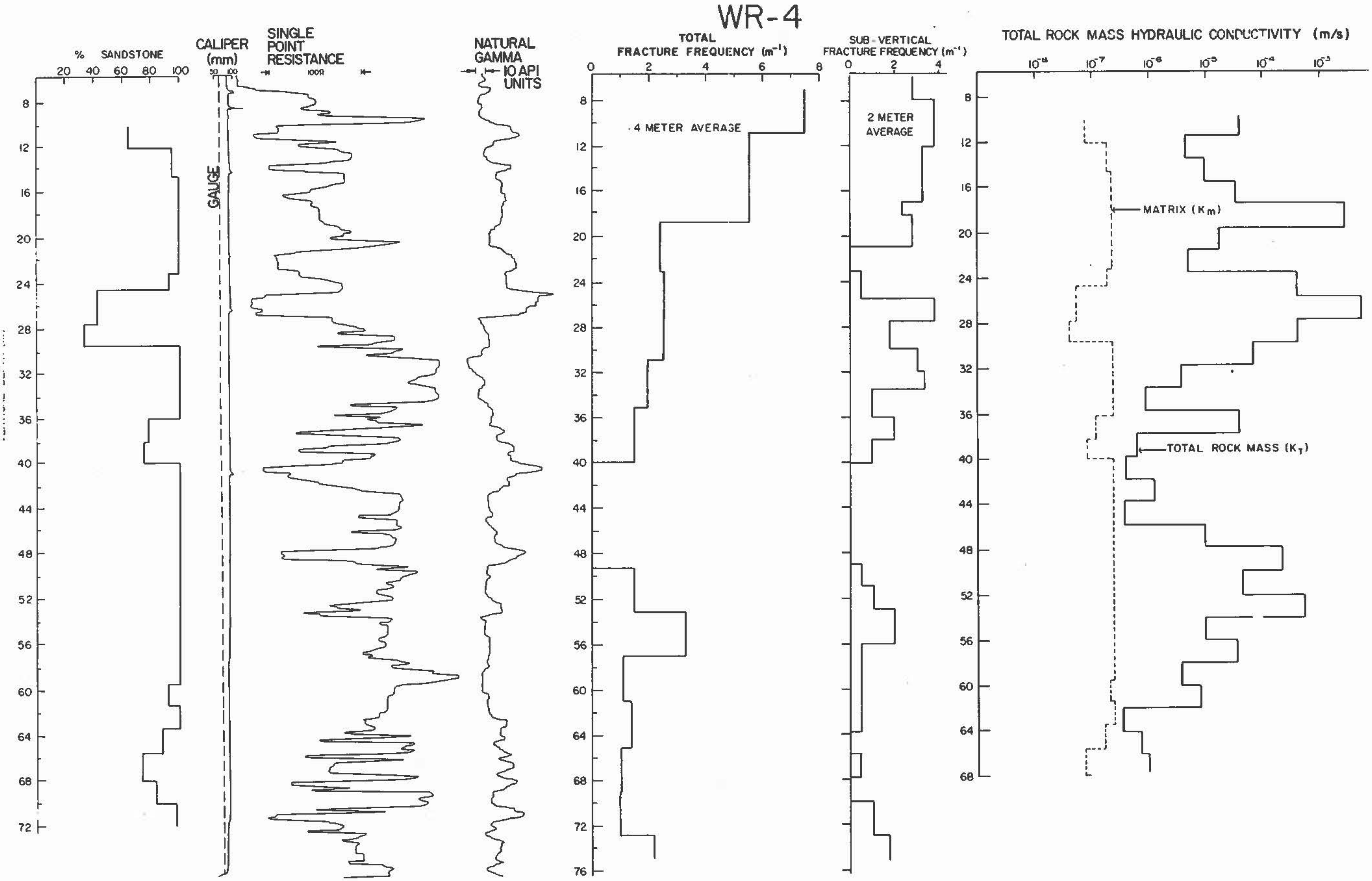

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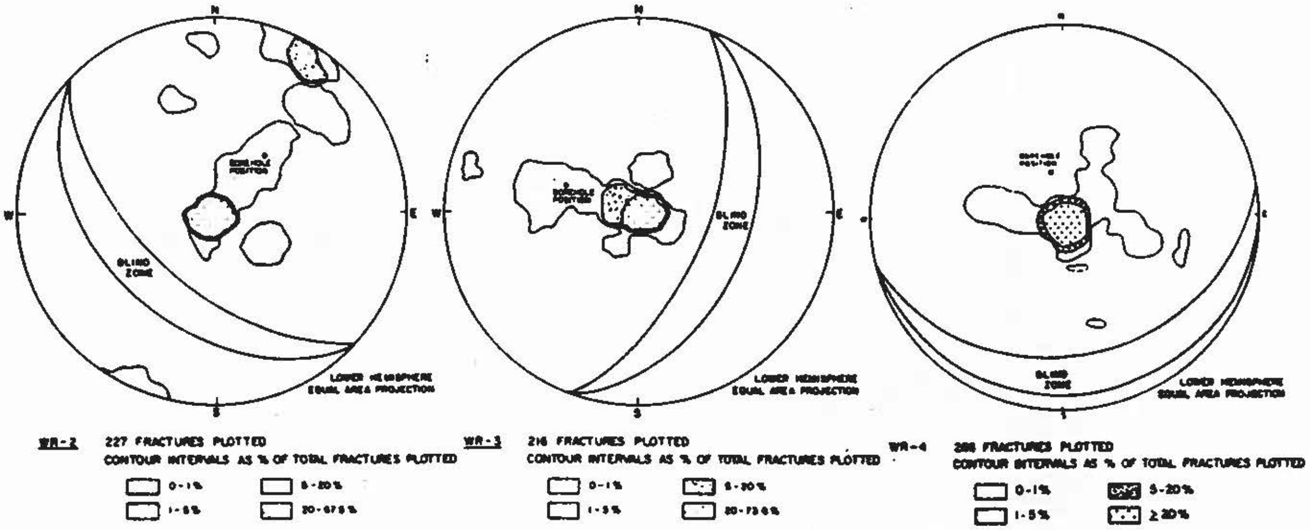


Figure 20. Stereonet of poles to fracture planes, Union coreholes.

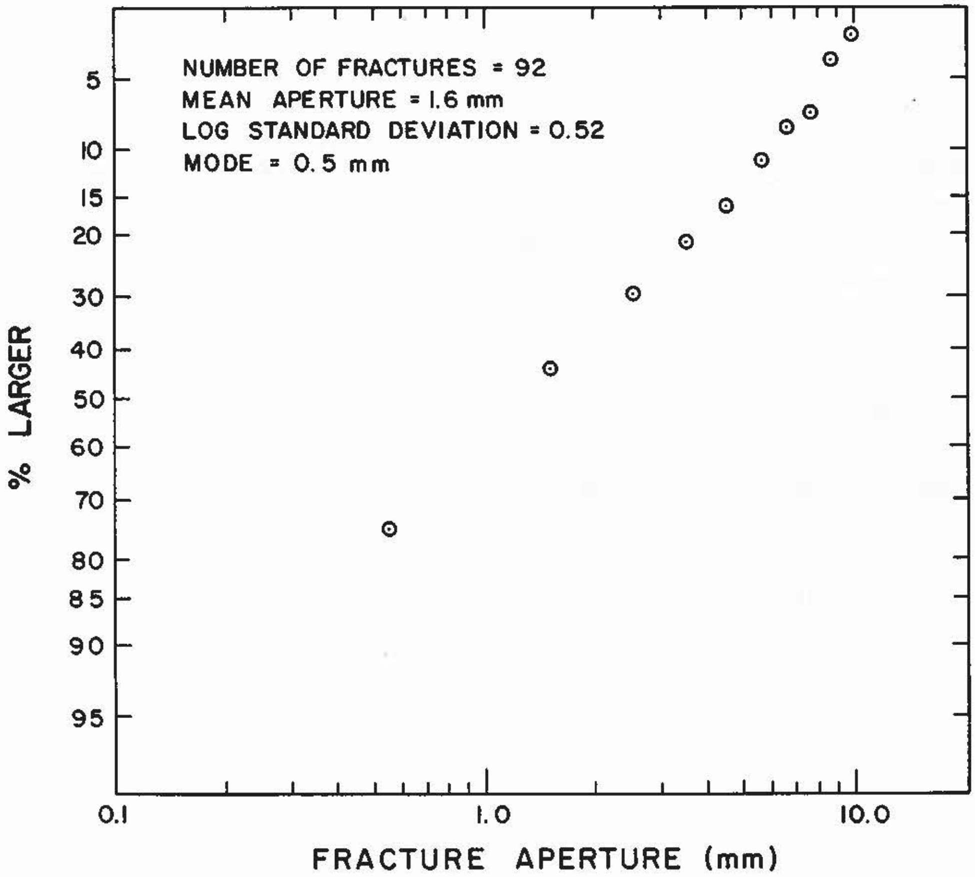


Figure 21. Log-probability plot of apparent fracture apertures measured using a borehole periscope.

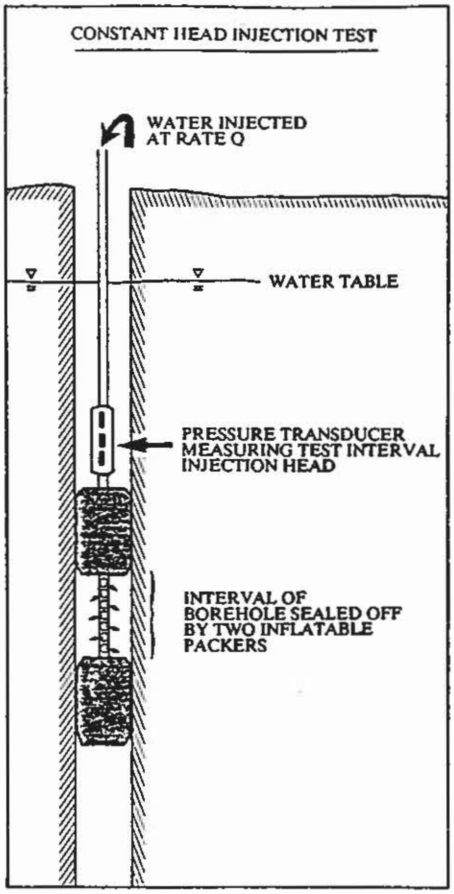


Figure 22. Pneumatic packer assembly, Union test site hydraulic conductivity measurements.

Total equivalent porous media hydraulic conductivity profiles along each borehole are presented in Figure 19. These values, representing the sum of fractures and matrix hydraulic conductivities, range from 10^{-7} m/s to 10^{-3} m/s. A general trend of decreasing hydraulic conductivity with depth was observed in WR-2, WR-3, and WR-4, and a consistent zone of low hydraulic conductivity occurred between 36 m and 45 m vertical depth.

The changes in hydraulic conductivity of three to four orders of magnitude from one test interval to another emphasize the variable properties of the rock mass at this scale. The trend of decreasing hydraulic conductivity is generally consistent with the decrease in total fracture frequency. While bedding plane fractures are, on the whole, the most important fluid conduits, a single subvertical fracture may contribute more to the bulk hydraulic conductivity than a single bedding plane fracture.

Laboratory measurements of intergranular hyudraulic conductivity were conducted to determine (1) the component of flow in injection tests due to flow through the matrix and (2) the variation of intergranular hydraulic conductivity among different rock types and within individual rock types. Utilizing a modified Bernaix type permeameter [26] (Figure 23), constructed at the University of Waterloo, measurements of the hydraulic conductivity of intact core samples were made both parallel to the core axis (axial flow) and perpendicular to the core axis (radial flow).

The results (Table 5) indicate that each rock type exibits a narrow range of hydraulic conductivities both perpendicular and parallel to the core axis. Sandstone values ranged

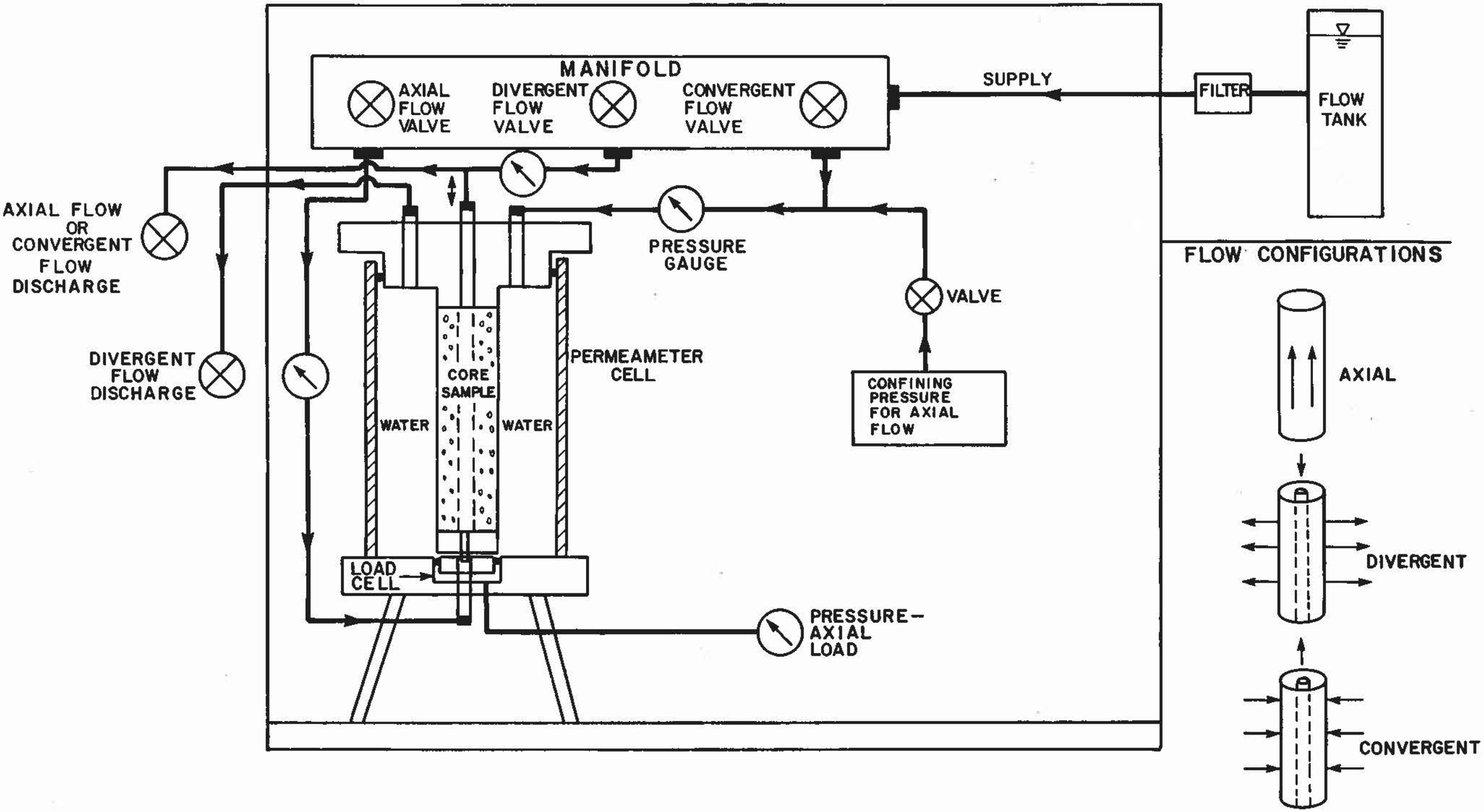


Figure 23. Bernaix permeameter.

from 10^{-8} m/s to 5×10^{-7} m/s. Siltstone and claystone permeabilities were less than 5×10^{-10} m/s. The ratio of horizontal to vertical permeabilities in sandstone samples ranged from 1.5 to 18.5, a function of mica flakes and other horizontal bedding features restricting vertical flow in the core samples. On a larger scale, the strong anisotropy created by the low permeability claystone and siltstone layers and lenses can be expected to locally restrict vertical movement of fluids through the aquifer.

Intergranular hydraulic conductivity estimates for each test interval were calculated based on the percentage of each rock type in the test interval and the above permeability values. Figure 19 shows these results, as well as the individual core sample measurements. The results suggest that the aquifer at Union well field can be considered as two distinguishable

Table 5. Summary of Intergranular Hydraulic Conductivity and Porosity Measurments, Core from Union Well Field Boreholes [8].

Sample No.	Lithology	K_m(Radial)m/s	K_m(Axial)m/s	K_r/K_a	Porosity (%)
1031*	Fg Ss	6.5E-06	3.5E-08	18.5	14.6
1061	Sltst	9.7E-11	<10E-11	>10	
1101	Fg-Mg Ss	2.8E-07	2.7E-08	10.5	
1111	Fg-Mg Ss	1.0E-07	3.8E-08	2.6	17.1
1112	Fg Ss	7.9E-08	5.4E-08	1.5	
1121	Fg Ss	2.3E-08			18.8
1131	Clstn		2.2E-10		38.4
1133	Sltst	4.2E-10	1.1E-10	4.0	
1151	Fg Ss	6.9E-08			
1161	Fg Ss		1.0E-07		21.3
1171	Fg Ss	3.0E-08	2.0E-08	1.5	12.7
1172	Fg Ss	7.5E-08			14.5
1181	Fg Ss	2.2E-08			
1211	Fg Ss		1.7E-07		18.4
1221	Fg Ss		1.4E-08		12.4
1231 (A)	Fg Ss		1.4E-08		13.9
1231 (B)	Fg Ss	2.7E-08	1.4E-08	1.9	
2011	Fg Ss	3.1E-07			
2091	Clyy Sltst	1.2E-10			
2101	Fg Ss	3.0E-08			
2151	Fg-Mg Ss	1.6E-07			
2251	Fg Ss	1.8E-07			
2301	Mg Ss	2.3E-07			
3041	Fg-Mg Ss	1.4E-07			
3091	Fg Ss	2.2E-07			
3161	Fg-Mg Ss	1.0E-07			
3201	Fg-Mg Ss	1.5E-07			
3231	Fg Ss	8.1E-08			
3271	Fg-Mg Ss	9.4E-08			
3301	Fg-Mg Ss	1.2E-07			
3331	Fg-Mg Ss	2.6E-08			

Legend

*1031= Borehole 1, Test Interval 03, Sample 1
K_r = radial hydraulic conductivity
K_a = axial hydraulic conductivity

Sltst - siltstone
Ss - sandstone
Clst - claystone
Clyy - clayey
Fg - fine grained
Mg - medium grained

aquifer zones - an upper highly fractured zone above about 35 m where the total rock mass hydraulic conductivity in two to three orders of magnitude above the matrix value, and a lower, less fractured zone where the total hydraulic conductivity is commonly within a factor of two of the matrix value.

Now that the relative contributions of fractures and matrix have been identified, the statistics of the fracture aperture distribution can be determined for each borehole. This requires a knowledge of the average fracture frequency and the relationship between the size of the fracture apertures and their frequency, i.e. the aperture distribution model [27]. Using the method of analysis described by Snow [27], and assuming a log-normal distribution of fracture apertures, the effective fracture aperture distributions for the upper and lower zones of boreholes WR-1, WR-2, and WR-3 were calculated. The results are listed in Table 6 and shown as a probability plot in Figure 24.

Table 6. Effective Fracture Aperture Distributions [8].

Borehole - Zone	Log $\overline{2b}$ (mm)	$\overline{2b}$ (mm)	Log Standard Deviation (mm)
WR-1 Lower	-0.91	0.12	±(-0.26)
WR-2 Upper	-0.71	0.19	±(-0.34)
WR-2 Lower	-0.88	0.13	±(-0.31)
WR-3 Upper	-0.77	0.17	±(-0.45)
WR-3 Lower	-1.10	0.08	±(-0.37)

The mean fracture aperture in the upper aquifer zone above 35 m is about 0.19 mm, consistently larger than in the lower zone, where the mean aperture is about 0.11 mm, a decrease of over 40 percent. This is very important when we consider that groundwater flow through a fracture is a function of the cube of its aperture. Note that these values are about one-tenth of the apparent apertures estimated from borehole periscope logging (Figure 21). The calculated values include the effects of variations in aperture and roughness in the fracture plane and fracture interconnection. It can be concluded that, at the test site, the decrease in hydraulic conductivity with depth is due to both a decrease in fracture frequency and a decrease in fracture aperture with depth.

A further field study was conducted at the Union test site to determine the effect of fracture geometry on the anisotropy, i.e. directional permeability, of the aquifer [28]. The test design (Figure 25) involved conducting a 72 hour constant rate pumping test in well PW#1 (at 1.3×10^{-2} m^3/s) and observing the response at fourteen observation points in WR-1, WR-2, WR-3, and F (Figure 26). Four aquifer zones were monitored in WR-2 and WR-3 using multiple packer assemblies. WR-1 was a multi-level piezometer.

The Papadopulos method [29] of identifying and quantifying horizontal aquifer anisotropy assumes two-dimensional flow to a well from an infinite, homogeneous, anisotropic aquifer. Using data from at least three observation wells, it determines the principal (T_{max}) and minor (T_{min}) axes and orientation of the ellipse describing the transmissivity of the aquifer. The proportion of flow from each aquifer zone to the pumping well was calculated from the previously determined permeability profiles. In this manner, the directional permeability in three aquifer zones of differing permeabilities could be determined.

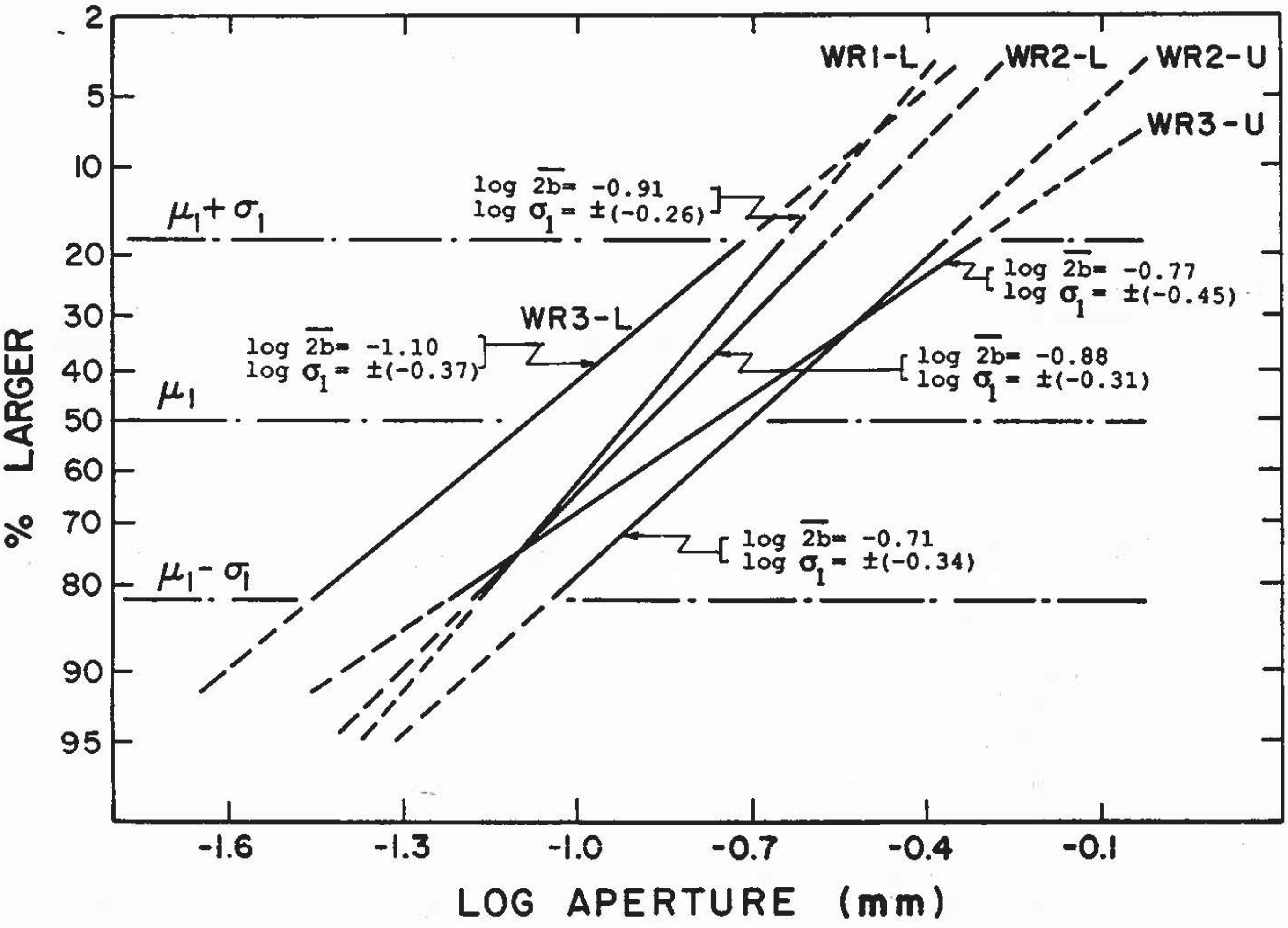


Figure 24. Probability plot of effective fracture aperture distribution.

The aquifer zones were found to have T_{max}:T_{min} ratios of approximately 9:1, 2:1, and 3:1 in P-1, P-2, and P-3 respectively (Table 7). The orientations of the principal axes of the transmissivity ellipses (Figure 27) are very similar for the three zones, with an average azimuth of 147 degrees. This coincides with the general northwest-southeast trend of the vertical and subvertical fractures observed in the borehole cores (Figure 20) and in nearby outcrops [25]. It can be expected that directional permeability in the horizontal plane will have a marked effect on the shape of drawdown cones around pumping wells and may also influence the direction of contaminant transport in the subsurface.

The preceeding section has dealt with detailed, relatively small-scale studies at the Union well field test site. Although these results can only be considered representative of conditions at the test site, they will aid interpretation of hydrogeological observations in the broader-based studies which follow.

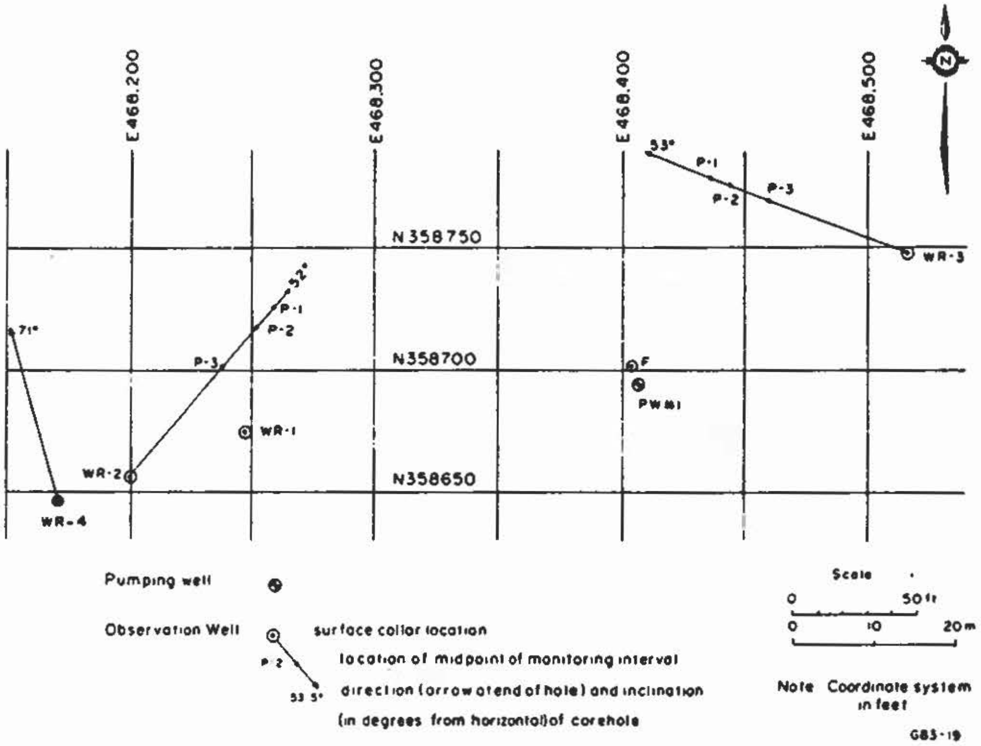


Figure 25. Map of test site for anisotropy study [9].

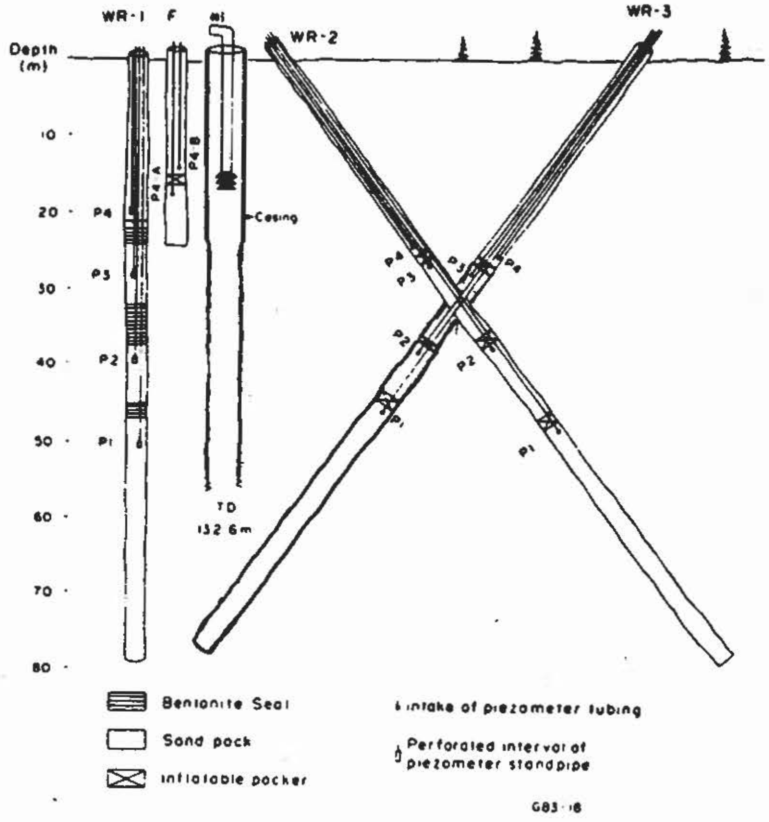


Figure 26. Schematic diagram of observation wells and monitoring zones, anisotropy study [9].

Table 7. Results of Papadopulos Analysis [9].

Aquifer Zone	T_{max} (m^2/s)	T_{min} (m^2/s)	$(T_{max} \bullet T_{min})^{1/2}$ (m^2/s)	Azimuth of T_{max}	Storativity
P-1	1.8E-03	2.0E-04	6.0E-04	136°	1.3E-04
P-2	1.5E-04	7.5E-05	1.1E-04	149°	2.2E-04
P-3	4.1E-03	1.3E-03	2.3E-03	157°	4.9E-04
			$\Sigma = 3.0E-03$		

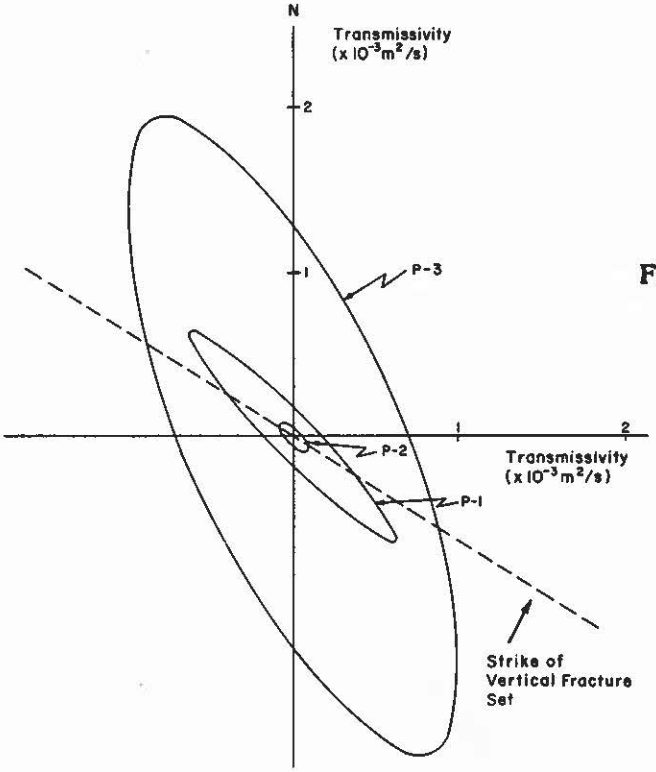


Figure 27. Magnitude and orientation of transmissivity ellipses for the three aquifer zones at Union well field [9].

4.2.4. Regional Distribution of Hydraulic Conductivity and Hydraulic Head

Freeze [30] describes a groundwater basin as ".. a three- dimensional, closed system containing the entire flow paths followed by all water recharging the basin ..". The chief variables which determine the path and rate of groundwater flow in the basin are the hydraulic conductivity and the gradient in groundwater potential, or hydraulic head. The relationship is given by Darcy's law:

$$q = -K\, dH/dl$$

where q is the groundwater flux or specific discharge (L/T), K is the hydraulic conductivity (L/T), H is the hydraulic head (L) and dH/dl is the hydraulic gradient.

A two-dimensional map of hydraulic head distribution in the basin (Figure 28) was prepared by Environment Canada [25] from water level measurements in private water wells. This map, having a contour interval of 5 m, provides a general picture of groundwater flow in the horizontal plane at the water table.

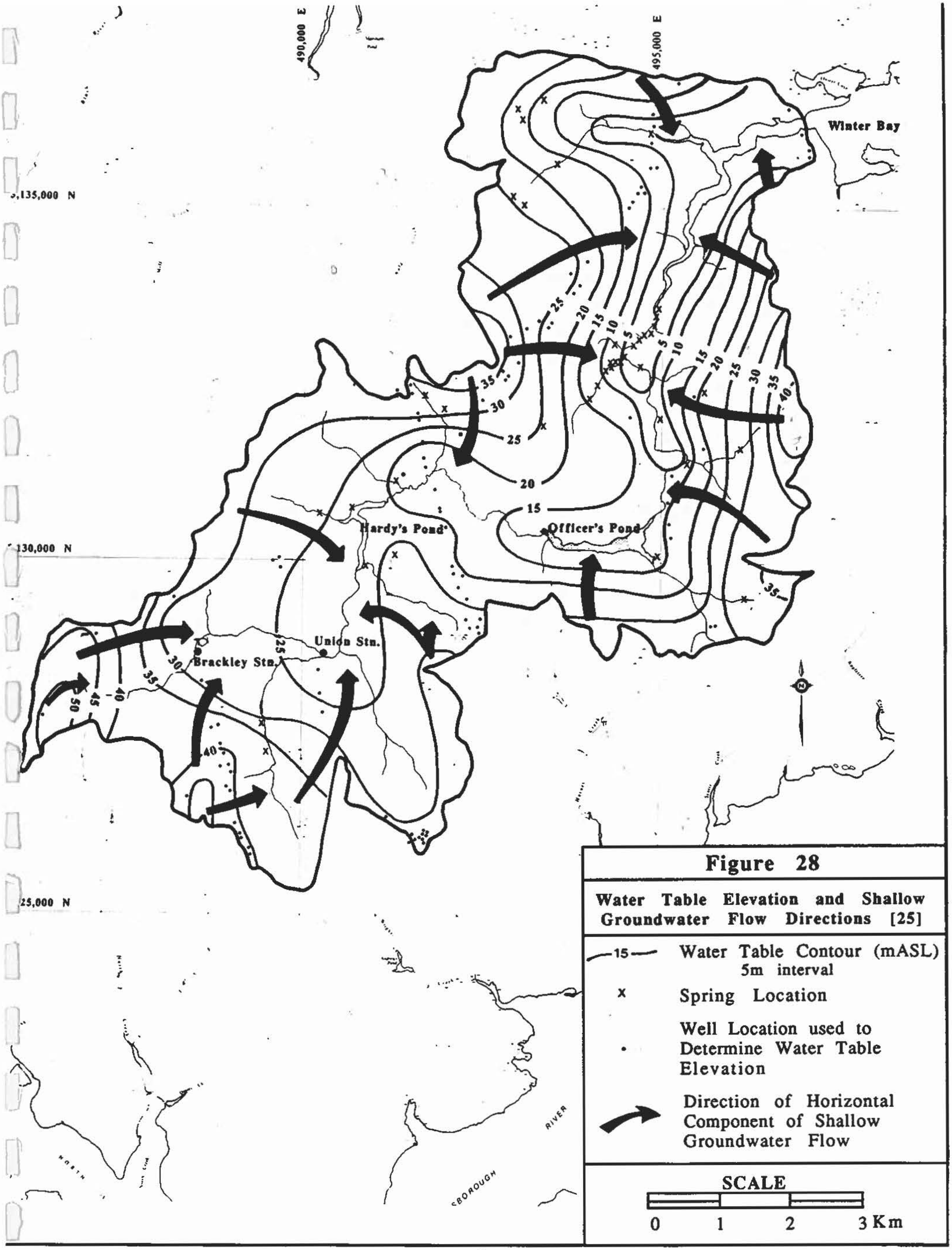


Figure 28

Water Table Elevation and Shallow Groundwater Flow Directions [25]

An additional study has been carried out [31] to measure the three dimensional distribution of hydraulic head and hydraulic conductivity in the basin as a function of depth, location, and lithology. The locations of the seven 150 m boreholes drilled for this study were shown previously in Figure 7 (Section 3.1.2). Geological logs were presented in Figure 8.

A borehole testing program was designed to measure hydraulic conductivity and hydraulic head in specific intervals along each borehole length and to allow collection of groundwater samples from isolated test intervals. A system of two pneumatic packers with one metre gland lengths and a packer spacing of 15 m provided the test interval isolation (Figure 29). Water level measurements were made in manometers above, below, and within the test interval. In high permeability zones, these levels stabilized within minutes but in low permeability zones, several days were sometimes required for a stable water level to be recorded.

The permeability of each test interval was determined utilizing a constant rate pumping test. Measurements of flow rate and drawdown were made until pseudo-steady state conditions were attained. In most intervals, several flow rates and respective drawdowns were recorded to characterize the relationship between these two variables. Water samples were collected for geochemical analyses after sufficient pumping to completely exchange the interval contents.

Data were analyzed using the steady state form of Darcy's law for radial flow:

$$q = -K\, dH/dr$$

where q is the specific discharge, K is the hydraulic conductivity of the medium, H is the hydraulic head, and r is the radial distance from the borehole. When the hydraulic conductivity is due to both fractures and matrix, it can be termed the equivalent rock mass

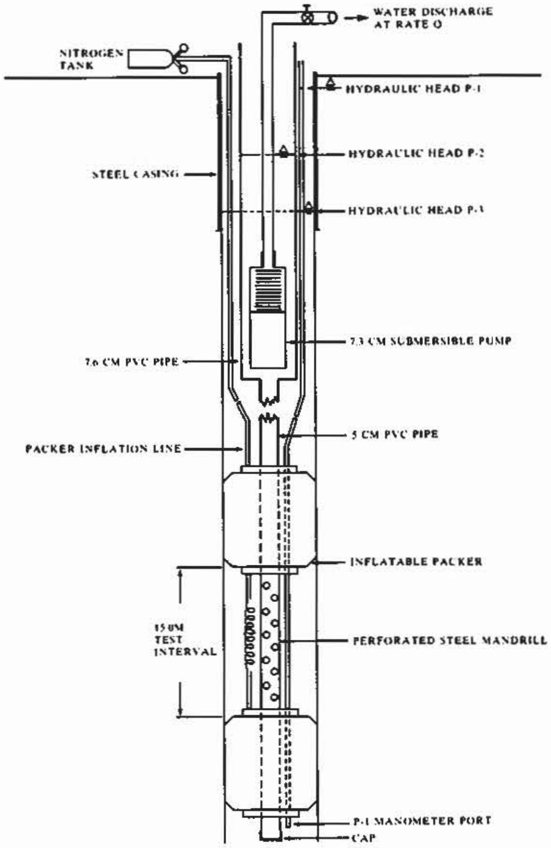


Figure 29. Schematic of downhole testing equipment, deep borehole testing [31].

hydraulic conductivity (K_e) and, over a test interval (L), is related to the flow rate for the test (Q) by:

$$K_e = \frac{-Q \ln(r_i / r_w)}{2\pi L (\Delta H)}$$

where r_i is the radius of influence of the test, r_w is the borehole radius and H is the drawdown at steady state. This equation was used to calculate the hydraulic conductivity of each test interval in this study. A radius of influence of 10 m was assumed for all tests.

Figure 30 illustrates three typical flow rate/drawdown relationships. Examples A and B are indicative of 22 of the 66 zones tested, where the relationship showed decreasing $\Delta Q / \Delta H$ slope with increasing Q. This has been interpreted to be the result of turbulent flow in the fracture planes during such tests [8, 32, 33]. In these zones the results were based on lowest flow rate data. In other zones, the $\Delta Q / \Delta H$ slope was relatively constant (Example C), indicating laminar flow conditions.

Profiles of hydraulic conductivity, hydraulic head and bedrock geology (expressed as percent sandstone) are presented in Figure 31. Hydraulic conductivity values ranged from a maximum of about 10^{-3} m/s in the upper test interval of borehole Y-35 to a minimum of about 10^{-7} m/s in the lowest intervals of several boreholes. The profiles show that the permeability of the bedrock aquifer generally decreases with depth in all locations. The lowest values are equivalent to intergranular hydraulic conductivity values measured on

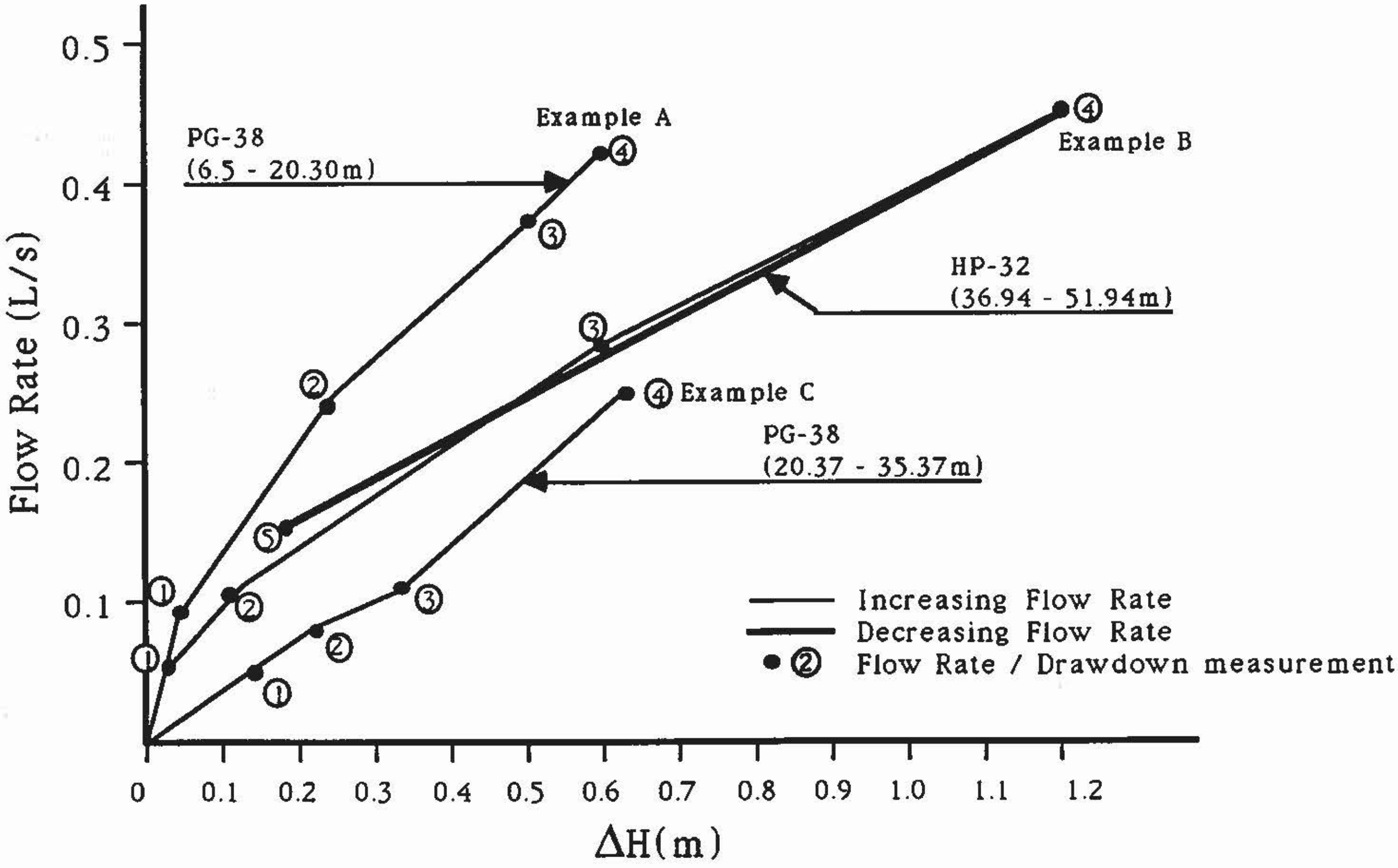


Figure 30. Characteristics of the flow rate - drawdown relationship for three test intervals [31].

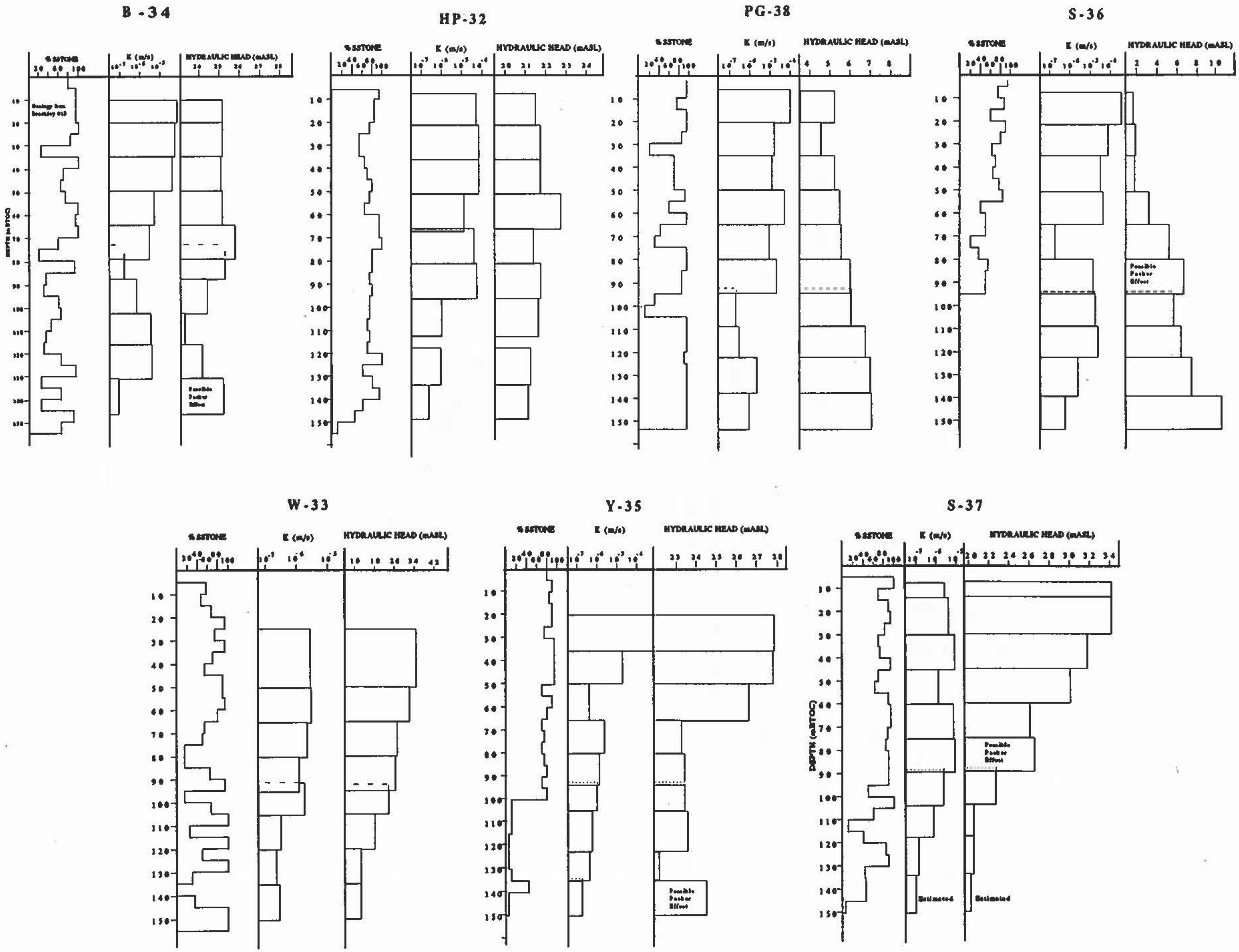
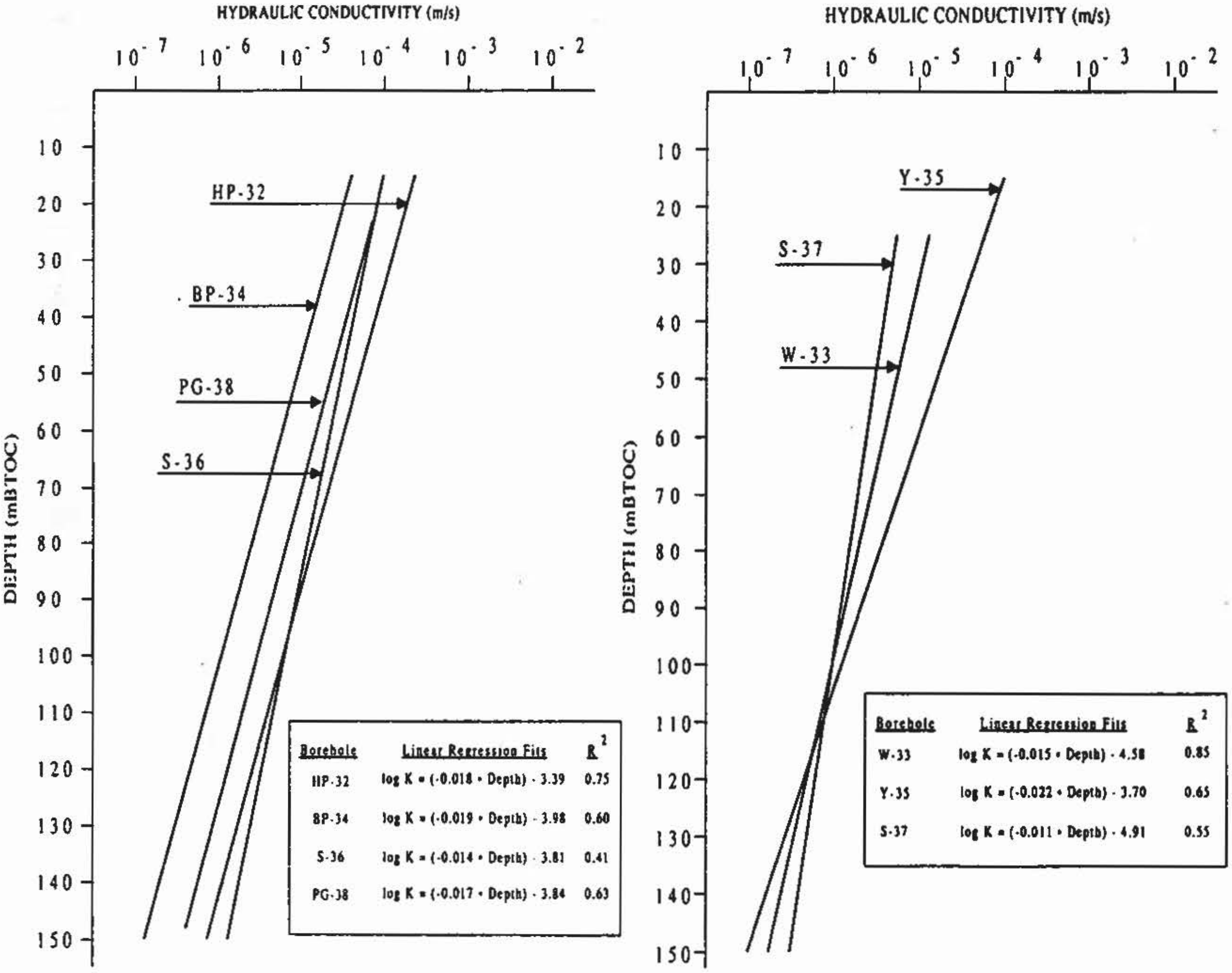


Figure 31. Profiles of lithology, hydraulic conductivity, and hydraulic head as a function of depth in seven 150 m boreholes.

core samples (Table 5). At the scale of these tests, lithological changes generally do not correlate with variations in hydraulic conductivity. It would appear that the less permeable siltstone and claystone beds are sufficiently thin that the permeability of the adjacent fractured sandstone in a test interval is the dominant factor.

Linear regression analyses were conducted to examine the variation of hydraulic conductivity with depth for each borehole (Figure 32). The midpoint of each test interval was chosen as the interval depth. The regressions clearly show the reduction in hydraulic conductivity with depth. Even though the coefficient of variation (R^2) for each profile ranges from 0.41 (S-36) to 0.85 (W-33), the similarity of the slope and intercept values for the individual regressions emphasizes the consistency of hydraulic conductivity trends at this scale across the basin. The individual fits are well represented by the overall regression fit (Figure 33) which shows an average reduction in hydraulic conductivity of an order of magnitude for each 60 m depth.

Frequency distributions of permeability values from all boreholes for depth zones 0-50 m, 50-100 m and 100-150 m below surface, are also shown on Figure 33. These show the order-of-magnitude decreases in the modal values from zone to zone and the permeability range shift toward lower values with depth. The truncation of the distribution in the 100-150 m interval at about 10^{-7} m/s is indicative of the matrix permeability's increasing importance at depths over 100 m.



Borehole	Linear Regression Fits	R^2
HP-32	log K = (-0.018 • Depth) - 3.39	0.75
BP-34	log K = (-0.019 • Depth) - 3.98	0.60
S-36	log K = (-0.014 • Depth) - 3.81	0.41
PG-38	log K = (-0.017 • Depth) - 3.84	0.63

Borehole	Linear Regression Fits	R^2
W-33	log K = (-0.015 • Depth) - 4.58	0.85
Y-35	log K = (-0.022 • Depth) - 3.70	0.65
S-37	log K = (-0.011 • Depth) - 4.91	0.55

Figure 32. Linear regression fits for hydraulic conductivity versus depth, seven 150 m boreholes [31].

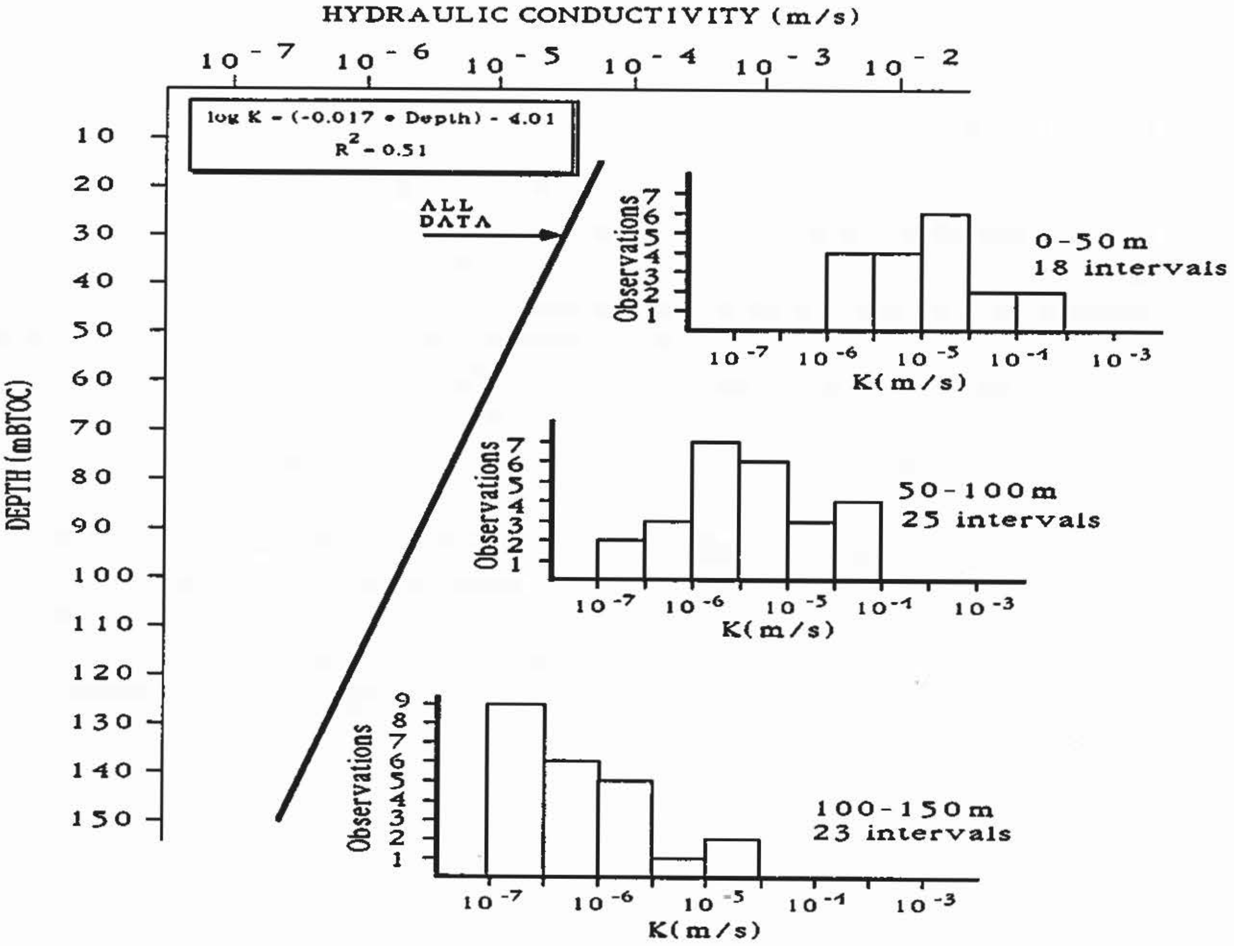


Figure 33. Linear regression fit and frequency distributions, hydraulic conductivity versus depth, all boreholes [31].

The composite frequency distribution (Figure 34a) for all permeability values from all boreholes shows an equal distribution of values in the 10^{-4} m/s to 10^{-7} m/s range over the 150 m depth investigated, and a much less frequent occurrence of values above 10^{-4} m/s. This means there is an equal probability of a random 15 m test interval in the upper 150 m of the aquifer yielding a permeability value anywhere from 10^{-7} m/s to 10^{-4} m/s. Investigation to further depths would no doubt increase the frequency of the lower permeability values.

A composite permeability distribution histogram for three 60 m boreholes (WR-2, WR-3, WR-4) at Union well field [28] is shown in Figure 35(b). Note that permeability measurements were made using injection tests on two metre intervals. The histogram shows a bimodal distribution with the right side very similar to the distribution observed in the 0-50 m zone of Figure 34, and the left side indicative of the intergranular permeability encountered when the two metre test interval did not include open fractures. Obviously one is very likely to encounter open fractures in the 0-50 m zone using a 15 m packer spacing. Fifteen metre intervals exhibiting intergranular permeability values are not common until the 100-150 m depth range. Therefore, the reduction in fracture frequency and fracture aperture with depth previously identified probably continues to depths of at least 150 m.

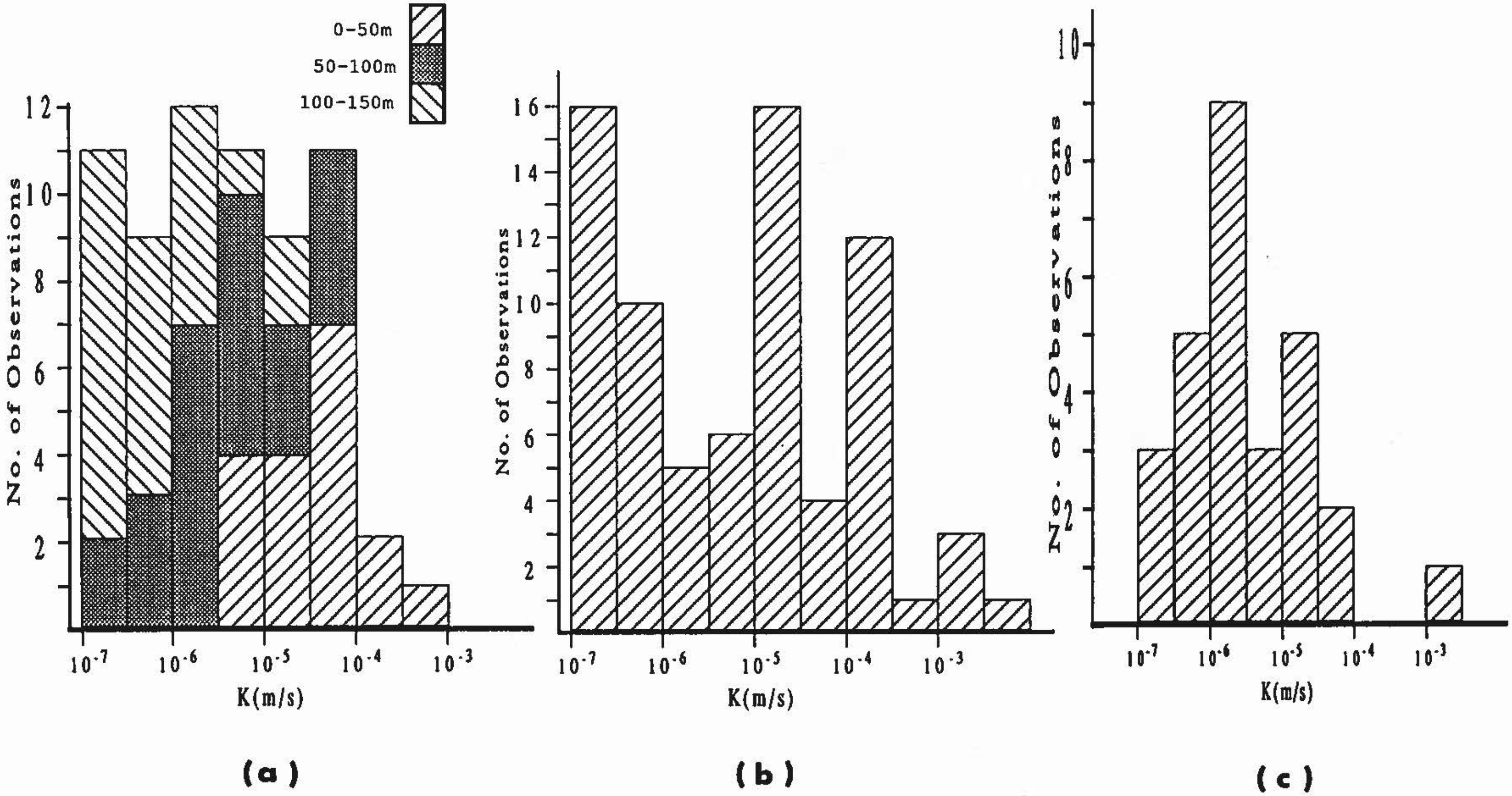


Figure 34. Composite hydraulic conductivity distributions (a) 150 m boreholes (b) Union well field (c) Augustine Cove.

As a further comparison, Figure 35(c) shows composite hydraulic conductivity distribution adapted from the results of 28 slug tests conducted in three coreholes at a test site near Augustine Cove, Prince Edward Island [34]. The coreholes, drilled to depths of 25 to 35 m, were tested in two metre intervals. The results at that location show that although fractures were present in all intervals tested, the hydraulic conductivity values are, on average, 50 to 100 times lower than in the same depth range within the Winter River basin.

The hydraulic conductivity profiles in our study were also analysed to evaluate correlations between the permeability of a test interval and its geodetic elevation, i.e., a possible horizontal layering of the aquifer zones, as opposed to the 'depth-below-surface' permeability function suggested by the data above. There was no significant relationship between bedrock permeability and geodetic elevation of the test interval.

The permeability data lead one to conclude that development of high capacity wells will be most successful in areas of high water table where the upper, most permeable zone is saturated and can be utilitized for water supply. Any contamination of the upper-most portion of the aquifer could have serious implications for both the potential yield of the aquifer and the cost of water supply if deeper, lower capacity wells need be constructed. Drilling wells to depths beyond 75-100 m in hope of increasing well yields is not likely to be cost effective. Location in the basin, in terms of local geology, does not appear to be an important factor in selecting optimum production well locations.

Profiles of hydraulic head as a function of depth for each borehole are shown in Figure 31. Three boreholes, W-33, Y-35, and S-37, are in areas of high hydraulic head and strong downward gradients. These boreholes are located at relatively high elevations near the watershed boundary. Two boreholes, S-36 and PG-38, are in areas of low hydraulic head and upward gradients and are located near the river in the lower half of the basin. HP-32 has intermediate head values with an upward gradient in the upper zone and a slight downward gradient at depth. Hydraulic head values at B-34 are strongly affected by well field pumping so that any natural gradients have been effectively erased. The intervals 52-67 m at HP-32 and 138-153 m at S-36 were both flowing artesian.

Topography is the predominant factor determining hydraulic head distribution. The highest elevations can be expected to be strong recharge areas, the low elevations near the river and the coastline, strong discharge areas. At the scale of these tests, geology does not appear to be a major factor in determining the distribution of hydraulic head. However, the abrupt changes in hydraulic head between some intervals is likely a result of restricted vertical hydraulic conductivity due to low permeability, poorly fractured claystones or siltstones. The regular, gradual change in vertical gradient observed in several boreholes suggests reasonably good vertical communication and a lack of any widespread confining layers which establish hydraulic barriers in those areas. The groundwater flow system in the basin will be discussed further in Section 7.

The combination of relatively high permeabilities and large vertical gradients observed in this study explains a number of phenomena observed in wells drilled in the bedrock aquifer. 'Cascading streams' are flows of water into a well from above the standing water level in the well. These results suggest that cascading streams are due to the open borehole exhibiting a water level which represents an average hydraulic head along the well bore, weighted in favor of the more permeable intervals. Thus, the standing water level in a well in an area with strong downward gradients may be below the true water table by several metres, and water will cascade from fractures between the water table and the standing water level in the well. The well is essentially pumping itself, top to bottom, and can result in deep wells dewatering adjacent shallow wells.

A second phenomena is contaminant migration through open wells. The high gradients and high permeabilities can cause large volumes of groundwater, in the order of tens or hundreds of litres per minute, to move from zones of high head to zones of low head. In an area of downward gradients, with a contaminated aquifer zone near the water table, the contaminant is quickly moved down the well to lower portions of the aquifer with potentially serious consequences.

Thirdly, flowing artesian wells are uncommon when wells are open-hole completions because the high pressure zone pumps its water into permeable lower pressure zones without much increase in the water level in the well.

4.2.5 Groundwater Level Fluctuations

The position of the water table and water table fluctuations in the overburden were discussed in Section 4.1.3. Seasonal and long-term variations of hydraulic head in the bedrock aquifer will be reviewed in this section.

Continuous hydrographs for the period 1984 - 1988 inclusive are available from seven bedrock observation wells in the basin area: 8-U, 11-U, 12-U, Brackley well field, Union well field, Harrington, and Charlottetown Airport #7; and overburden piezometer 9-U. The locations of these are shown in Figure 7 and Figure 11. Well construction details for the first four are presented in Appendix 2. For the others this information is given in Table 8.

The pumping station observation wells have been in operation since 1981 and are influenced by well field operation. These hydrographs have been smoothed to remove the short-term, off-on pumping effects. The Harrington observation well and Airport #7 have been in operation since 1974 and 1977, respectively, as part of a provincial groundwater observation well network. The Brackley Point Road well is just outside the Winter River basin.

Wells 8-U, 9-U, 11-U, 12-U, Airport #7, and Brackley Point Road can be considered water table wells because they are drilled only to the first bedrock fracture zone after the water table is reached. The two locations at the well fields are open hole completions but are relatively shallow and reflect near-surface hydraulic head values.

Figure 35(a) and 35(b) present five year hydrographs for each of the observation wells from 1984 to 1988. Figures 36(a) and 36(b) show maximum, minimum and mean monthly values for the period of record at each location. The hydrographs from locations outside the direct well field influence show that groundwater levels typically reach a peak in April or May of

Table 8. Observation Well Information.

Observation Well	Depth(m)	Diameter(cm)	Casing Length(m)	Elevation (m) Top of Casing
Brackley Well Field	11.9	15	9.5	31.73
Union Well Field	24.4	15	12.2	27.28
Harrington	Approx. 20	15	Approx. 6	39.97
Charlottetown Airport #7	17.4	10	6	57.4

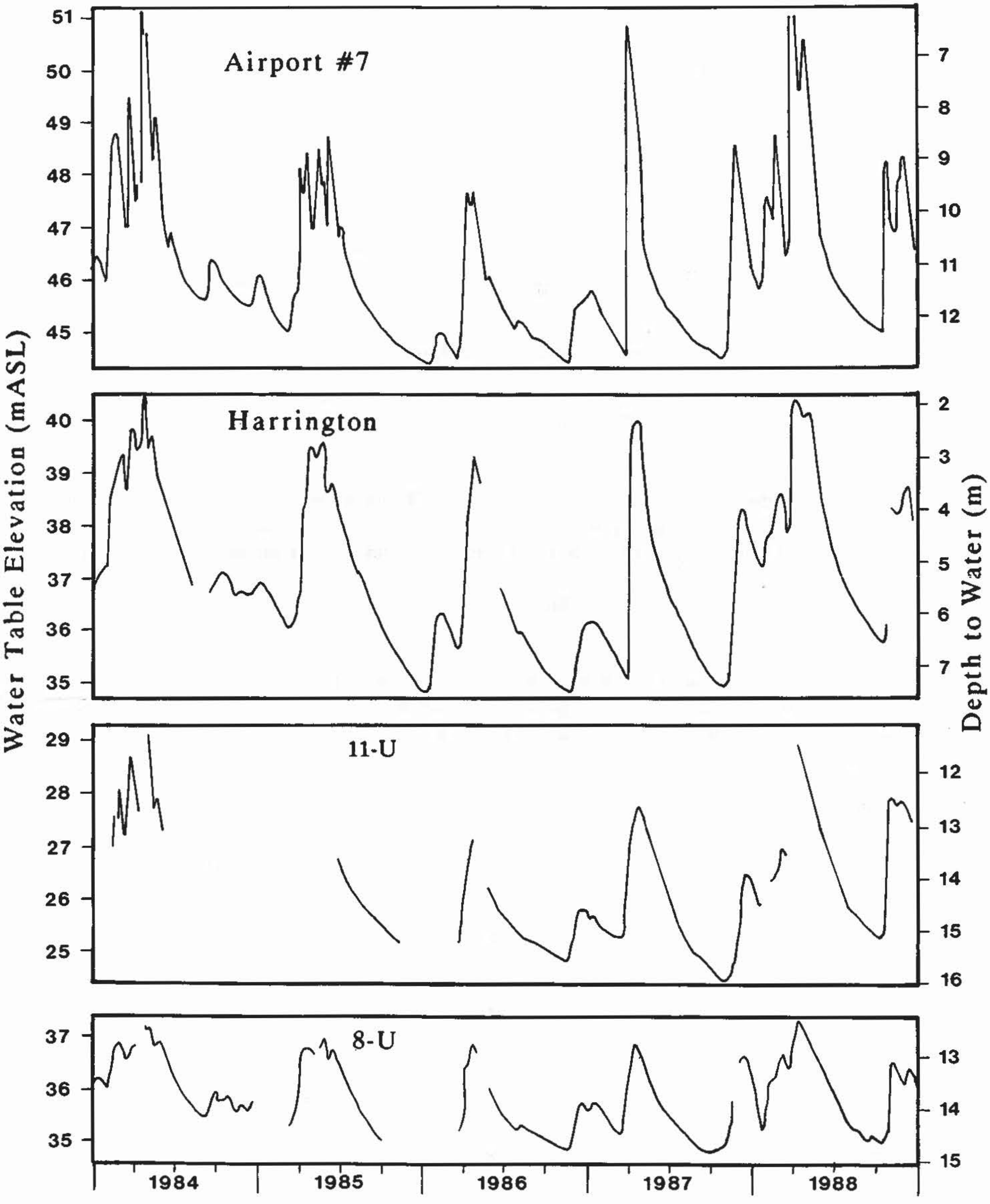
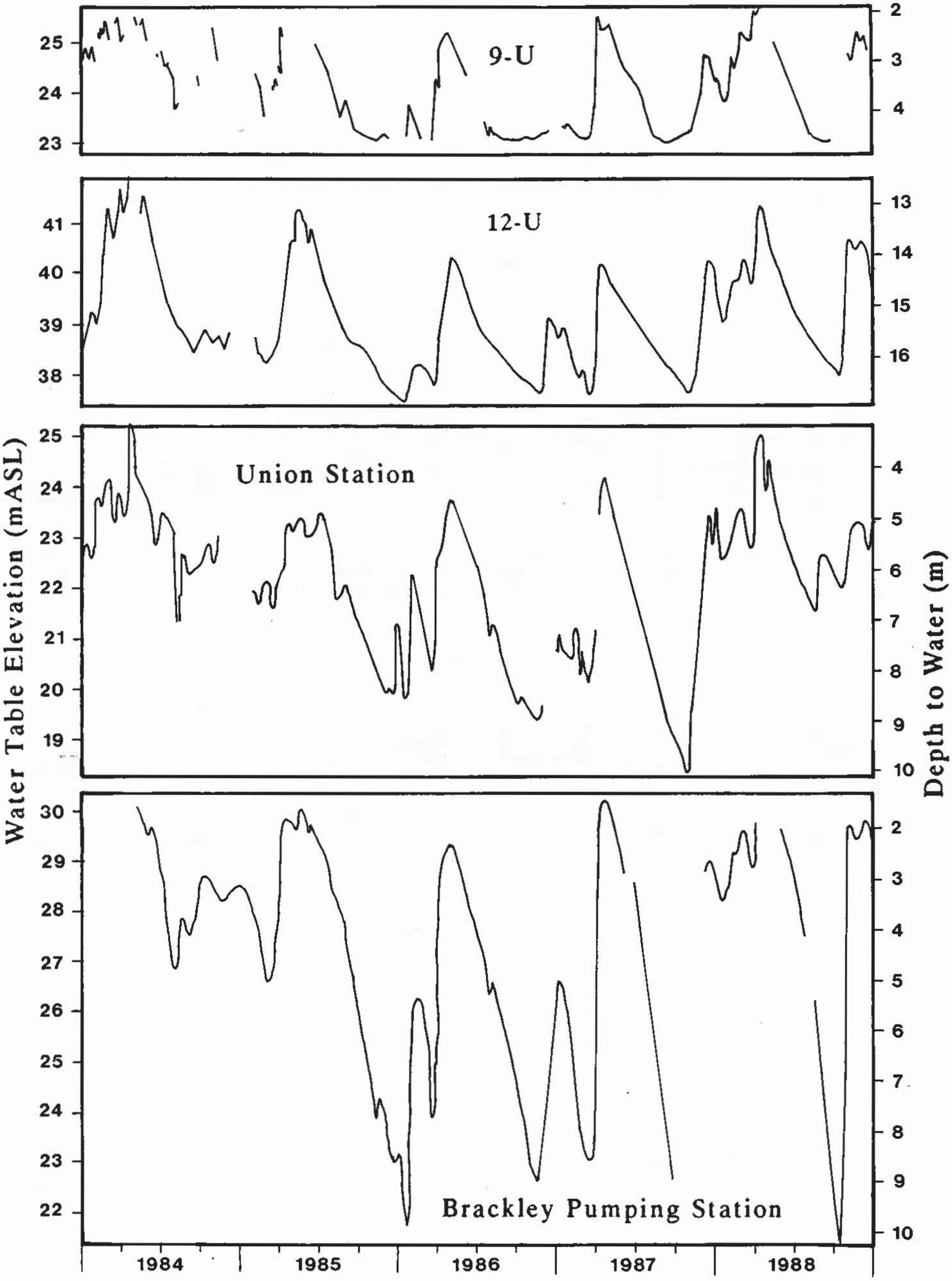


Figure 35. Groundwater hydrographs, 1984-88, several locations.



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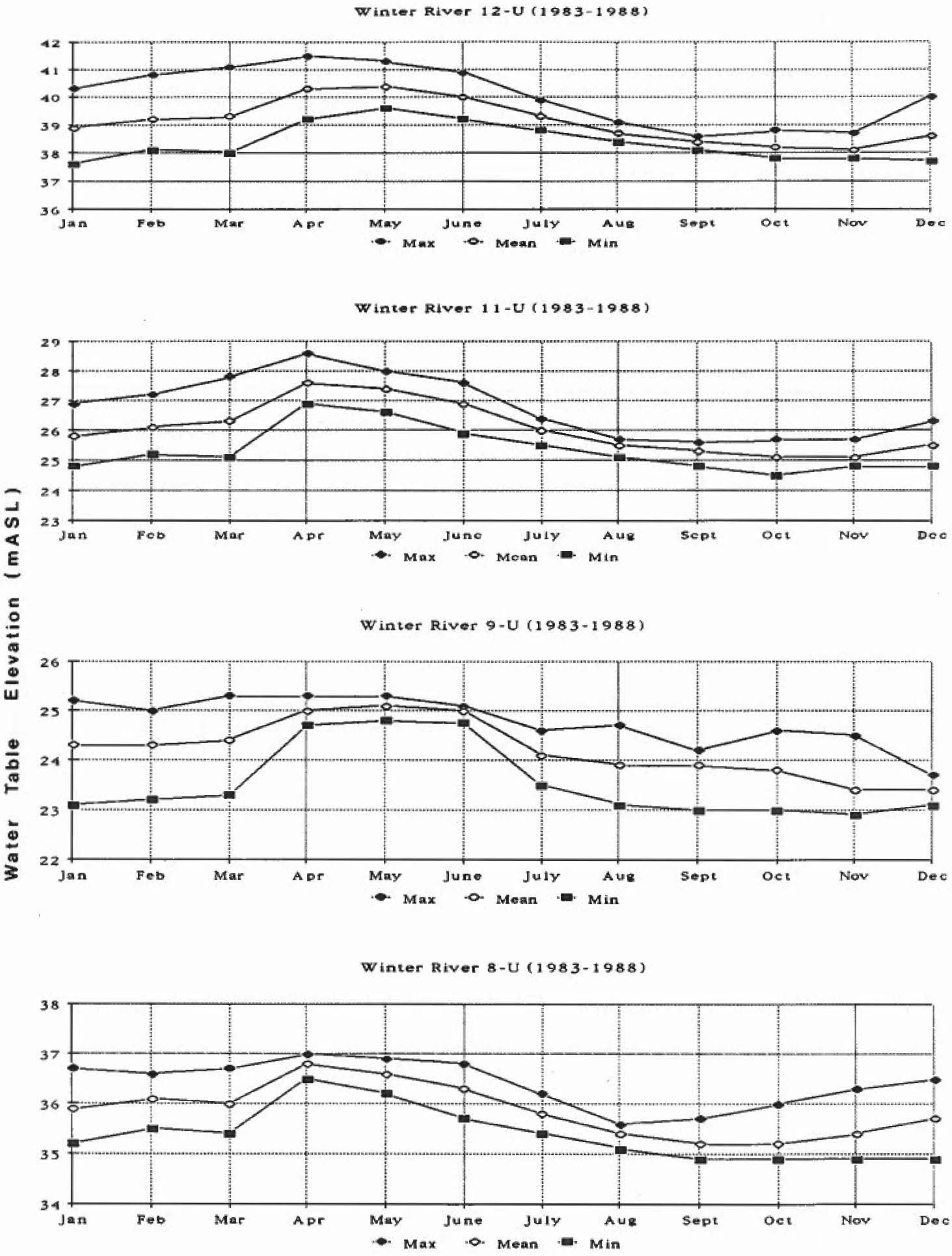


Figure 36. Maximum, minimum and mean monthly groundwater hydrographs for available period of record, several locations.

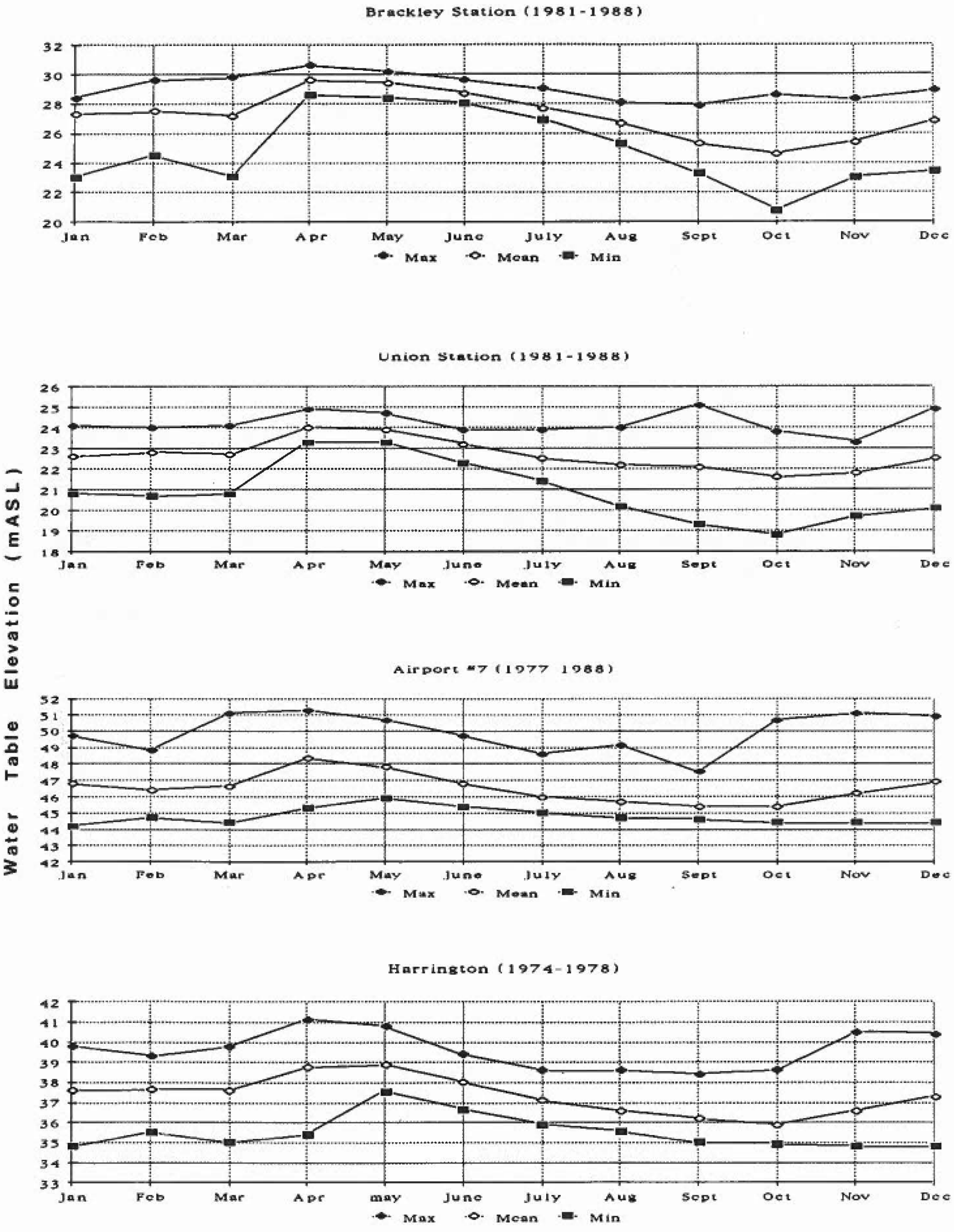


Figure 36. (Cont')

each year when warming temperatures, melting snowpack, and spring rains promote rapid groundwater recharge. Groundwater levels then gradually decline until September or October, with no recharge to the groundwater system unless rainfall exceeds evapotranspiration for a lengthy period, a particularly wet summer season. Consequently, as evapotranspiration decreases in the fall, rainfall increases soil moisture and, pending sufficient fall rains, a secondary recharge event occurs. The lowest water levels are typically recorded in the winter of years when no fall recharge occurs (e.g. 1985 - 1986, Figure 35, 36). Recharge events in the December-March period are relatively common, a result of winter rain and snowmelt. Frost is commonly up to a metre thick in the winter months and while its presence appears to reduce the recharge rate, it does not prevent recharge.

The magnitude of water level fluctuations is a direct reflection of the elevation of the observation well, and thus its position in the groundwater flow system. For example, the March-October groundwater recession in 1987 was over 6 m at Charlottetown Airport #7, 5 m at Harrington, 3 m at 11-U, and 2 m at 8-U. The steep slope of the summer recession curves in upland areas (Airport #7 and Harrington) is a result of rapid flux of groundwater from areas of high hydraulic head to areas of low hydraulic head, the rate of flux declining as water levels recede and gradients decline. Water table response is much 'flashier' at higher elevations due to the strong downward gradients in those areas (Section 4.2.4). Water table response is 'damped' at lower elevations (e.g. 8-U) because of lower vertical gradients (or even upward gradients) and the inflow of groundwater from higher elevations. The range of mean monthly values is also subdued at lower elevations.

At Union and Brackley welll fields, the observation wells are within the drawdown cones of the various production wells. Pumping rates at each well field are relatively constant, although production wells automatically cut in or are shut off as required. The hydrographs are very similar to those from outside well field influence, responding to seasonal recharge events and summer recession. The notable difference is the very large amplitude of the annual recessions, some 7 m to 9 m at Brackley and 4 m to 6 m at Union. The response is most similar to the Airport #7 and Harrington observation wells in their 'flashy' response to recharge events. This is a result of the strong downward gradients created by continuous groundwater withdrawal at a rate of about 73 L/s in each well field. Water table decline is much reduced by significant recharge (e.g. fall of 1984) but is much increased when fall recharge events are delayed (e.g. fall of 1987). Water table decline in the early part of the summer recession is not as rapid as at Airport #7 and Brackley Point Road because the well field areas benefit from the flow of groundwater from the upland areas. This points out that, other factors being equal, locating production wells near discharge areas will be more economical due to lower drawdowns during recession periods.

Mean annual groundwater levels at each observation well, along with annual maximum and minimum values, are shown in Figure 37. Airport #7 and Harrington locations, with the longest period of record, show that mean annual water levels vary by less than two metres. No general trend of decreasing groundwater levels is observed. Also shown in Figure 39 is total annual precipitation at the Charlottetown 'A' meteorological station (Figure 1). Variations in mean annual groundwater levels are primarily due to variations in total annual precipitation. Maximum and minimum values each year generally follow a similar trend, the years with less evenly distributed precipitation showing more extreme variability.

Mean annual groundwater levels at the pumping station observation wells have a remarkably similar behaviour pattern. No continual recession in the average position of water

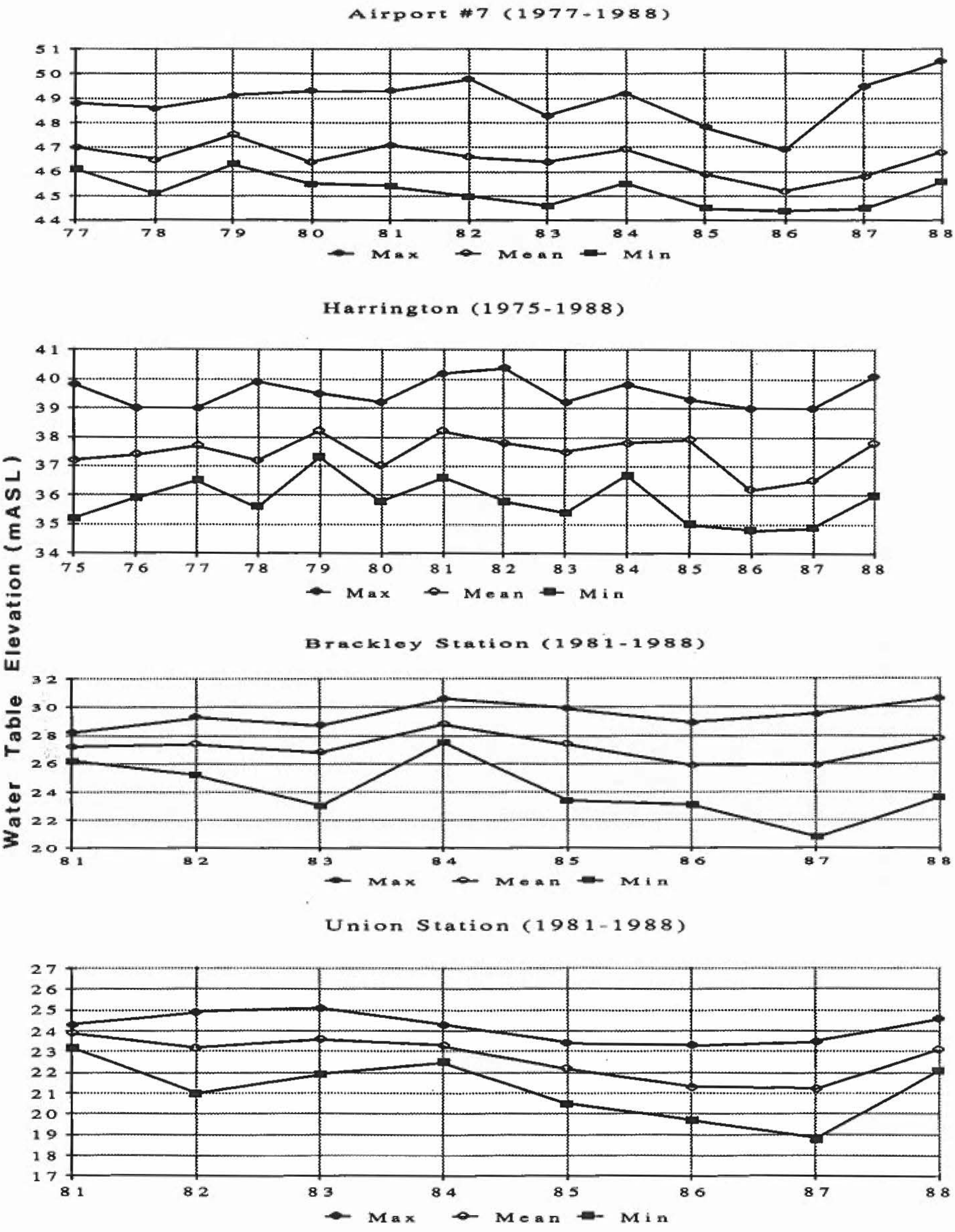


Figure 37. Maximum, minimum and mean annual groundwater hydrographs for available period of record, several locations.

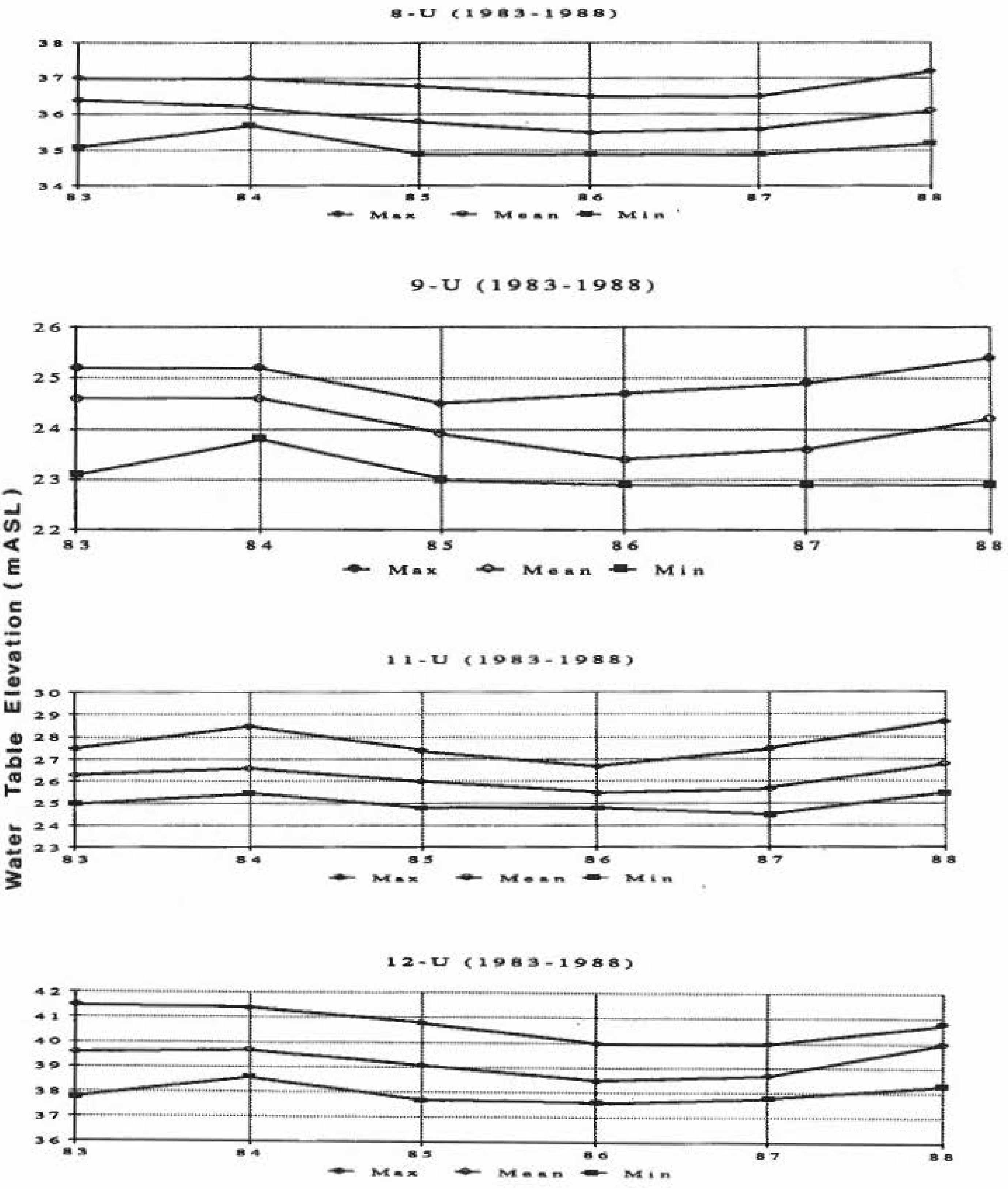


Figure 37. (Cont')

levels is observed, and precipitation is a predominant factor. Even with this short period of record, it is clear that groundwater 'mining' is not occurring. The high mean, maximum and minimum values observed at Brackley pumping station in 1984 occurred when the well field was shut down for several months during renovations.

Data from all observation wells in the basin (overburden and bedrock) were used to determine the average water table decline at each for the May 15 - October 15 period in a typical year. A contour plot of this water table decline, as far as the Hardy's Pond sub-watershed, is presented in Figure 38. Drawdown cones at the well fields are not included. The average baseflow at Hardy's Pond for the same period (pro-rated from Suffolk data) is estimated at 3.3 x 10^6 m^3. Withdrawals by pumping are approximately 1.9 x 10^6 m^3. Since the baseflow and pumped withdrawals are both derived from groundwater storage (during the May-October period of no recharge), their total should equal the volumetric decline in the water table position times the specific yield of the aquifer. The specific yield is the percentage of the total rock mass which drains when the water table declines. Applying the above method, the specific yield of the aquifer is estimated at 10%. This is a very reasonable value when we recall that the bedrock porosity is about 20%.

4.3 Well Field Dynamics

4.3.1 Introduction

The City of Charlottetown and surrounding municipalities have obtained water supply from the well fields at Union and Brackley since 1939 and 1941 respectively. Until 1983, each pumping station withdrew groundwater from a series of shallow (5 m to 10 m deep) wells connected to a suction pumping system. At Brackley this supply was, for several years prior to 1983, supplemented by two deeper wells equipped with submersible pumps. In 1983 both pumping stations underwent extensive modification, installing submersible pumps in several existing deep wells (25 to 150 m) and abandoning the shallow system. Plan views of well field areas are shown in Figure 39 and Figure 40, along with well construction details. All wells are open-hole completions with sufficient surface casing to prevent both caving of unconsolidated materials and surface water infiltration, and with open, unlined boreholes below.

In this section, the hydraulics of well response during pumping will be documented, leading to a conceptual model of aquifer response to pumping withdrawals. The extent of the drawdown cone around each well field will be discussed with a view to defining well field protection zones.

4.3.2 Aquifer Parameters from Yield Tests

Extensive well test information is available from the results of step-drawdown and constant-rate yield tests carried out at the well fields. These tests occurred over the past 20 years under a range of testing methods and degrees of precision. An assessment of these data, utilizing conventional methods of interpretation, was conducted by Callan [2]. Histograms of the transmissivity (T) and storativity (S) results are shown in Figure 41. The range of values is a function of both the natural variation in hydraulic conductivity within the aquifer, and the fact that T & S values will, by definition, vary in direct proportion to the thickness of the aquifer tested. The large range of storativity values also suggests that the aquifer may not always respond as a confined system.

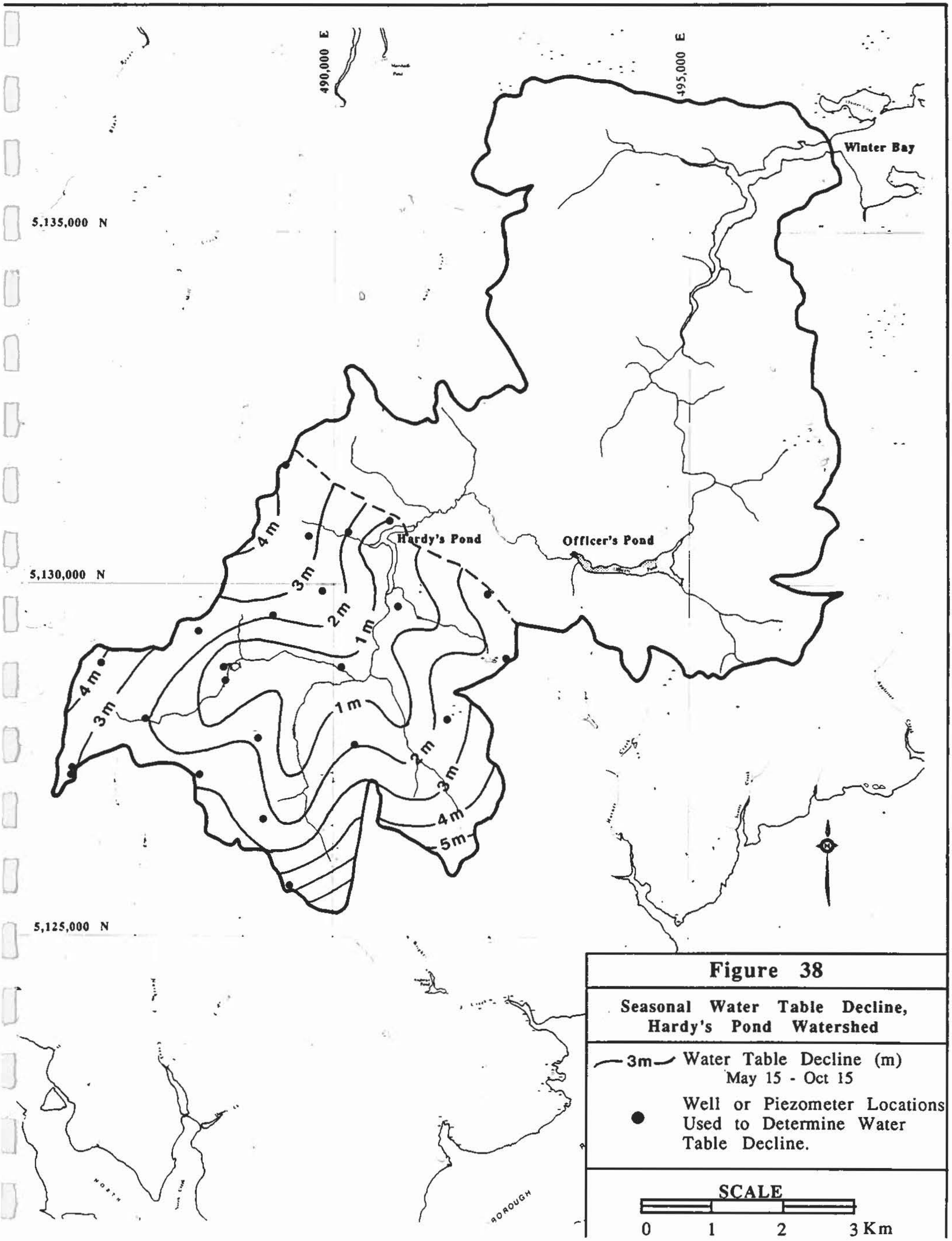


Figure 38

Seasonal Water Table Decline, Hardy's Pond Watershed

— 3m — Water Table Decline (m) May 15 - Oct 15

● Well or Piezometer Locations Used to Determine Water Table Decline.

SCALE

0 1 2 3 Km

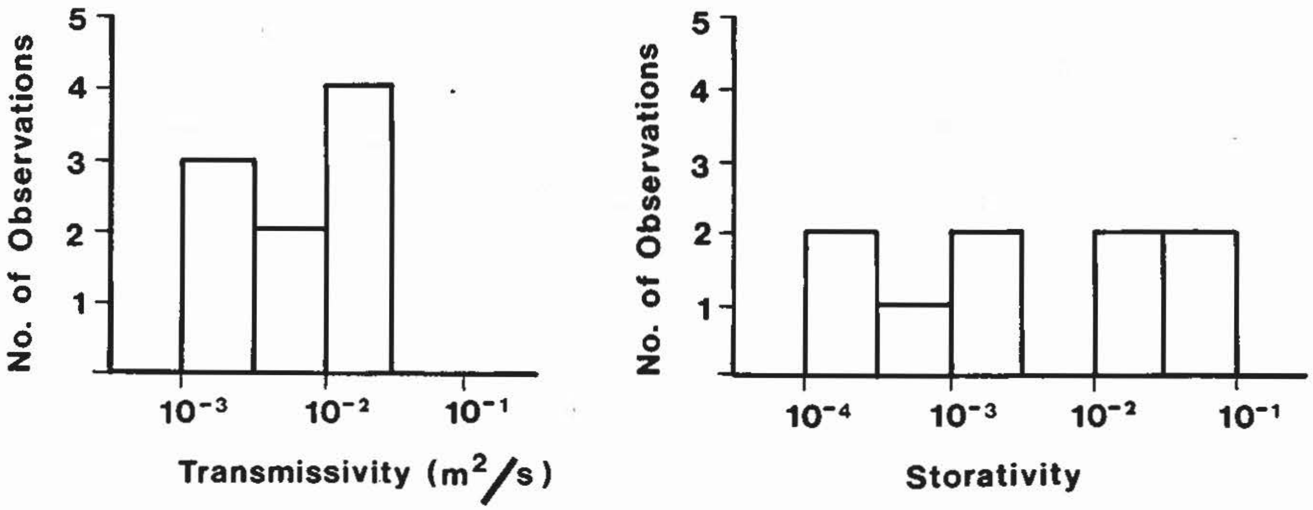


Figure 41. Histograms of transmissivity and storativity values, Union and Brackley well fields.

Figure 42 shows a typical observation well response to pumping during a constant rate yield test. Even though the aquifer is a fractured porous media, response generally followed the Theis ideal response curve. The fracture spacing and interconnection in the aquifer are sufficient to permit a typical 'porous media' response, especially in areas where the more highly fractured upper bedrock is saturated. Distance drawdown responses often conform to theoretical predictions in such cases. The transmissivity value obtained from yield tests in these rocks represents the transmissivity of the fracture system; the storativity value represents the sum of the storativity of the fracture system and of the rock matrix [15, 16]. The latter is predominant in rocks having the intergranular permeability and porosity of the red bed sandstone and results in more reduced drawdowns than would be the case if the sandstone had lower matrix permeability.

Late time yield test data (Figure 42) usually follows a 'leaky' response. The usual theoretical explanation for this phenomena is that leakage from an overlying aquitard (low permeability formation) is providing water to the aquifer below by slow, vertical drainage. However, there is no definite aquitard overlying the red bed aquifer on Prince Edward Island, particularly in the Winter River basin. The red bed aquifer has generally been considered a 'semi-confined' system [35, 36], based on the storativity values obtained from yield tests. There is substantial evidence to suggest that the red bed aquifer should be modelled as an anisotropic unconfined aquifer with K_r:K_z probably between 10 and 1000.

The rapid response of the water table to precipitation events and susceptibilty to contamination supports the unconfined model. Barometric efficiencies of 30 to 40% have been reported [35], but with K_z much less than K_r, the aquifer could be said to confine itself, the degree of 'confinement' increasing with depth as the vertical interconnection of the various horizontal strata decreases. Thus, the 'leakage' noted in yield tests is more likely the delayed yield from gravity drainage of the water table, as described by Neuman [37]. The aquifer properties, e.g. the K_r:K_z ratio, are such that the specific yield of the aquifer cannot be effectively measured by this method in these aquifer materials.

The response of the pumping well during yield tests is also unconventional. Drawdowns in production wells are usually much larger than predicted from T and S values obtained from

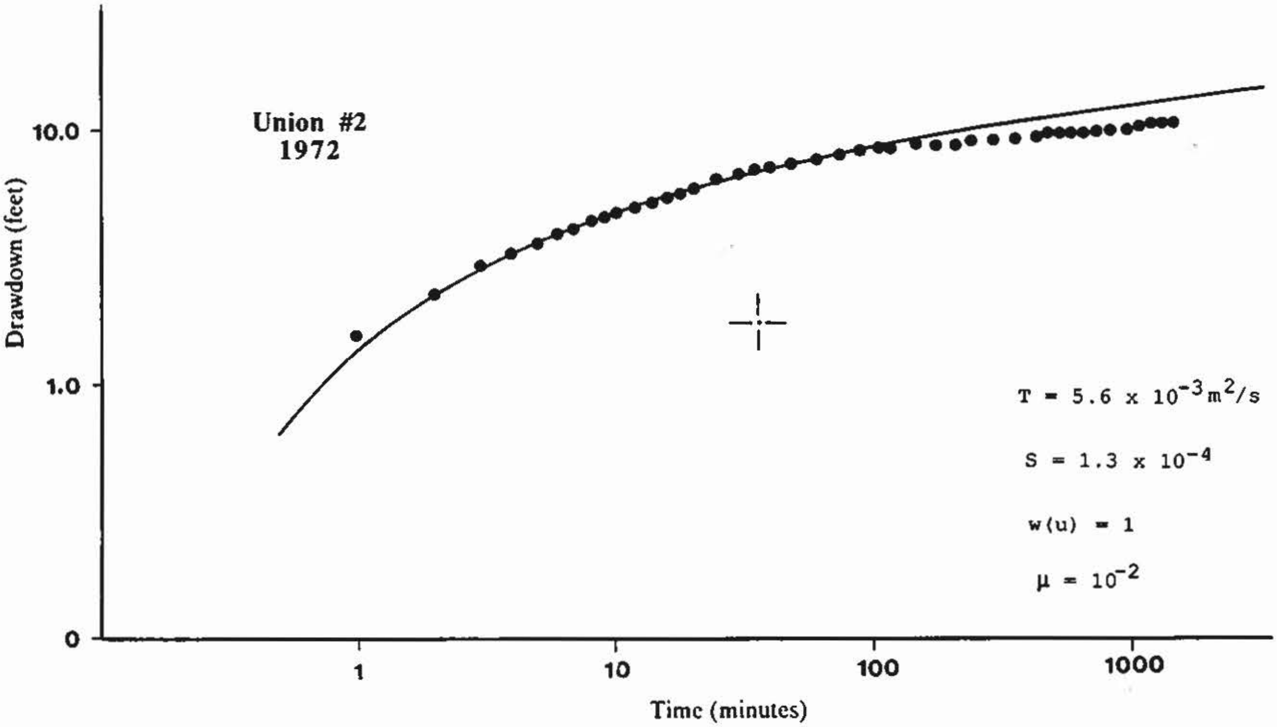


Figure 42. Typical drawdown-time response for an observation well in the well field area.

observation wells during the same test. The apparent T values are substantially lower if calculated from drawdown data at pumping wells. The additional drawdown in the pumping well, usually termed 'well loss', is the result of energy losses in or near the well bore. These energy losses can be due to (1) turbulence within fractures near the borehole, (2) entrance effects as the water level in the well bore declines below producing fractures, or (3) turbulence in the well bore [38]. In the red bed aquifer the first two of these appear to predominate and can result in well 'efficiencies' (theoretical drawdown/actual drawdown) of less than 25%.

In Figure 43, specific capacity (pumping rate/drawdown at a specific time) is plotted as a function of pumping rate during step-drawdown tests (usually at 30-60 minutes per step). As pumping rates increase, the specific capacity values decrease. It has been noted that the specific capacity declines markedly when the water level drops below the first productive fractures, illustrating the importance of the entrance effect noted above. Figure 44 is a histogram of all specific capacity values for wells at Union and Brackley. The average specific capacity of these wells is about 10.7 L/sm, six times those in the Summerside area [35].

The pumping response of the red bed aquifer suggests that a number of steps are necessary to properly evaluate the capacity and 'safe yield' of a proposed production well:

(1) A step-drawdown test consisting of three or more steps of 30-60 minutes duration, which, at maximum, equal or exceed the proposed production rate will allow optimization of the rate/drawdown function and prescribe pump settings, i.e. the 'safe yield' of the well.

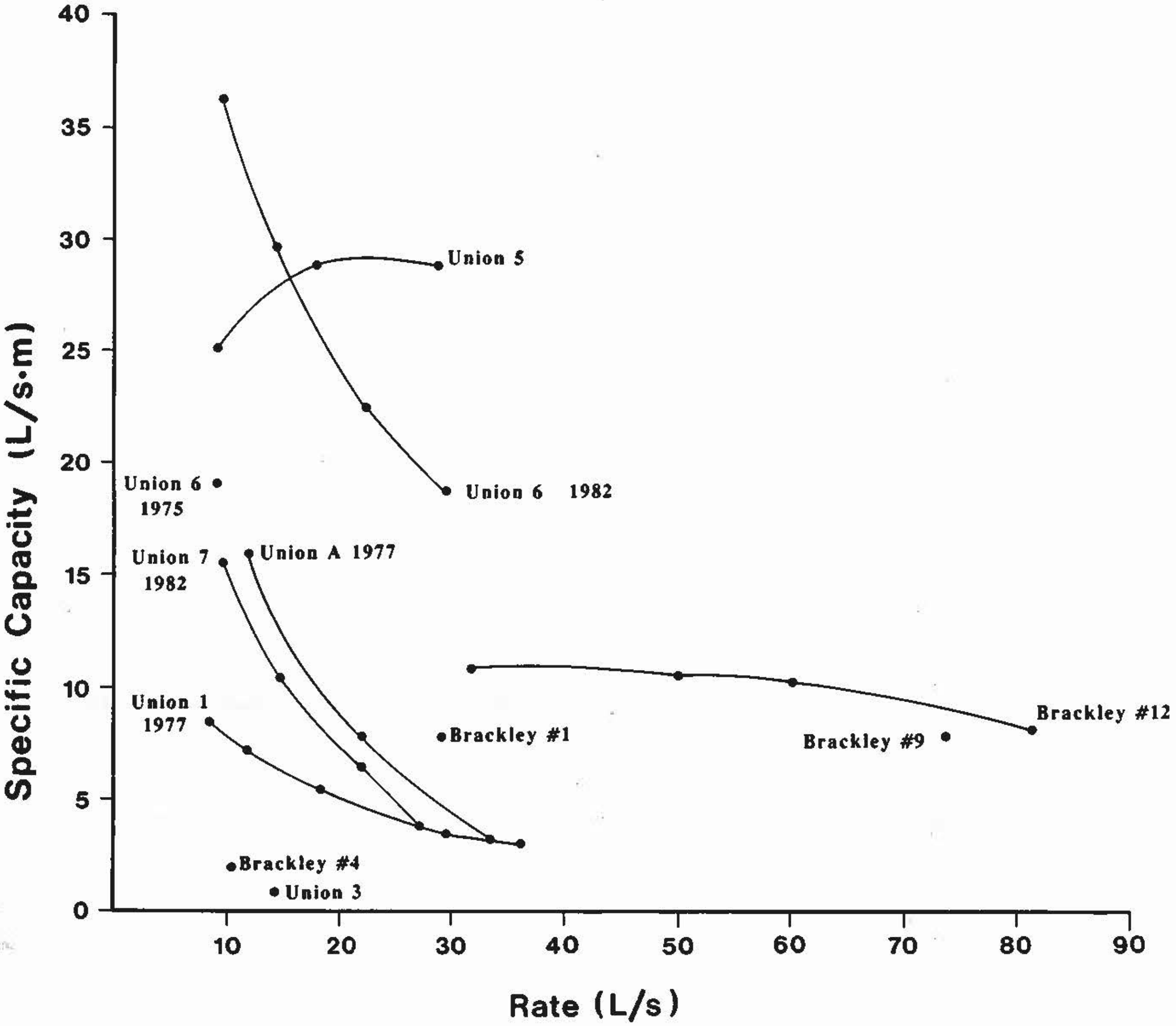


Figure 43 Specific capacity versus pumping rate, Union and Brackley well fields.

(2) A constant rate yield test shall be conducted, the rate determined by the results of the step drawdown test and the length of the test determined by the proposed rate and duration of regular operation. Drawdown and recovery measurements should be made in the pumping well, in at least one observation well of similar depth to the pumping well and in other wells as available. This will allow determination of aquifer parameters and prediction of distance-drawdown effects, i.e. the safe yield of the well field.

(3) The water budget should be evaluated, especially in projects involving very large groundwater withdrawals where the potential for baseflow reduction in streams or groundwater mining must be considered, i.e. the safe yield of the watershed.

4.3.3 Long Term Response To Pumping

The shape and size of the drawdown cone induced by pumping at each well field has two important implications. The first is the potential effect on other wells in the area. The

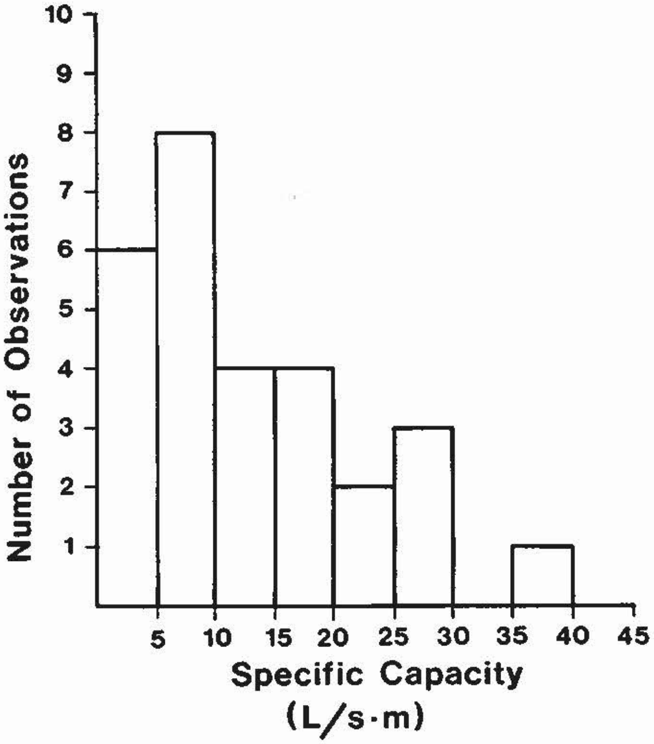


Figure 44. Histogram of specific capacity values, Union and Brackley well fields.

second is the increased gradient toward the well fields and thus the increased rate of migration of potential contaminants toward production wells.

Conventional analysis of pumping effects would involve using known T and S values for the aquifer to calculate distance drawdown effects and some estimate of induced gradient and effective porority to calculate average linear groundwater velocity. However, the usual analytical treatment of these questions does not include the effects of a sloping water table (or piezometric surface) or recharge events. Table 9 shows the results of drawdown calculations for various periods of pumping at Brackley well #12 at a rate of about 80 L/s, as predicted for the Brackley well field observation well (Figure 39), 238 m away and at a distance of 1000 metres. Also listed are the observed drawdown values at the observation well, obtained from its 1988 hydrograph (Figure 45). The hydrograph has been modified to remove the effects of pumping other nearby wells. No drawdowns related to pumping were observed at piezometer 4-B, 1000 metres away. Well #12 was pumped essentially continuously for the year. Table 9 shows that observed drawdowns are substantially less than calculated drawdowns assuming pumping began on May 1 when the actual drawdown was about 1.2 m. During the summer recession, drawdowns tend toward the predicted values, but are always less. Fall recharge in October again reduces the observed drawdown.

The explanation for the reduced drawdown lies in the effects of recharge and a sloping water table. As shown in Figure 45, recharge in March and early April is much greater than withdrawals, so that any existing drawdown cone is essentially 'filled in' by recharge. By mid-April recharge is only equal to withdrawals and the piezometric surface begins to decline. The rate of drawdown is less than predicted because some recharge is still occurring and a second phenomena, the 'horizontal recharge' due to a sloping water table is becoming

Table 9. Drawdown Effects at Brackley Well Field.

Date	Predicted Drawdown (m)[1]		Observed Drawdown (m)	
1988	r=238m	r=1000m	r=238m	r=1000m
May 1	3.6	2	1.2	ND[2]
June 1	4.5	3.2	2.2	ND
July 1	4.8	3.5	3	ND
Aug 1	5	3.7	3.9	ND
Sept 1	5.2	3.9	4.4	ND
Oct 1	5.3	4.1	4.9	ND
Nov 1	5.4	4.2	3	ND

Note 1. Assumptions: T=1.3E-02 m^2/s, S=1E-04

Note 2. ND=Not Detected

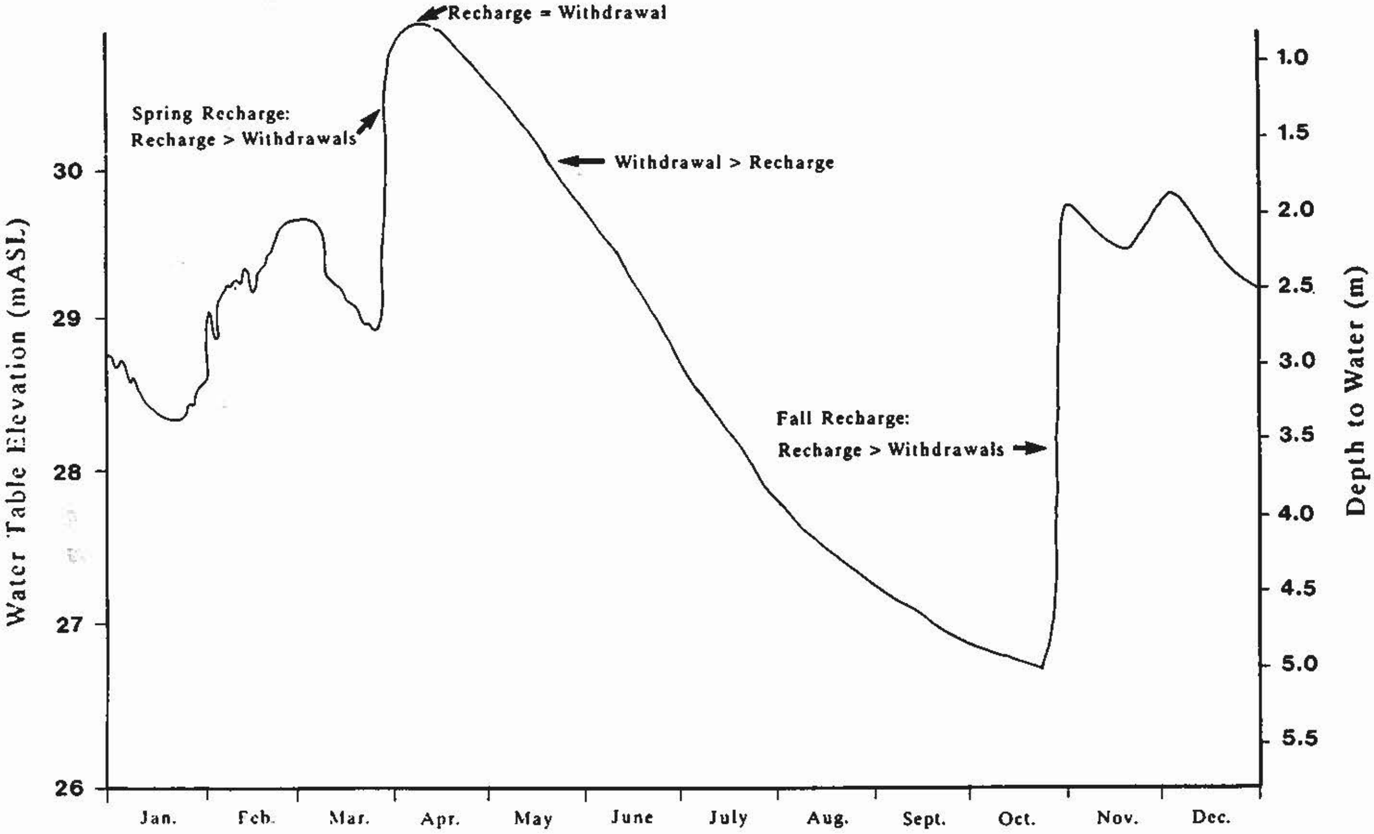


Figure 45. 1988 hydrograph, Brackley well field observation well.

important. This is depicted in Figure 46 which shows cross section A-B in the basin previously described in Section 4.1.3 (Figure 16), this time with Brackley well #12 pumping at a rate of 80 L/s. This is equivalent to the average pumping rate at the well field. The Brackley pumping station observation well is shown and Airport #7 observation well. The position of the water table (piezometric surface near the well field) is shown as observed on May 1, June 1 and September 1. Typically, the cone of depression is steep near the pumping well, quickly reducing away from it. During the May 1 - June 1 period the drawdown observed at the Brackley observation well is 2.2 m. However, the natural decline of the water table at Airport #7 is almost 4 m. The natural decline of the water table is much larger than the effect of pumping observed less than 250 m away. Groundwater is moving toward the well field as a result of the natural gradient of the water table, providing 'horizontal recharge' to the cone of depression and subduing the drawdown effect.

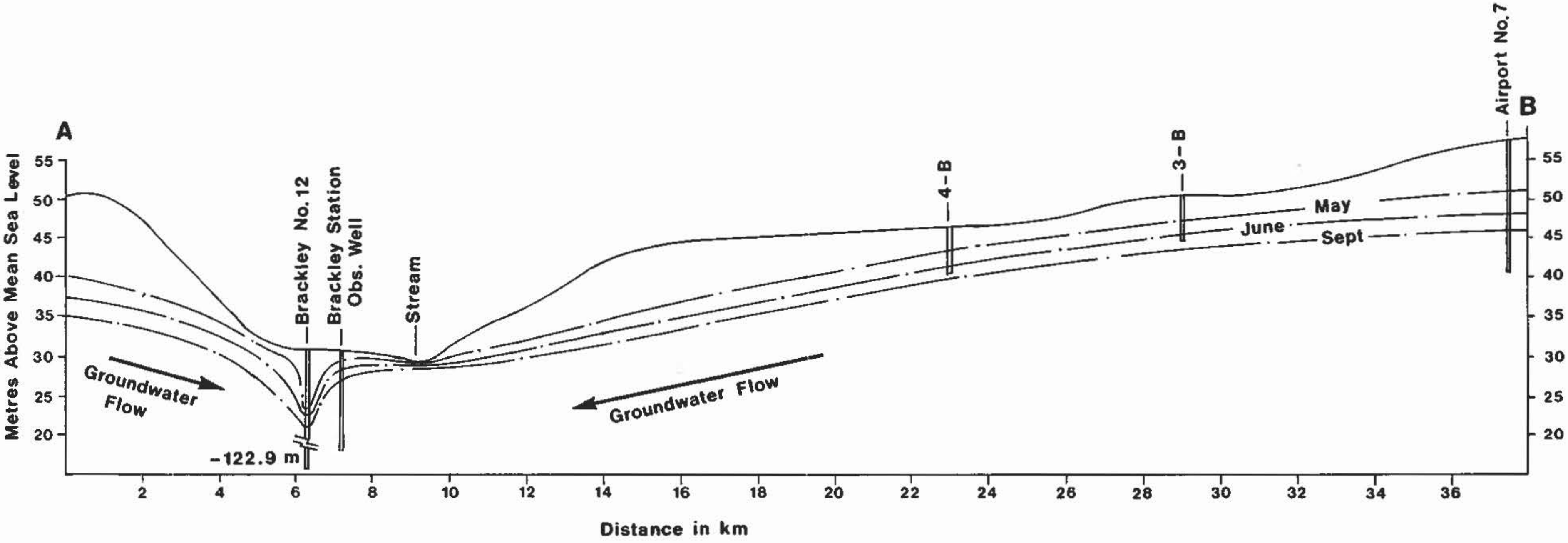


Figure 46. Water table position and drawdown cone at Brackley well field. Well #12 is pumping at 80 L/s.

The average natural gradient between Airport #7 and the Brackley well field observation well is about 0.006. This is equal to the theoretical average gradient between the Brackley observation well and a point 100 m from the pumping well. Therefore, beyond a radius of about 250 m the average gradient induced by pumping is less than the average natural gradient. It is impossible to distinguish the natural slope of the water table from the slope of the drawdown cone beyond this distance. The effective 'radius of influence' of the well field is therefore about 250 m, increasing to perhaps 300-400 m as the natural water table gradient reduces during the summer recession.

Returning to Table 9, the observed drawdown approaches the theoretical drawdown in late summer because the amount of 'horizontal recharge' is now reduced. At Union well field, the multiple well operation (Figure 40) makes separation of these effects more difficult. However, a map of the piezometric surface at Union (Figure 47) shows that, in close proximity to the well field, the drawdown cone cannot be distinguished from the natural piezometric surface.

4.3.4 Well Field Protection Zones

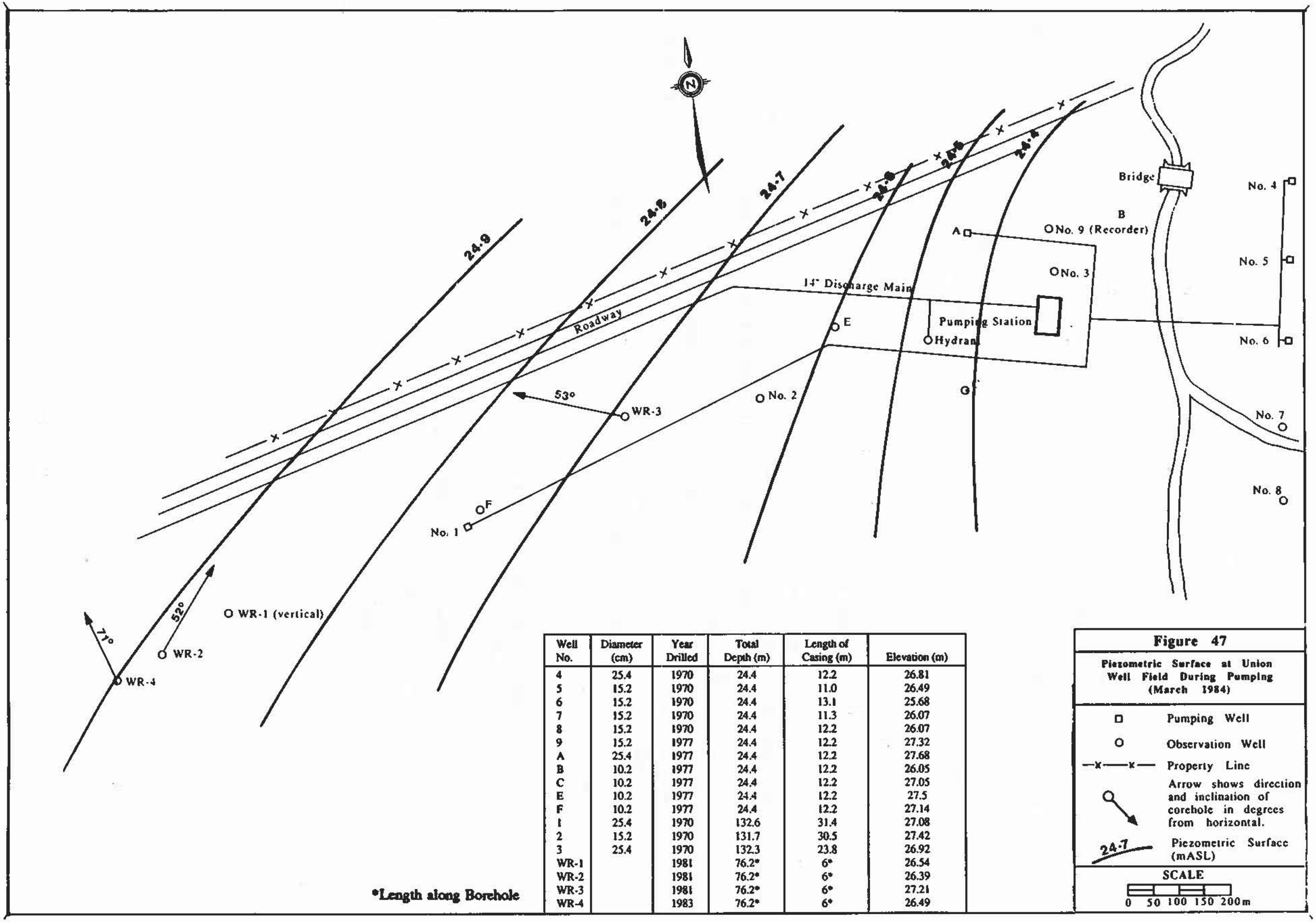
The preceding interpretation has specific implications for determining the critical areas for groundwater quality protection near the well fields. The concept of groundwater protection zones [39] recognizes that source areas for groundwater supply to the public require special protection to prevent groundwater contamination. It recognizes that prevention is the only satisfactory way of dealing with groundwater contamination and that a time lag exists between the introduction of a potential contaminant into the groundwater system and its arrival and detection in a groundwater supply. On the other hand, groundwater protection zones must recognize the local socio-economic conditions, existing developments, and existing land use and strike a responsible balance between safety and level of restriction of human activity.

Technical approaches to establish a groundwater protection zone usually involve definition of a 'time of travel' zone, capture zone, arbitrary limited development zone or recharge area [39]. In this section, groundwater protection zones around the well fields at Union and Brackley will be defined from a hydrogeological viewpoint only, so as to provide a starting point for considering more comprehensive definition of them.

Average linear groundwater velocity ($\bar{v}$) can be calculated from a modification of Darcy's Law, such that:

$$\bar{v} = \frac{-K}{n} \frac{dH}{dl}$$

where K is the hydraulic conductivity of the aquifer, dH/dl is the hydraulic gradient, and n is the effective porosity. The latter value is relatively easy to estimate for porous media. Limited tracer testing in the red bed aquifer [40] suggests that the effective porosity is in the range of 0.01 to 0.005. Using $K = 10^{-4}$ m/s and $dH/dl = 0.005$ results in $\bar{v} = 4.3$ m/d to 8.6 m/d. For a 60 day protection zone to be established, for example, a protected radius of about 250 to 500 m from the well field centre would be required. Theoretically, this would allow a minimum 60 day period in which to instigate remedial action following introduction of a contaminant into the groundwater system outside the groundwater protection zone.



Well No.	Diameter (cm)	Year Drilled	Total Depth (m)	Length of Casing (m)	Elevation (m)
4	25.4	1970	24.4	12.2	26.81
5	15.2	1970	24.4	11.0	26.49
6	15.2	1970	24.4	13.1	25.68
7	15.2	1970	24.4	11.3	26.07
8	15.2	1970	24.4	12.2	26.07
9	15.2	1977	24.4	12.2	27.32
A	25.4	1977	24.4	12.2	27.68
B	10.2	1977	24.4	12.2	26.05
C	10.2	1977	24.4	12.2	27.05
E	10.2	1977	24.4	12.2	27.5
F	10.2	1977	24.4	12.2	27.14
1	25.4	1970	132.6	31.4	27.08
2	15.2	1970	131.7	30.5	27.42
3	25.4	1970	132.3	23.8	26.92
WR-1		1981	76.2*	6*	26.54
WR-2		1981	76.2*	6*	26.39
WR-3		1981	76.2*	6*	27.21
WR-4		1983	76.2*	6*	26.49

*Length along Borehole

Figure 47

Piezometric Surface at Union Well Field During Pumping (March 1984)

Given the uncertainties associated with the estimation of effective porosity for this aquifer, it is suggested that the more conservative value of 500 m to be used for Union and Brackley well fields at this time.

Proposed levels of groundwater protection for the well field areas are shown on Figure 48. On property owned by the Charlottetown Water Commission, activities should be limited to those involving provision of water supply. Within a radius of 250 m of production wells (the effective radius of influence estimated for each well field) no commercial, industrial or residential development should occur and restrictions should be placed on agricultural activities. Within a radius of 500 m of each well field (60 day protection zone) the storage and handling of hazardous materials, including petroleum products, should be prohibited, and all development proposals should be subjected to an environmental impact assessment. In the remainder of the recharge area for the well fields, (Figure 48) major development proposals should be subjected to an environmental impact assessment.

4.4 Groundwater-Surface Water Interaction

4.4.1 Introduction

The degree of interaction between the groundwater and surface water systems is an important element in understanding the hydrogeology of an aquifer. Streams and ponds may either gain water from the aquifer through groundwater discharge, or lose water as they recharge the groundwater system beneath. The direction and magnitude of water movement between groundwater and surface water systems depends on location, stream stage, water table position, physical properties of the aquifer, streambed materials and such external influences such as groundwater withdrawal.

The presence of prolific springs along rivers and streams in Prince Edward Island shows that watercourses are gaining, i.e., receiving groundwater discharge, in those areas. Many springs have also been mapped along the Winter River and its tributaries (Figure 28), but in reaches of the river without obvious springs, the nature of groundwater-surface water interaction was unclear. Near Union and Brackley pumping stations, it was observed that groundwater withdrawals from the bedrock aquifer lower water levels in the glacial deposits (Section 4.1.3). This suggested that the well fields may directly influence groundwater flow to or from the river.

To address those questions, a study of groundwater-surface water interaction [41] has been carried out. Its objectives were: (1) to characterize and quantify groundwater movement beneath the streambed of the Winter River, and (2) to evaluate the temporal influence of well field operations on groundwater baseflow in the local streams.

4.4.2 Methodology

The important variables in characterizing groundwater surface water interaction are: (1) seepage flux through the streambed, (2) hydraulic gradients beneath the streambed, and (3) hydraulic conductivity of the streambed materials.

Seepage meter and mini-piezometer techniques described by Lee [42] and Lee and Cherry [43] were adopted for this project. Seepage meters (Figure 49A) were used to make 159

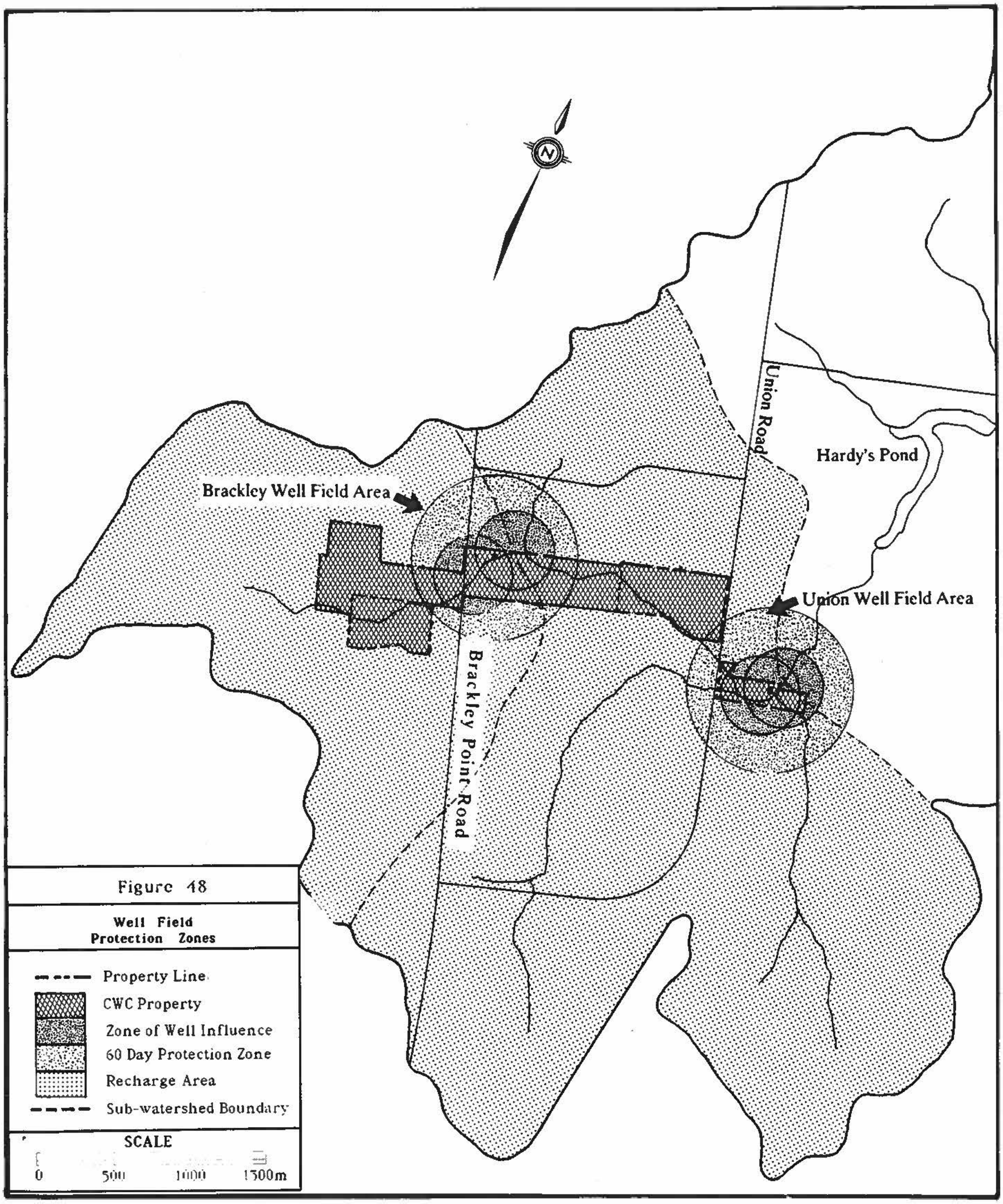
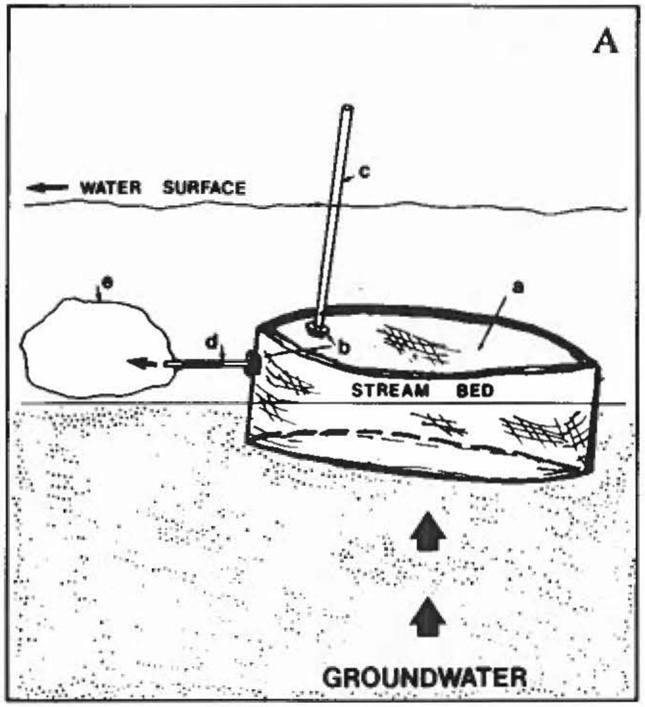


Figure 48

Well Field Protection Zones



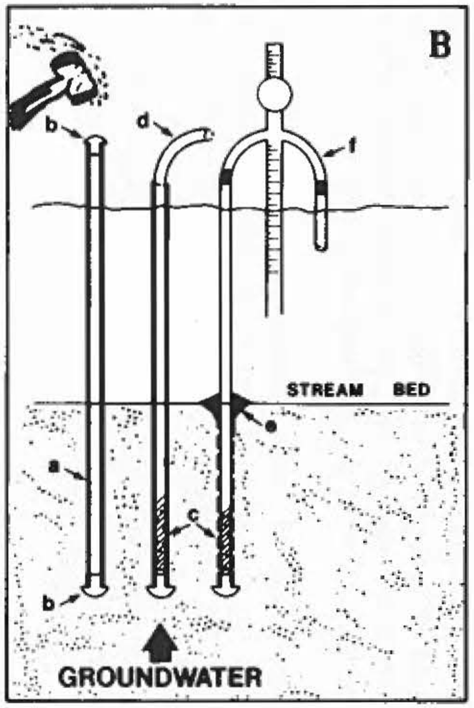


Figure 49A. General features of seepage meter: (a) end section of a steel drum (208 litres: 45 Gal. Brit.); (b) Circular holes with suitable size rubber stoppers; (c) vent pipe semi-rigid 0-31 cm (1/8 in.) ID polyethylene tubing; (d) rubber band wrap; (e) 2 litre plastic bag [41].

Figure 49B. General features of mini-piezometer. (a) 1.9 cm. (3/4 in.) ID steel drive pipe; (b) 1.3 cm (1/2 in) loosely fitted lag bolt; (c) 0.64 cm (1/4 in.) ID transclucent tygon tubing, perforated and wrapped with fibreglass cloth; (d) semi-rigid 0.31 cm (1/8 cm.) ID polyethylene tubing; (e) bentonite seal; (f) manometer [41].

direct measurements of seepage flux in 29 different locations at eight of nine study sites (Figure 50). The 'Brackley Stream' site was not instrumented due to a lack of streamflow.

Mini-piezometers (Figure 49B) were installed in fifty-two locations at the nine study sites. These were used to determine the hydraulic gradient adjacent to and beneath the streambed and to conduct hydraulic conductivity measurements of the streambed materials. Horizontal hydraulic conductivity was measured by falling head tests in the mini-piezometers. Vertical hydraulic conductivity of the streambed materials at each location was calculated by applying Darcy's Law to the results of seepage flux and hydraulic gradient measurements. Streamflow was measured during the study period (June-August, 1984) at the Brackley and Suffolk stream gauging stations and is summarized in Table 10.

Twenty stream sediment samples were collected along the Winter River at the study sites that ranged from silty clay to coarse sand and gravel. Descriptions of the sediments are summarized in Table 11. The bed materials are predominantly silty sand and sandstone fragments (gravel) suggestive of glacial material (either till or glaciofluvial) which has been reworked by streamflow and the finer clay fractions removed. At Brackley Pond and Officers Pond the impoundments have allowed settling of finer clay and silt alluvium so that the bed materials are generally finer grained.

Experiments were conducted at Brackley and Union well fields to determine whether changes in pumping rates would cause changes in the magnitude of seepage flux or hydraulic gradient. Low, intermediate, and high pumping rates at each well field, as well as off-on cycles were used to induce responses beneath the stream.

4.4.3 Results

Table 12 summarizes hydraulic gradient and seepage meter measurements at all locations. Average seepage flux ranges from 0.036 $cm^3/m^2 \cdot s$ at Brackley Pond to 3.0 $cm^3/m^2 \cdot s$ at Hardy's Pond. Each value represents the average of all measurements made at seepage meter placements at each of the eight study sites.

Average hydraulic gradients were downward (negative values) near Union and Brackley well fields and upward at all other locations. Both well fields were operating during the study period. The results show that, under natural conditions, groundwater is effluent to streams in all locations. Gradients were upward even during and after a heavy rainfall event when the stream stage increased dramatically. While this was only one observation, it indicates that the groundwater system near the stream also responds rapidly to recharge events and continues to provide baseflow.

Under natural conditions, hydraulic gradients appear to be controlling seepage flux through the streambed. Hydraulic gradients (Table 12) are directly proportional to seepage flux in all non-pumping locations except Hardy's Pond. At the Hardy's Pond location, the average hydraulic gradient of 0.024 was the lowest value observed under natural conditions while the average seepage flux was the highest recorded (3.0 $cm^3/m^2 \cdot s$). The streambed material at the Hardy's Pond location is composed of coarse sand and gravel and its high permeability appears to be responsible for this anomally.

Large variations in seepage flux occur due to the action of stream currents on seepage meter measuring bags [44]. In this study, other factors such as natural variations in seepage flux and the effects of well field pumping also contributed to the high coefficent of variation

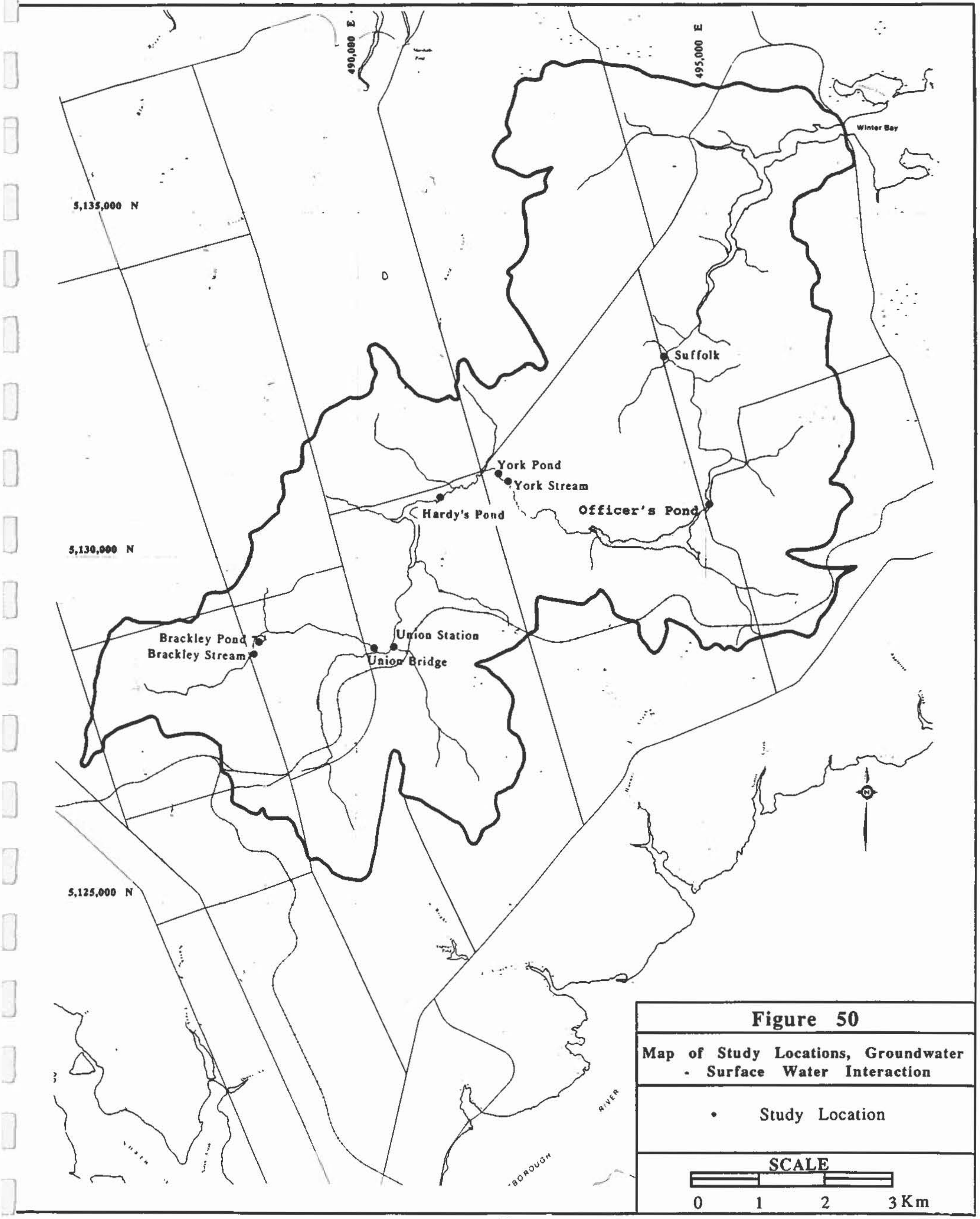


Figure 50

Map of Study Locations, Groundwater - Surface Water Interaction

Table 10. **Stream Flow at Brackley and Suffolk Gauging Station, 1984 [41].**

m^3/s		Brackley			Suffolk	
	June	July	Aug	June	July	Aug
Mean	0.083	0.014	0.004	0.848	0.375	0.353
Max.	0.255	0.03	0.027	1.710	0.543	0.974
Min.	0.031	0.001	0.0	0.535	0.252	0.211

Table 11. **Descriptions of Stream Sediments [41].**

Location	Site	Description and Comments
Brackley Stream	a	Silty sand
Brackley Pond	a	Black organics, fine to medium sandy silty clay occupies all measurement sites
Union Bridge	1a	Sandy Silt
	1b	(below bridge) Silty clay
	2a	Silty clay
Union Station	1a	Silty clay and gravel
	2a	Silty gravelly sand
	3a	Silty sand and gravel
	4a	Silty coarse sand
	1b	Silty pebbly sand
	2b	Silty gravelly sand
Hardy's Pond	a	Sand and gravel (all sites similar)
York Pond	1a & 1b	Sandy silt
York Stream	b	Medium sand; all sites similar
Officers Pond	a	Clayey sandy silt (all sites similar, loose and incompetent). Drive pipe ends in top few centimetres of fissile sandstone bedrock.
Suffolk	1	Fine to medium sand
	2c	Sandy, pebbly gravel
	3	Fine sand

Table 12. **Seepage Flux And Hydraulic Gradient Variations, Winter River [41].**

Location	Average Gradient*	Coeff. of Var. $100\,s/\bar{x}$	Avg. Flux cm^3/m^2 • s	Coeff. of Var. $100s/\bar{x}$
Brackley Stream	-0.24	48%	0.0	
Brackley Pond	-0.001	41%	0.036	167%
Union Bridge	-0.15	109%	0.20	160%
Union Station	-0.22	133%	0.31	129%
Hardy's Pond	+0.024	60%	3.0	93%
York Pond	+0.05	26%	0.25	56%
York Stream	+0.08	25%	0.59	120%
Officers Pond	+0.12	75%	0.50	70%
Suffolk	+1.12	85%	2.1	16%

*Negative gradient indicates a downward gradient.

values (Table 12), especially at the well field locations. Variations in hydraulic gradients may be a result of precipitation events or transient effects of well field operations.

The observation of downward gradients coincident with groundwater discharge to seepage meters at the well field locations suggests that, during pumping, most but not all shallow groundwater flow is diverted to pumping wells. This will be discussed further in the context of well field effects. The discharge must be confined to the upper 20 to 30 cm of the streambed materials, above the zone of downward gradients detected by most mini-piezometers.

The data in Table 12 suggest that groundwater discharge to the stream, measured as seepage flux, increases as one moves from the headwaters of the basin to downstream areas. Notwithstanding pumping influences, seepage flux increases to a maximum at Hardy's Pond, drops considerably at the York Pond location, and increases again as we move toward the end of the freshwater reach of the river at Suffolk. While this could be simply a chance occurrence, it is consistent with the concept of more regional groundwater flow supplementing local shallow groundwater discharge as we move down the watershed.

The data suggest that the majority of groundwater recharge in the upper portion of the basin is discharged to the stream at or before the Hardy's Pond study location. This may be due to the local streambed conditions discussed earlier, combined with the effect of basin topography, which tends to create a bottleneck in this area. In any case, it is clear that seepage flux, and thus baseflow to streams, may be influenced by regional groundwater flow patterns as well as local, shallow flow systems. As a result, groundwater baseflow to streams may increase in irregular steps as we move down a watershed, as opposed to a smooth increase downstream.

Vertical hydraulic conductivity values were calculated for each seepage meter/mini-piezometer installation and are presented in Table 13. The streambed materials have vertical permeabilities ranging from 1.9×10^{-7} m/s at Union Bridge to 2.0×10^{-4} m/s at Hardy's Pond, averaging 2.8×10^{-5} m/s.

These values are generally higher than those obtained from grain size analyses on surficial deposits (Section 4.1.2). There are several possible explanations. The materials beneath the streambed examined in this study are generally of a silty-sand to gravel size and probably represent water-worked glaciofluvial deposits or sandy till, overlain by recent streambed alluvium. Second, these sites are in groundwater discharge areas, with considerable groundwater flow through the river bed. This constant movement of water through the sediments would tend to open preferential flow channels and clean fine clay size particles from the pore spaces. Finally, in some of these locations, mini-piezometers were installed within centimetres of the bedrock surface. Higher measurements may reflect the influence of highly fractured rock beneath. The first two factors may be predominant because vertical hydraulic conductivity values are significantly higher (one to two orders of magnitude) than horizontal values at most sites (Table 13).

Monitoring installations for measurements of sub-stream responses to pumping at Brackley and Union well fields are shown in Figure 51 and Figure 52. Table 14 records the average seepage flux at each seepage meter site under the influence of three rates of well field production. At both well field locations, groundwater discharge to the stream continued to occur during well field operation, even at the maximum pumping rate. However, the rate of groundwater discharge decreased in direct response to increases in the well field pumping

Table 13. Summary Of Vertical and Horizontal Hydraulic Conductivity Values Winter River Stream Bed [41].

Location	Seepage Meter	No. of Tests	K (m/s)	Coefficient of Var. 100 s/$\bar{x}$
Vertical				
Brackley Pond	3A	8	3.8E-07	107%
Union Bridge	1A	6	1.3E-06	109%
	2A	8	1.9E-07	351%
Union Station	1A	6	3.6E-05	52%
	1B	10	5.9E-06	101%
	3A	7	6.8E-06	42%
Hardy's Pond	B	4	2.0E-04	80%
	C	4	1.6E-06	14%
	D	4	2.9E-05	18%
York Stream	A	2	1.9E-06	7%
	B	7	3.2E-06	34%
York Pond	A	5	4.3E-06	14%
	B	4	4.7E-05	14%
Officers Pond	A	6	2.3E-05	5%
	B	4	2.7E-05	15%
	C	2	1.7E-06	13%
Suffolk	1A	5	1.4E-05	41%
	2B	5	7.6E-05	18%
	2C	5	1.8E-05	43%
	3	5	4.3E-05	17%
Horizontal				
Brackley Stream		1	2.5E-07	—
Brackley Pond		4	6.1E-07	57%
Union Bridge		5	6.7E-08	47%
Union Station		11	1.3E-06	104%
Hardy's Pond		5	1.9E-05	50%
York Stream		6	1.3E-06	58%
York Pond		4	2.9E-05	90%
Officers' Pond		4	1.3E-06	15%
Suffolk		11	1.0E-07	77%

rates. Seepage flux declined by about 80% in the Brackley Pond location when the pumping rate increased from 75 L/s to 153 L/s. At Union, an increase in pumping rate from 72 L/s to 131 L/s caused an 11% and 57% decline in seepage flux at Union Bridge and Union Station locations, respectively. Comparing periods of minimum and maximum pumping at Union, seepage flux declined by 49% at Union Bridge and by 83% at Union Station. These declines in seepage flux represent the diversion of groundwater flow to the production wells and away from the streams.

Table 15 shows the variations in hydraulic head which resulted from changing pumping rates at the two well fields. In general, hydraulic gradients were progressively more negative (downward) as pumping increased, at both well fields. The responses in the mini-piezometers were very rapid, with drawdown occuring within minutes of pumping rate increases and recovery almost immediate. Exceptions to this pattern were apparent at Brackley Pond, where low permeability conditions dampened the response both in magnitude and time. Shallow mini-piezometers at Union Station also gave erratic responses, indicating again that the very shallow groundwater (less than 50 cm below the streambed) is, in some locations, less affected by pumping stress.

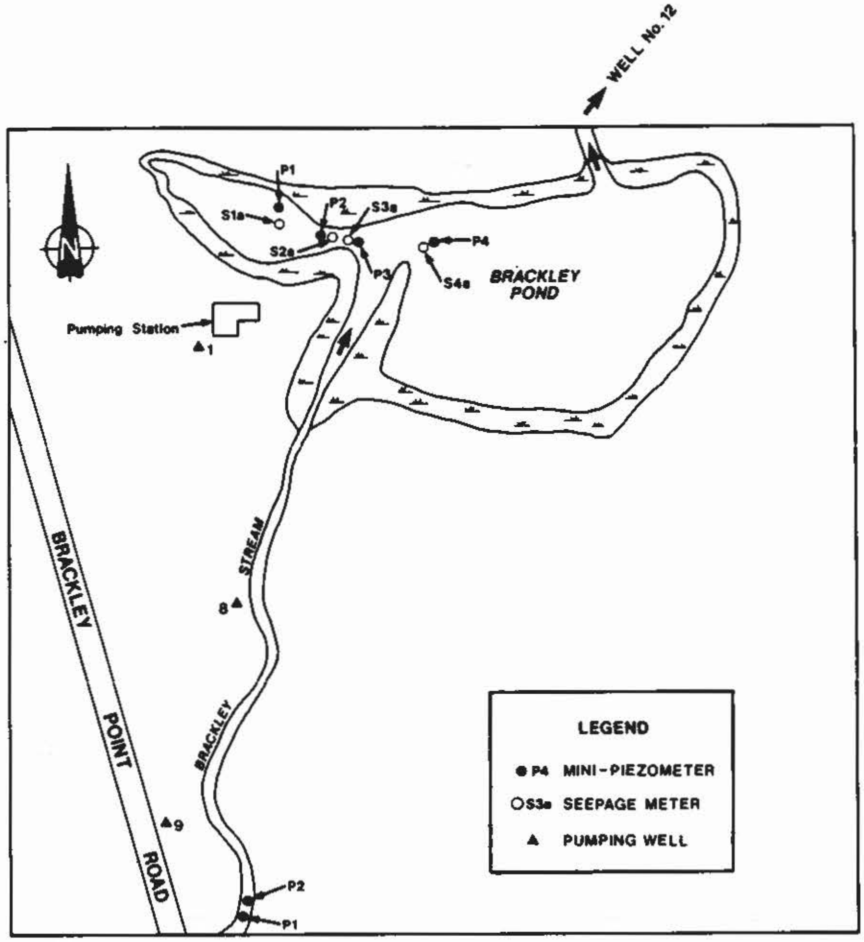


Figure 51. Map of instrumented sites at the Brackley Stream and Brackley Pond study locations[51].

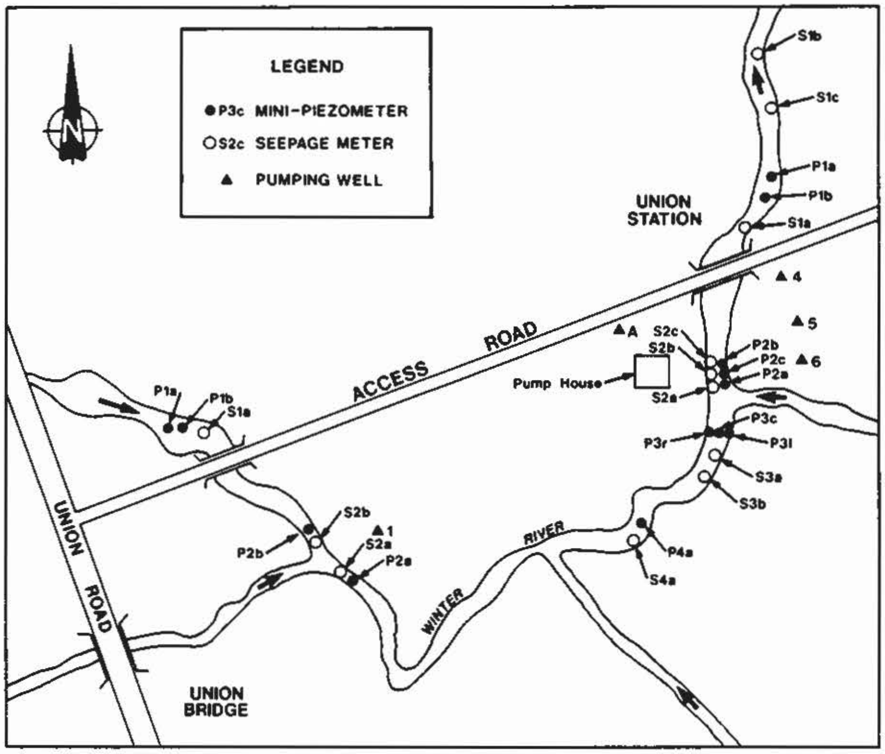


Figure 52. Map of instrumented sites at the Union Bridge and Union Station study locations [51].

Table 14. **Variations In Seepage Flux Due To Changes In Well Field Pumping Rates [41].**

Location	Pumping Status and Rate (L/s)	Avg. Flux (cm^3/m^2s)	n	Coeff. of Var. $100s/\bar{x}$
Brackley Pond	Minimum (40)	0.166	14	79%
	Intermediate (75)	0.034	22	145%
	Maximum (153)	0.031	23	70%
Union Bridge	Minimum (0)	0.061	12	91%
	Intermediate (72)	0.035	24	54%
	Maximum (131)	0.031	20	70%
Union Station	Minimum (0)	0.194	15	83%
	Intermediate (72)	0.077	23	89%
	Maximum (131)	0.033	21	64%

Table 15. **Mini-Piezometer Data, Well Field Pumping Experiment [41].**

Brackley Well Field

Study Location	Site	Piezometer Depth[1]	Hydraulic Heads[2]		
			Minimum Pumping Rate (40 L/s)	Intermediate Pumping Rate (75 L/s)	Maximum Pumping Rate (153 L/s)
Brackley Stream	1	108	-29.5	-27	-52.4
	2	107.5	-35.5	-23.8	-46.5
Brackley Pond	1	108	-1.5	-0.8	-1.6
	2	116.8	-8.8	-4.7	-2.4
	3	101.6	-8.1	-3	-7.2
	4	115.6	0.8	0.4	0.9

Union Well Field

Study Location	Site	Piezometer Depth	Hydraulic Heads		
			Minimum Pumping Rate (0.0 L/s)	Intermediate Pumping Rate (72 L/s)	Maximum Pumping Rate (131 L/s)
Union Bridge	1a	116.8	-6.9	-8.9	-15.8
	1b	86.4	-9.2	-9.6	N.A.
	2a	106.7	0	-7.8	-10.4
	2b	30.5	-0.8	-1.2	-1.6
Union Station	1a	121.9	-3.8	-6.1	-8.3
	1b	134.6	-2.3	-7.3	-3.1
	2a	127	12.5	-34.6	-29.8
	2b	119.4	12.5	-30.7	71.5
	2c	21.6	-0.8	0.8	-9.1
	3c	24.1	0.8	-1.7	0.4
	3d	132.1	-11.3	-21.5	-29.1
	4a	25.4	-3.7	-1.8	3.6

Note 1. Values in centimetres below streambed.

Note 2. Values in centimetres, relative to stream water level.

The mini-piezometer data appear to reflect a modified version of the induced streamflow infiltration scenario described by Rahn [45]. Figure 53A represents natural, non-pumping conditions for an effluent stream similar to the Winter River. As pumping begins (Figure 53B), the piezometric surface is lowered below the river surface on the well side of the stream. Both upward and downward gradients exists, depending on the point of measurement. Under heavy pumping (Figure 53C), the piezometric surface is lowered completely below the streambed. Groundwater discharge is captured and baseflow reduced, and induced infiltration may be taking place. Some discharge to the stream will continue to occur as long as the water table is not lowered completely below the stream through dewatering of the surficial materials. Pressure transients are quickly transmitted from the

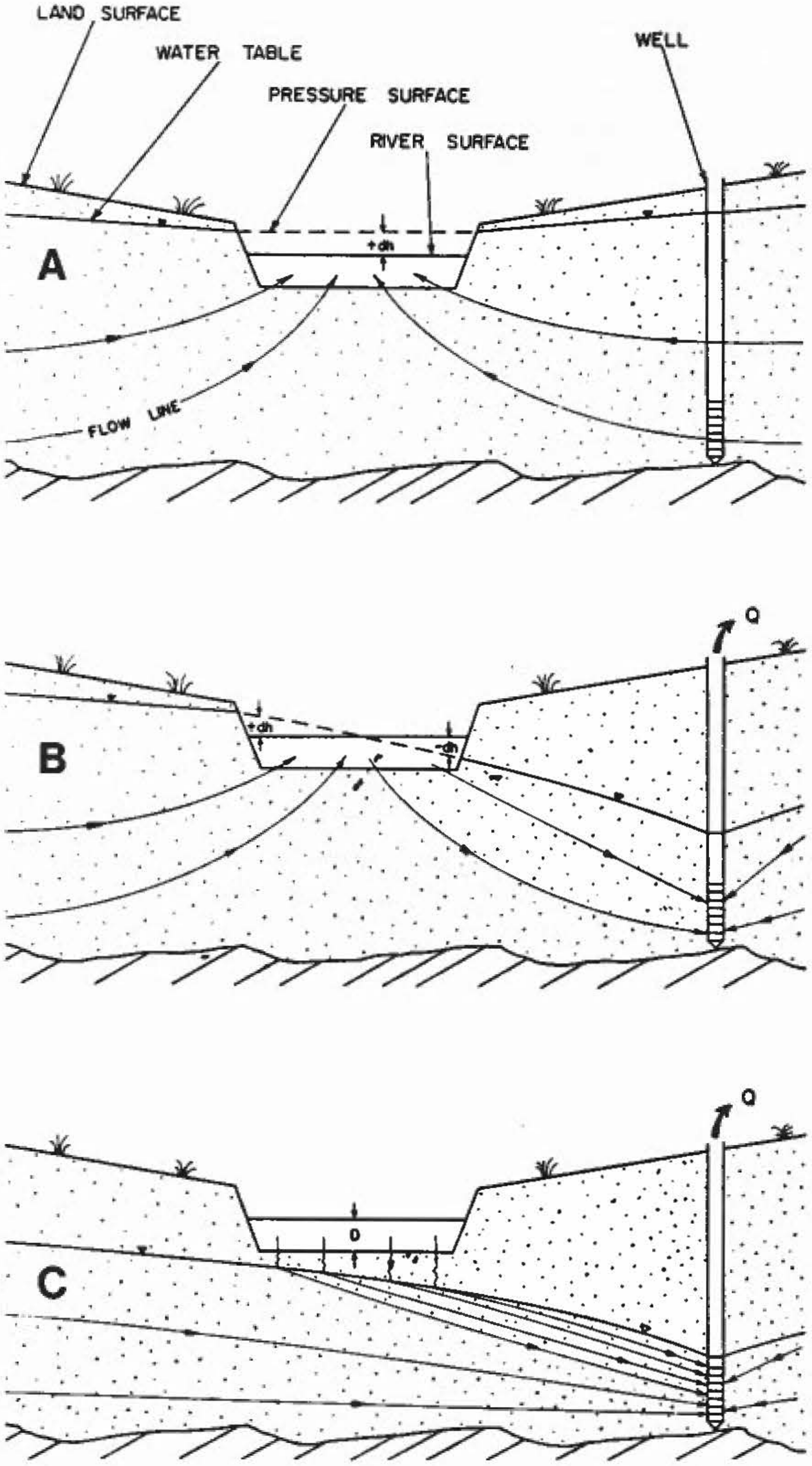


Figure 53. Sub-stream response to groundwater withdrawals [45].

pumping wells to the shallow aquifer but drainage of the pore spaces occurs slowly. At both the Brackley Stream and Union Bridge (north tributary) locations the streams go dry during continuous pumping of the well fields in late summer when streamflow is naturally low.

These studies of pumping effects on groundwater-surface water interaction clearly show that the production wells divert baseflow which would naturally discharge to the river and, depending on the water table-piezometric surface relationships beneath the streambed, some induced infiltration is likely. The near-stream area and parts of the streambed itself are recharge areas during portions of the year when they would naturally be discharge areas. The implications of these effects on the water budget will be evaluated in the next section.

5. HYDROLOGIC BUDGET AND SAFE YIELD

5.1 Introduction

A hydrologic budget is a quantitative statement of the balance between the amount of water entering and leaving a drainage basin. The equation for this water balance can be defined as:

$$P = Q_s + Q_g + E \pm U \pm \Delta S_s \pm \Delta S_{sm} \pm \Delta S_g$$

Where:
P – Precipitation
Q_s – Surface runoff
Q_g – Groundwater component of streamflow (baseflow)
E – Evapotranspiration
U – Underflow, in or out of the basin
ΔS_s – Change in surface water storage
ΔS_{sm} – Change in soil moisture
ΔS_g – Change in groundwater storage, including pumping withdrawals.

In a watershed where the surface water divides and groundwater divides coincide, and in which there are no external inflows or outflows of groundwater, if we average over many years of record, the above equation can be simplified to:

$$P = Q + E,$$

the remaining variables being precipitation, streamflow ($Q - Q_s + Q_g$), and evapotranspiration. A schematic presentation of the hydrologic budget is given in Figure 54.

The annual hydrologic budget for typical Prince Edward Island watersheds is shown in Table 16. The location of these watersheds is shown in Figure 55. Streamflow accounts for 60 to 70% of total precipitation on an annual basis while evapotranspiration is estimated at 30 to 40%. It is notable that these values do not vary substantially across the province, being a function of the general similarity of climate, physiography, and geology. In small sub-watersheds, (less than 10 km^2) underflow is probably significant as groundwater recharge within the basin, which would normally contribute to the Q_g component, discharges some distance downstream of the stream gauging station. The Emerald Creek system is illustrative (Table 16).

In the Winter River watershed, the hydrologic budget is a crucial part of water resource planning and management. As shown by the general equation for the budget, water removed from the watershed by pumping (ΔS_g) reduces either the groundwater component of streamflow (baseflow) or underflow to downgradient portions of the basin, or both. Thus, the balance between groundwater withdrawals and maintenance of acceptable

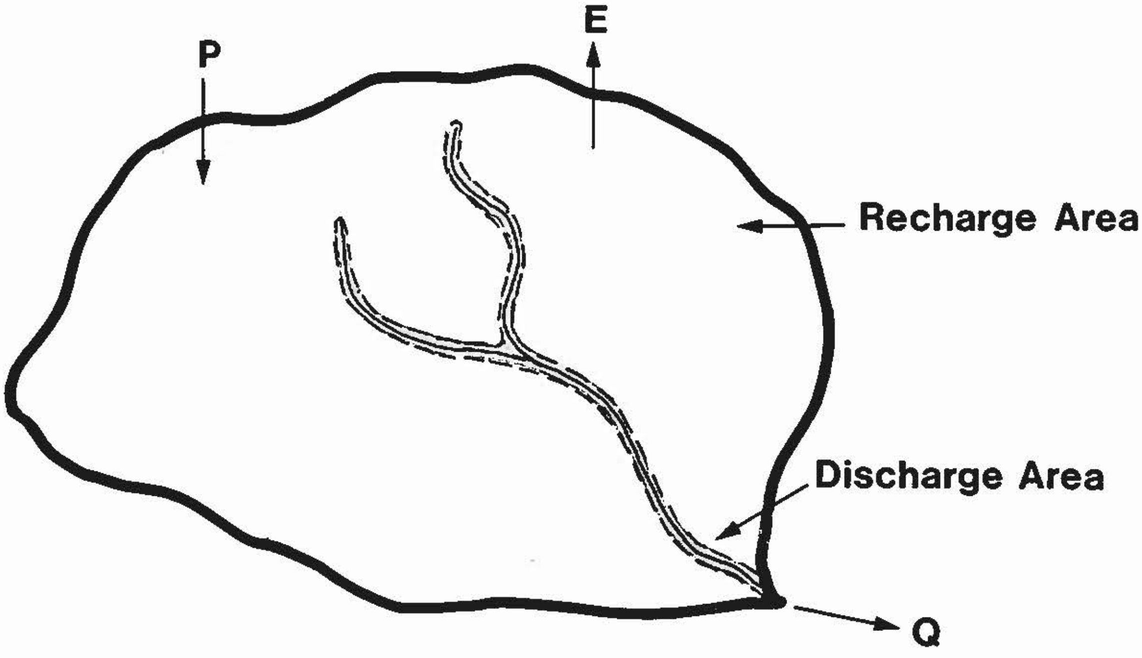


Figure 54. Schematic of the hydrologic budget [11].

baseflow levels must be quantitatively assessed to determine allowable groundwater use rates.

If we consider only the precipitation and streamflow components of the hydrologic budget for the Winter River basin (Table 16), we note that, for the sub-basins above the Brackley and Suffolk gauging stations, streamflow forms a significantly smaller percentage of annual precipitation than in other watersheds. To examine the reasons for this and to evaluate the influence of groundwater withdrawals, the baseflow component of the hydrologic budget will be examined in detail.

5.2 Baseflow

Methods of determining the relative contributions of surface runoff and groundwater discharge to total streamflow include graphical interpretations, monitoring of geochemical indicators or environmental isotopes, and numerical modeling of the hydrologic system [11, 46].

The relatively high hydraulic conductivity of the overburden and bedrock units in Prince Edward Island and the nature of the stream systems result in a very direct relationship between groundwater stage (i.e. position of the water table) and stream discharge. As previously discussed, numerous bubbling springs and small seeps along watercourses, and observation of substantial flow in small and large streams even months after significant precipitation events, attest in a qualitative manner to the significance of groundwater discharge to streamflow.

Quantitative estimates of baseflow contributions to streams in the Winter River basin have previously been made using graphical techniques and suggest that baseflow contributes in the range of 70% to 73% of total streamflow annually [47, 48]. Evidence from detailed

Table 16. Hydrologic Budget for Typical Prince Edward Island Watersheds.

Watershed	Station Identifier	Area (km²)	Precipitation (mm)	Streamflow (mm)	$\frac{\text{Streamflow}}{\text{Precipitation}}$ %	Evapotranspiration (mm)	Period of Record
Carruthers Brook	01CA003	46.8	1081	645	60%	436	1962 - 1986
Dunk	01CB002	114	1061	725	68%	336	1961 - 1983
Wilmot River	01CB004	45.4	1124	683	61%	441	1972 - 1988
Emerald Creek	01CB006	5.59	1091	544	50%	N/A	1974 - 1986
Winter River (at Suffolk)	01CC002	37.5	1202	583	49%	N/A	1968 - 1988
Winter River (at Brackley)	01CC003	4.92	1199	435	36%	N/A	1969 - 1988
Morell	01CD003	133	1160	762	66%	398	1969 - 1988
Brudenell	01CE003	46.8	1081	645	60%	436	1962 - 1986

Note 1. Precipitation Data from Environment Canada, Atmospheric Environment Services
Meteorological Stations: Carruther Brook-O'Leary Station;
Dunk River, Wilmot River; Emerald Creek-Summerside 'A' Station;
Winter River-Charlottetown 'A' Station;
Morell-Bangor Station;

Note 2. Streamflow data from Environment Canada, Water Survey of Canada.

Note 3. N/A- Not Applicable. Evapotranspiration does not equal precipitation minus streamflow in these watersheds because of small watershed size or pumping withdrawals, or both.

Table 17. Comparison of Streamflow and Baseflow Characteristics, Several Watersheds.

Watershed	Station Identifier	Area (km²)	Precipitation (P) (mm)	Streamflow (Q) (mm)	Baseflow (Q_g) (mm)	Q/P%	Q_g/Q%	Q_g/P%	Period of Record
Carruther's Brook	01CA003	46.8	1081	645	334	60%	52%	31%	1962 - 1986
Dunk River	01CB002	114	1061	725	432	68%	60%	41%	1961 - 1983
Wilmot River	01CB004	45.4	1124	683	446	61%	65%	40%	1972 - 1988
Winter River (at Brackley)	01CC003	4.92	1199	435	232	36%	57%	21%	1969 - 1988
Winter River (at Suffolk)	01CC002	37.5	1202	583	395	49%	68%	37%	1968 - 1988
Morell	01CD003	133	1160	762	495	66%	64%	42%	1969 - 1988
Winter River[1] (at Union)		16.6	1202	452	263	38%	57%	22%	Estimate

Note 1. Winter River at Union data obtained by pro-rating data from Winter River at Suffolk according to ratio of drainage areas.

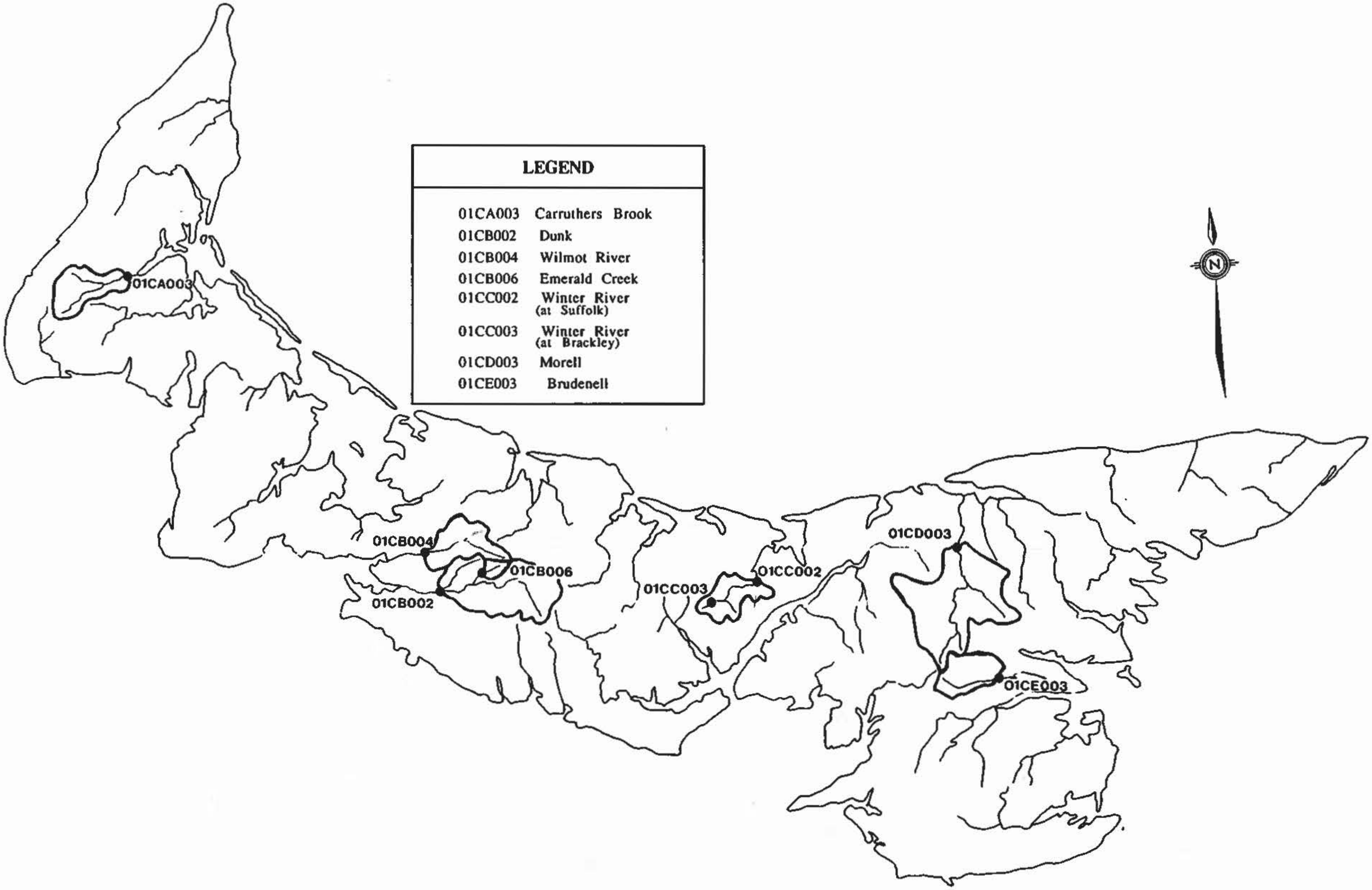


Figure 55. Watershed locations, water budget evaluation.

studies of single storm events in other areas, using geochemical techniques, show that relatively high baseflow contributions to total streamflow should be expected where bedrock and overburden permabilities are high [11].

In this study, a graphical technique known as the 'Envelope Curve Method' was used to determine the baseflow component of streamflow. By comparing stream hydrographs, plotted on arithmetic scale, with precipitation data and local groundwater hydrographs for the same time period, one can readily correlate changes in the position of the water table and changes in the baseflow contribution to streamflow. An example of this method is presented in Figure 56. Applied over a long period of record, a reasonable assessment of groundwater discharge to streams can be obtained. Table 17 and Figure 57 show the results of baseflow separation using the 'Envelope Curve' technique for several watersheds in Prince Edward Island, including the Winter River basin.

Baseflow comprises 60% to 70% of streamflow in most watersheds, except for the Carruthers Brook system and at the Brackley gauging station. The Carruthers Brook system is in an area of relatively low relief in western P.E.I.,and the bedrock in the area is predominantly siltstone and claystone of lower permeability than the sandstone which predominates in the other watersheds. The smaller baseflow component at Brackley is probably a result of underflow - groundwater which recharges in the headwater area above the gauging station, but discharges downstream - or the result of groundwater withdrawal or both. The effects of groundwater withdrawal will be discussed later in this section.

Another factor which must be considered at Brackley and Suffolk is the effect of dams and associated ponds adjacent to both stream gauging stations. These impoundments may tend to smooth out the stream hydrographs following a runoff event by providing storage for peak flows which are subsequently released more slowly to the stream. Given the small size of these impoundments this effect is not considered important.

Table 17 also shows that the baseflow component, expressed as a percentage of annual precipitation, ranges from 40% to 43% in basins of similar physiography and geology, and is 31% at Carruthers Brook. Again, the Winter River stations show significantly lower baseflow/precipitation ratios, 21% and 33% at Brackley and Suffolk, respectively.

Figure 58 shows, for the period 1969-81, the average monthly distribution of streamflow and baseflow at Suffolk and Brackley. At both locations, baseflow is highest in March, April, May, December and January, periods of greatest groundwater recharge. However, streamflows are also higher so that the relative baseflow contribution is lowest. Baseflow is lowest in the July to October period, as expected, but at that time it is the major component of streamflow (70% to 80% at Suffolk). At Brackley, baseflow appears to attain its highest percentage of streamflow in June to August, but this is because the tributary at Brackley gauging station often completely dries up in late summer. Streamflow then occurs only during heavy rainfall and runoff events. It is obvious from these figures, that maintenance of baseflow in the July to October period is crucial to maintaining streamflows.

If we consider a steady state watershed where groundwater withdrawal is not significant and, over a number of years, the position of the water table does not vary ($\Delta S_g = 0$) then the average annual recharge to the groundwater system will be equal to the groundwater discharge, or baseflow to the stream. In Table 17, the baseflow values determined for watersheds other than the Winter River are reasonable estimates of the annual groundwater

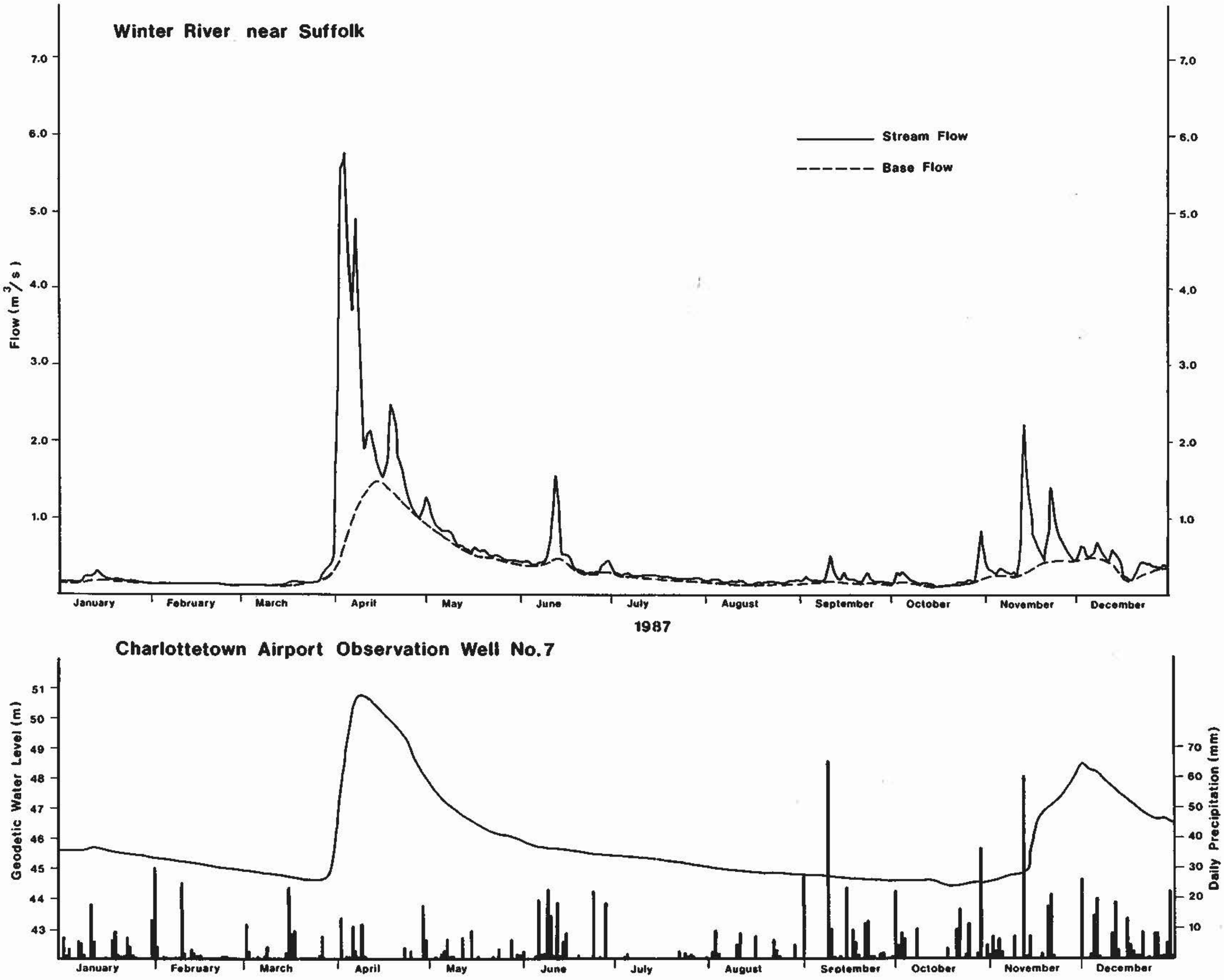
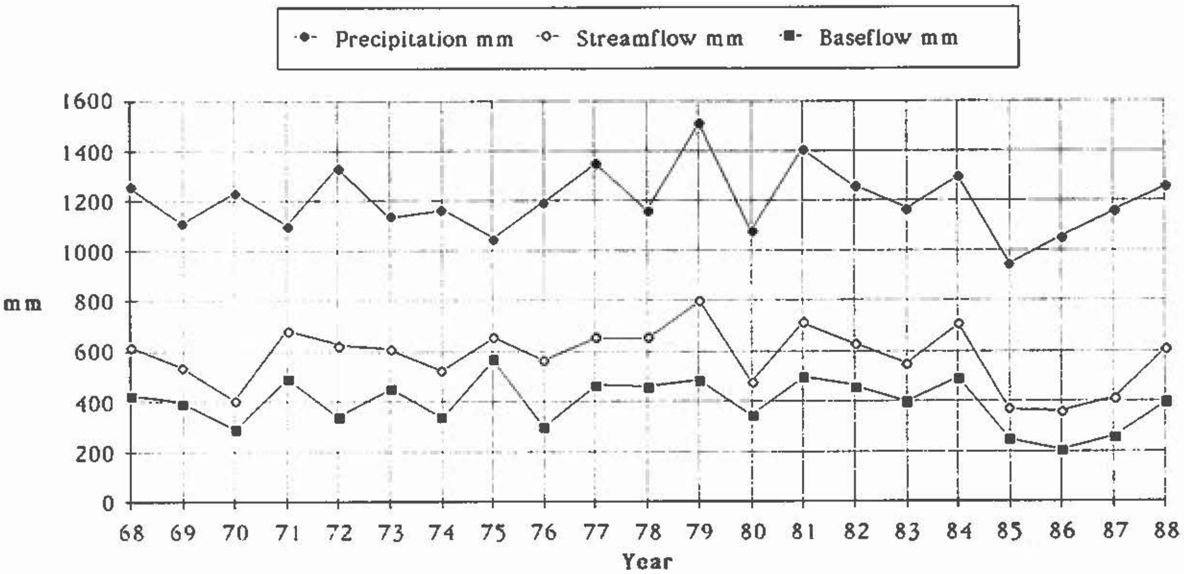


Figure 56. Baseflow separation using data from Suffolk gauging station and Airport #7 observation well. Daily precipitation for 1987 is also shown.

recharge rate. Thus, for central and eastern Prince Edward Island, annual recharge is estimated to be 40% to 43% of total precipitation. Further definition of recharge rates and the hydrologic budget for the Winter River system will be provided in the next section, once groundwater withdrawals are described.

SUFFOLK



BRACKLEY

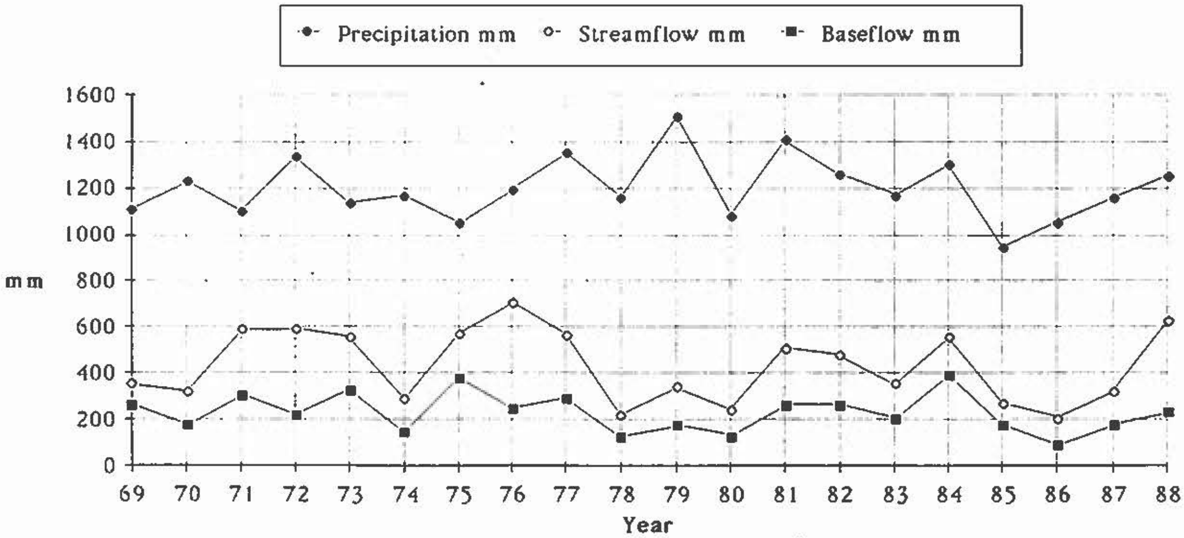
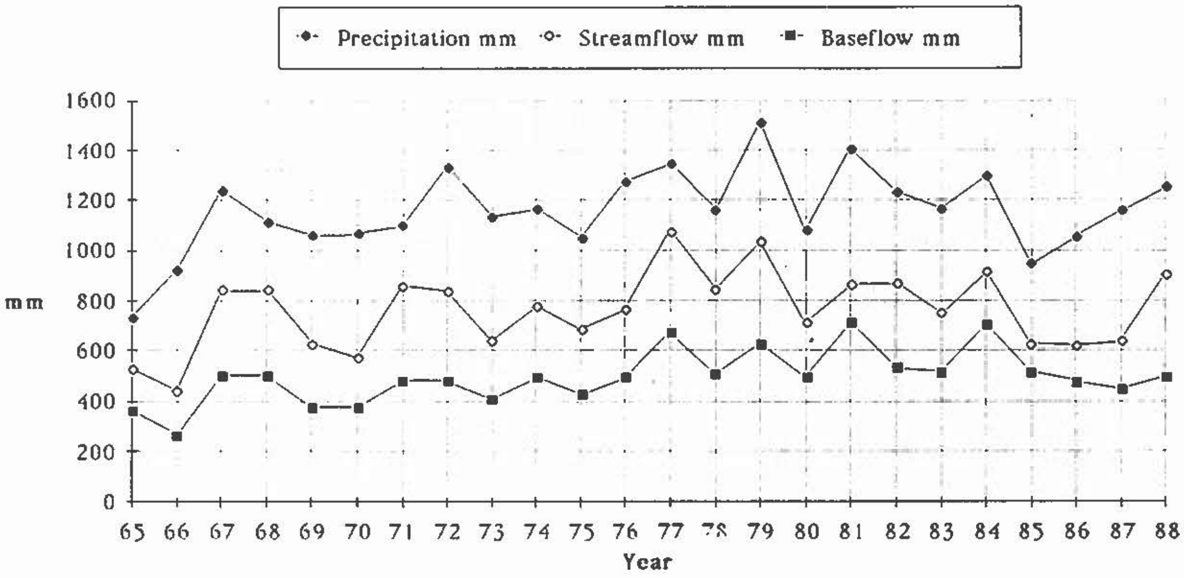


Figure 57. Results of baseflow separation for each year of record at Suffolk, Brackley, Morell and Wilmot.

MORELL



WILMOT

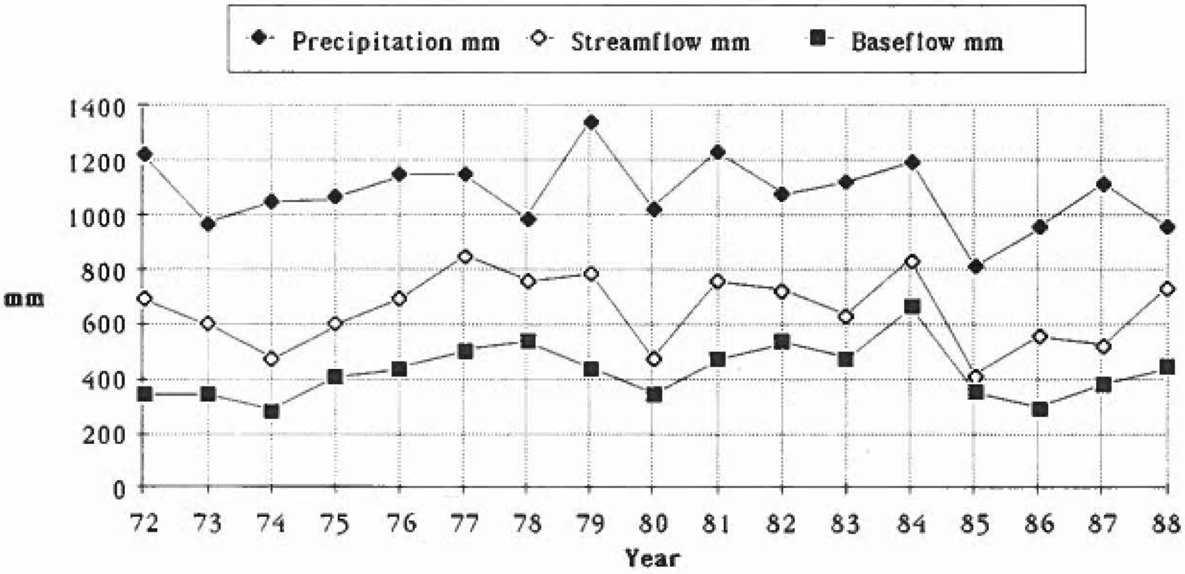


Figure 57. (Cont')

5.3 Effect of Groundwater Withdrawals

As discussed previously, the well fields at Union and Brackley pumping stations provide water supply to the City of Charlottetown and surrounding municipalities. Until recent years, the 'Lower Malpeque' and 'Main Malpeque' pumping stations (Figure 1) have also provided a significant portion of the total supply.

Figure 59 shows historical trends in pumping rates at Union and Brackley and total water consumption by the Charlottetown Water Commission (CWC) from 1954 to 1988. Total

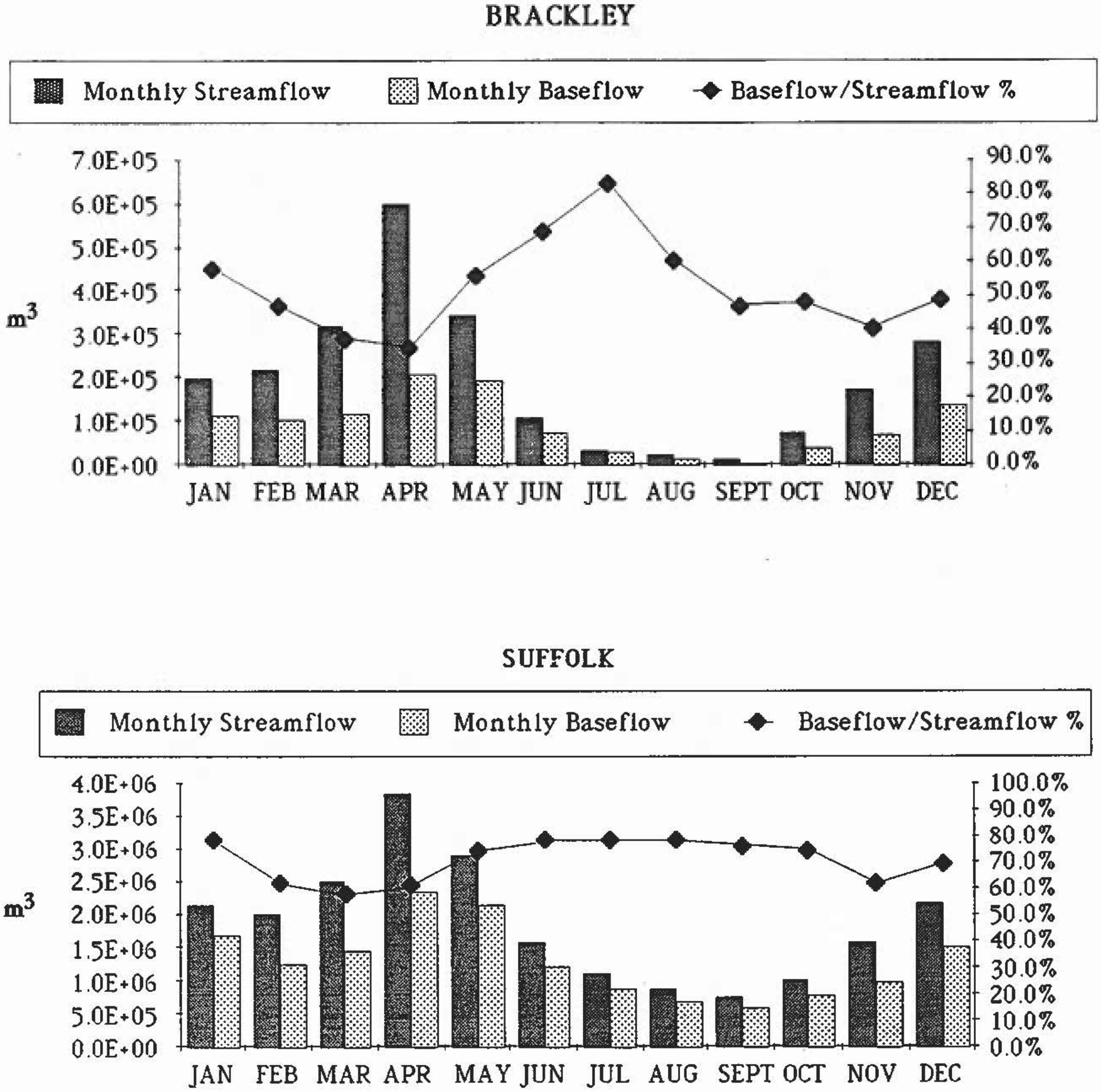


Figure 58. Monthly distribution of baseflow and streamflow at Union and Brackley gauging stations, 1968-82. The solid line shows monthly baseflow as a percent of monthly streamflow.

water use almost doubled in the 1954 - 1974 period, reaching a maximum of over 4.8 million cubic metres in 1978. While total demand has been relatively steady for the last 10 years, the contribution of Brackley and Union well fields has continued to increase. The CWC has reduced dependence on the 'Malpeque' systems because of water quality concerns and higher production costs. Since 1977, 'Malpeque' has provided less than 10% of annual production, and in the last five years, essentially all water supply has been from Union and Brackley. Withdrawals at Brackley station increased markedly in 1976 and 1977, when a high capacity well was brought into production.

Table 18 summarizes available information on the historical changes in annual production by the well fields, and total CWC production. As will be discussed later, monthly withdrawals are relatively constant, with a slight increase during July and August.

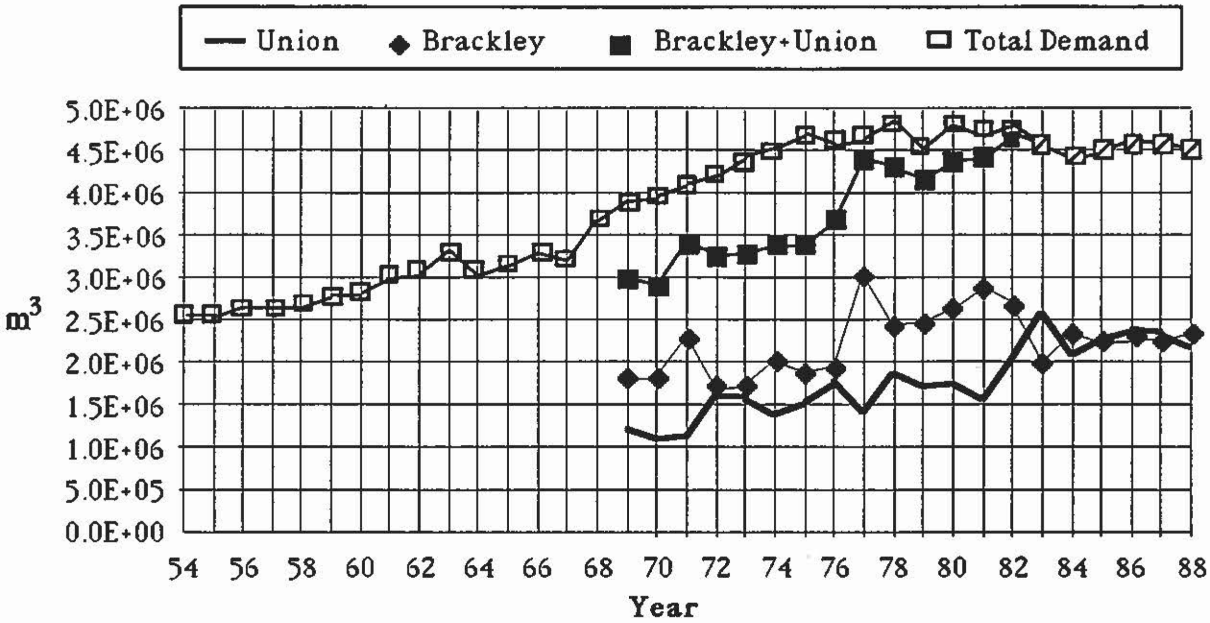


Figure 59. Annual withdrawals from Union and Brackley well fields for available period of record.The "Total Demand" values include pumping from other well fields. For 1983-88, "Union plus Brackley" equals "Total Demand."

Table 18. Historical Trends in Brackley and Union Well Field Production and Total Water Use.

Period of Record	Brackley Well Field (m^3)	Union Well Field (m^3)	Union + Brackley (m^3)	Total (m^3)
1954-1959	N/A	N/A	N/A	2.66E+06
1960-1968	N/A	N/A	N/A	3.17E+06
1969-1976	1.89E+06	1.41E+06	3.30E+06	4.31E+06
1977-1982	2.68E+06	1.72E+06	4.40E+06	4.73E+06
1983-1988	2.24E+06	2.30E+06	4.54E+06	4.54E+06

N/A - Not Available

For the sub-watersheds above the Brackley and Suffolk gauging stations, if we assume for the moment that underflow is negligible, the water budget should be written:

$$P = Q_s + Q_g + E + \Delta S_g$$

with the ΔS_g value representing groundwater withdrawal in the watershed above the gauging station. Taking the period of record of streamflow data (1969 - 1988) as a representative time period, and using the pumping data from Table 18, it is now possible to re-evaluate the water budget for these sub-watersheds.

If we assume that all groundwater withdrawn by pumping would, without pumping, have discharged to the river, forming baseflow and streamflow, we can 'recreate' the water budget for the sub-watersheds. The results are shown in Table 19. Other watersheds in central and eastern Prince Edward Island are included again for comparison purposes.

This scenario suggests that at Suffolk the streamflow, baseflow, and thus recharge characteristics of the system are now quite similar to the unpumped watersheds of Morell, Wilmot, and Dunk Rivers. Fifty-seven percent of precipitation would form streamflow, 73% of streamflow is baseflow, and 42% of precipitation is baseflow. The average annual recharge rate for the Suffolk sub-watershed is therefore estimated at 42%.

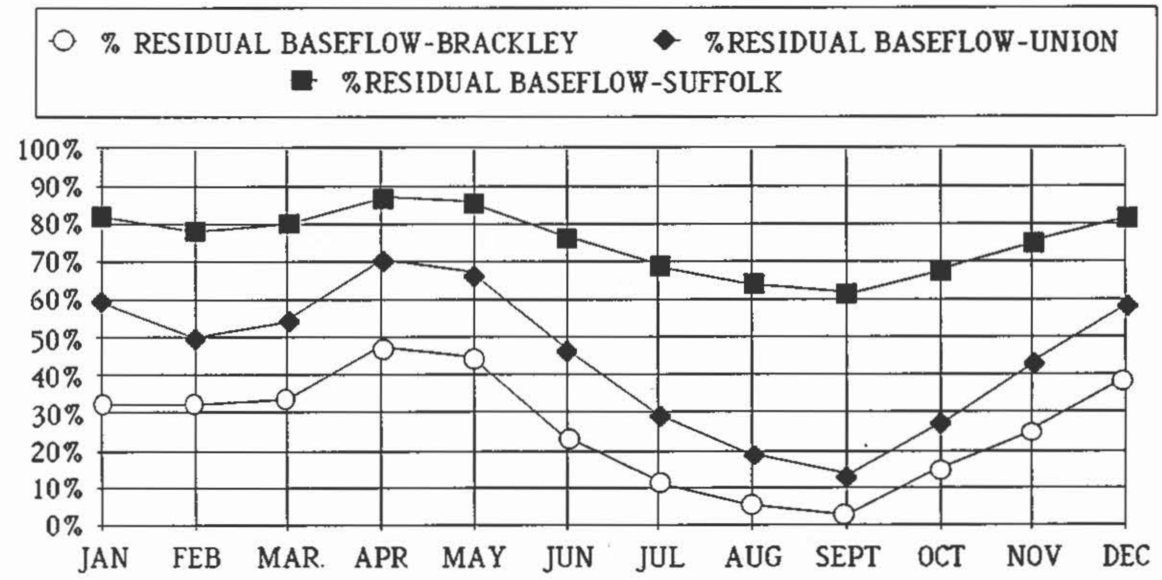


Figure 60. Monthly residual baseflow (normal baseflow minus pumping withdrawals) at Brackley, Union and Suffolk sub-watersheds.

The residual baseflow is distributed through the year in a pattern similar to total baseflow because pumping each month is relatively constant. As expected, the residual baseflows are lowest at all three locations during the July-October period. At Brackley, residual baseflows are less than 50% throughout the year, and less than 10% during an average August-September period. This would account for the fact that no discharge occurs through the stream gauging station in dry periods of some years at Brackley.

At the sub-watershed to Union, residual baseflows are at least 30%, except for the August-October period. In September, the residual baseflow is only about 13%. Again, this would explain the drying up of one tributary west of Union well field in August-October each year. Residual baseflows are greater than 60% throughout the year at Suffolk.
In the smaller Brackley sub-watershed, the results do not agree with other watersheds. The predicted annual baseflow and thus recharge rate, is 58% of total precipitation, and total streamflow is 74% of precipitation. These high values probably result from a combination three factors:

(1) Continuous groundwater withdrawal has increased the effective recharge area by expanding the drawdown cone around the well field (Section 4.3.3).

(2) The actual groundwater recharge area is somewhat larger than the surface water drainage basin because in either (1) or (2), an increase in recharge area of only one km^2 would decrease the apparent recharge rate to 47%.

(3) As discussed in Section 4.4.3, pumping withdrawals increase downward gradients in the area of the well fields, so that induced recharge occurs. The rapid response of observation wells in the well fields to recharge events (Section 4.2.5) supports this explanation.

A fourth explanation for an artifically high recharge rate, i.e. continuous lowering of the water table and removal of groundwater in excess of annual recharge, has not been observed. The true recharge rate is probably somewhere between 42% and 58%, but the very high value of 58% will be utilized in further calculations for the Brackley sub-watershed to account for the unknowns listed above.

We can now look at the specific effects of groundwater withdrawals on streamflow and baseflow in the Winter River watershed. Table 20 shows 1988 groundwater withdrawals by pumping as a percent of annual recharge. In the Brackley sub-watershed, annual pumping is reducing streamflow by 53%, and baseflow by 70%. In the Union sub-watershed, pumping is reducing streamflow by an estimated 39%, and 54% of annual recharge (equivalent to baseflow) is being utilized. In the watershed at Suffolk, streamflow is reduced by only 17%, and 24% of annual recharge is removed by the two well fields.

In no part of the watershed is pumping exceeding annual recharge. There should be no continual lowering of the water table, based on these results. However, the calculated reduction in baseflow and streamflow is substantial, and this should be observable between time periods when different pumping rates were used. Comparing data for the Brackley gauging station for the periods 1969 - 1976 and 1977 - 1982, baseflow decreased from an average of 22% of precipitation to 16%, a reduction of 27%. Streamflow as a fraction of precipitation decreased by 21%. Groundwater withdrawals in the same period increased by 41%. A reduction in streamflow or baseflow between the two periods was not observed at the Suffolk gauging station, probably because the change in groundwater withdrawal was a relatively small fraction of total recharge (less than 6%).

As shown previously in Figure 58, baseflow and streamflow vary dramatically from month to month in an average year and the relative contribution by baseflow varies inversely with the amount of streamflow. The very direct connection between baseflow and groundwater withdrawals means that streamflow is most sensitive during the late summer - early fall period when streamflow is lowest and predominantly comprised of baseflow. Figure 60 shows residual baseflows and groundwater withdrawals each month for each sub-watershed. The residual baseflows are the percentage of total baseflow (assuming no pumping) that is left each month after withdrawals at respective well fields in each sub-watershed are subtracted.

Table 19. **Assessment of Water Budget, Winter River Basin, including Pumping Withdrawals.**

Watershed	Area (km^2)	Precipitation (mm)	Streamflow (mm)	Baseflow (mm)	Pumping[1] (mm)	STR + Pump[3] (mm)	Base + Pump (mm)	TS/P%	TB/TS%	TB/P%
Brackley	4.92	1202	435	232	453	888	685	74	77	58
Suffolk	37.5	1202	583	395	105	688	500	57	73	42
Union[2]	16.6	1202	452[2]	263[2]	237	689	500	57	73	42
Morell	133	1160	762	495	—	—	—	66	65	43
Wilmot	45.4	1124	683	446	—	—	—	61	65	40
Dunk	114	1061	725	432	—	—	—	68	60	41

Note 1. Pumping volume converted to equivalent depth of water spread evenly over the watershed.

Note 2. Union Streamflow = (Suffolk Streamflow • 16.6 km^2 + 37.5 km^2) - Pumping; Union Baseflow = (Suffolk Baseflow • 16.6 km^2 + 37.5 km^2) - Pumping

Note 3. STR = Streamflow
TS =Total Streamflow = Streamflow + Pumping
P =Precipitation
TB =Total Baseflow = Baseflow + Pumping

Table 20. **Effect of Groundwater Withdrawals on Streamflow and Baseflow.**

Watershed	1988 Annual Pumping (m^3)	Annual Recharge Rate	Streamflow (m^3) (No Pumping)	Annual Recharge (m^3)	Pumping / Streamflow	Pumping / Recharge
Brackley	2.34E+06	58%	4.37E+06	3.38E+06	53%	70%
Union[1]	4.50E+06	42%	1.15E+07	8.32E+06	39%	54%
Suffolk	4.50E+06	42%	2.58E+07	1.88E+07	17%	24%
Hardy's Pond (present)	4.50E+06	42%	1.76E+07	1.28E+07	25%	35%
Hardy's Pond[2] (developed)	6.75E+06	42%	1.76E+07	1.28E+07	38%	53%

Note 1. The recharge rate of 42% estimated for the Suffolk sub-watershed has been applied to Union as well.

Note 2. Assumes developed well field with pumping rate of 75 L/s.

5.4 Implications for Future Resource Development

The characteristics of the hydrologic budget in the Winter River basin have now been evaluated. It is clear that any water removal from a hydrologic system, in this case by provision of groundwater supply, has some influence on other variables of the water budget. The acceptability of these effects to other resource users must be determined in order to define a 'safe yield' for each of the sub-watersheds now utilized for large scale groundwater supply, or to identify potential for future expansion and development of new supplies.

In previous sections, it has been seen that the primary effect of groundwater withdrawals from the well fields at Union and Brackley is reduction of baseflow and streamflow. Neither withdrawal in excess annual recharge (with resultant lowering of groundwater levels and increased pumping costs), nor interference with private wells in the area is occuring. During some months of the year, present pumping rates can reduce baseflow to near zero, especially in the smaller Brackley sub-watershed. However, even without pumping, use of streamflow during dry weather months would be limited at Brackley because of the small size of the watershed. As larger portions of the watershed are affected, the implications of baseflow reduction on other surface water resource uses - sports fishery, aquaculture, recreation, cattle watering, irrigation, and the aquatic environment in general - must be considered.

It is apparent from Figure 60 that, considering the normal variability of baseflow from year to year, further reduction in residual baseflow at Union station would lead to extended periods of extremely low flow. Given that 54% of annual recharge is now being removed by pumping in the Union sub-watershed (Union and Brackley well fields), it is recommended that withdrawals from the existing well fields be limited to 60% of average annual recharge, or 5.0 x 10^6 m^3/year. Further, this should be considered an interim maximum, reducing to 55%, or 4.6 x 10^6 m^3/year, as soon as additional groundwater supplies are developed.

Good potential for future development of groundwater supplies exists further down the Winter River watershed. Total annual groundwater withdrawals (all well fields) in the recharge area above any proposed development site should be planned at 50% of average annual recharge, or about 2.5 x 10^5 m^3/year for each km^2 of recharge area. For example, a well field developed near the Hardy's Pond - York Road area (recharge area 25.6 km^2) could withdraw about 2.0 x $10^6 m^3$/year in addition to current pumping at Union and Brackley.

6. HYDROGEOCHEMISTRY

6.1 Inorganic Chemistry

6.1.1 Previous Work

The inorganic chemistry of the shallow groundwater and surface water in the Winter River basin has been adequately characterized in a planning study for the basin conducted by Environment Canada [1] and in an assessment of the impact of the Charlottetown Airport redevelopment project [7]. The planning study sampled 24 domestic wells (depth range 17 m to 43 m), two municipal wells, and seven springs in the basin. Table 21 presents the results; the major ion chemistry is shown on a multiple-trilinear diagram [63] in Figure 61.

All well and spring waters are a calcium-magnesium-bicarbonate type, the result of open-system dissolution of dolomite from the sandstone matrix. This reaction usually proceeds to saturation with respect to dolomite or calcite above the water table. The groundwater is hard to very hard. Sodium and chloride values are very low, marine aerosols being their natural source. The natural groundwater quality meets the Canadian Guidelines for Drinking Water Quality [50] quite adequately. Elevated nitrate levels, apparently due to agricultural sources, were noted in several samples. There is no significant difference between the well and spring water chemistry.

Groundwater and surface water sampling for the Airport study [7] showed that streamflow quality was very similar to groundwater quality during most periods of the year. This is due to the very large groundwater component of streamflow. Even during flood periods, the streamflow is essentially diluted groundwater.

6.1.2 Current Study

Groundwater geochemistry was examined in a number of shallow piezometers and deep boreholes in an attempt to map the groundwater flow system through variations in the chemical composition of the groundwater.

The shallow piezometers (Section 4.1) sampled groundwater in the glacial deposits. From deep boreholes, single composite samples were collected along with a series of samples from isolated test intervals in each borehole (Section 4.2.2). The composite samples are not true 'composites', but represent the groundwater quality in the zone or zones of an open borehole having the highest hydraulic head and significant hydraulic conductivity. These zones, the upper zones of boreholes in recharge areas and the lowest zones of boreholes in discharge areas, will dominate the open borehole sample because of the natural gradients in the well bore. Similarly, isolated test intervals will only yield representative samples if groundwater flow in the well bore prior to isolating the interval did not introduce groundwater from another interval. Knowledge of the hydraulic head and hydraulic conductivity along the length of the well (Figure 31) provides reasonable assurance of the

Table 21. Statistics for Water Samples Winter River Watershed.

	Wells			Springs		
Parameter	Maximum Value	Minimum Value	Average Value	Maximum Value	Minimum Value	Average Value
Calcium	52.0	20.0	31.8	35.0	5.2	22.2
Magnesium	25.0	11.0	16.1	18.0	1.7	11.1
Sodium	10.0	4.7	7.0	8.0	5.3	6.2
Potassium	4.75	1.1	1.99	2.30	0.70	1.53
Sulfate	22.3	5.0	10.2	17.7	7.0	10.9
Chloride	22.0	8.7	14.6	34.0	12.0	16.7
Nitrate (N)	9.9	0.2	3.2	4.1	0.9	2.0
Alkalinity (as $CaCO_3$)	197	69	113	113	3.0	72
Hardness (as $CaCO_3$)	267	101	163.6	185	50	137
T.D.S.	660	50.	253	430	60	202
Specific Conductance	510	180	318	330	120	271
pH	8.5	7.1	7.8	8.2	4.2	7.3
Total Iron	0.2	<0.1	<0.1	0.9	<0.1	0.1
Manganese	0.08	<0.02	0.02	0.15	<0.02	0.02
Lead	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Zinc	0.35	<0.02	0.07	0.23	<0.02	0.06
Copper	0.05	<0.02	<0.02	0.20	<0.02	0.03
Ammonia (N)	0.5	<0.2	<0.2	0.4	<0.2	<0.2
Phosphate	0.19	0.04	0.10	0.16	0.04	0.11

Note: All values are in mg/L except pH (units) and specific conductance (µmhos).

suitability of selected samples. Figure 62 shows each borehole and shallow piezometer in relation to its elevation and position (from southwest to northeast) in the watershed. Intervals yielding representative samples are also shown.

Two distinct types of groundwater were identified in the watershed (Table 22). 'Type 1' is typical Ca-Mg-HCO_3 groundwater with low sodium and slightly alkaline pH. This is the type of groundwater identified in all domestic wells, municipal wells and springs as discussed in the previous section. Intervals exhibiting this groundwater chemistry are labeled accordingly in Figure 62. They include shallow piezometers and the shallow intervals of boreholes in recharge areas (W-33, BP-34, Y-35, and S-37). Samples from shallow piezometers at 15-Y and 18-Y have elevated chloride values, indicative of road salt contamination. 'Type 2' is a Na-HCO_3 groundwater, with high sodium concentrations (up to 190 mg/L), very low hardness (9 to 42 mg/L), high alkalinity (up to 321 mg/L), and high pH (up to 9.1) (Table 22). This type of groundwater has been encountered only rarely on P.E.I., in several deep wells on the coast (e.g. Rustico Deep Well - 150 m deep, 100 m casing; Hebrides - 160 m deep, 120 m casing) and in several shallow wells in the Enmore area of western Prince Edward Island. The groundwater type has been identified elsewhere [51], [52], and is attributed to the effects of cation exchange in strata with significant amounts of clay minerals with exchangeable sodium [11]. It would appear that the softened water re-encounters carbonate minerals along its flow path because the alkalinity and pH are somewhat higher than normal Type 1 waters. This could result from closed-system dissolution of the carbonate minerals. Subsequent cation exchange again removes the calcium or magnesium ions from solution.

This Na-HCO_3 groundwater exists only at depths of more than 50 or 60 m in areas of upward gradients and is apparently absent in 100 to 150 m deep wells at Union and Brackley well fields. This would indicate that at a depth greater than 150 m, groundwater encounters geologic materials having sodium-rich clay minerals, and the cation exchange process takes place. Flow is mostly intergranular at these depths, and the geological sequence could be a series of siltstones, claystones and shales. The significance of these groundwater types in characterizing the basin groundwater flow systems will be discussed in Section 7.

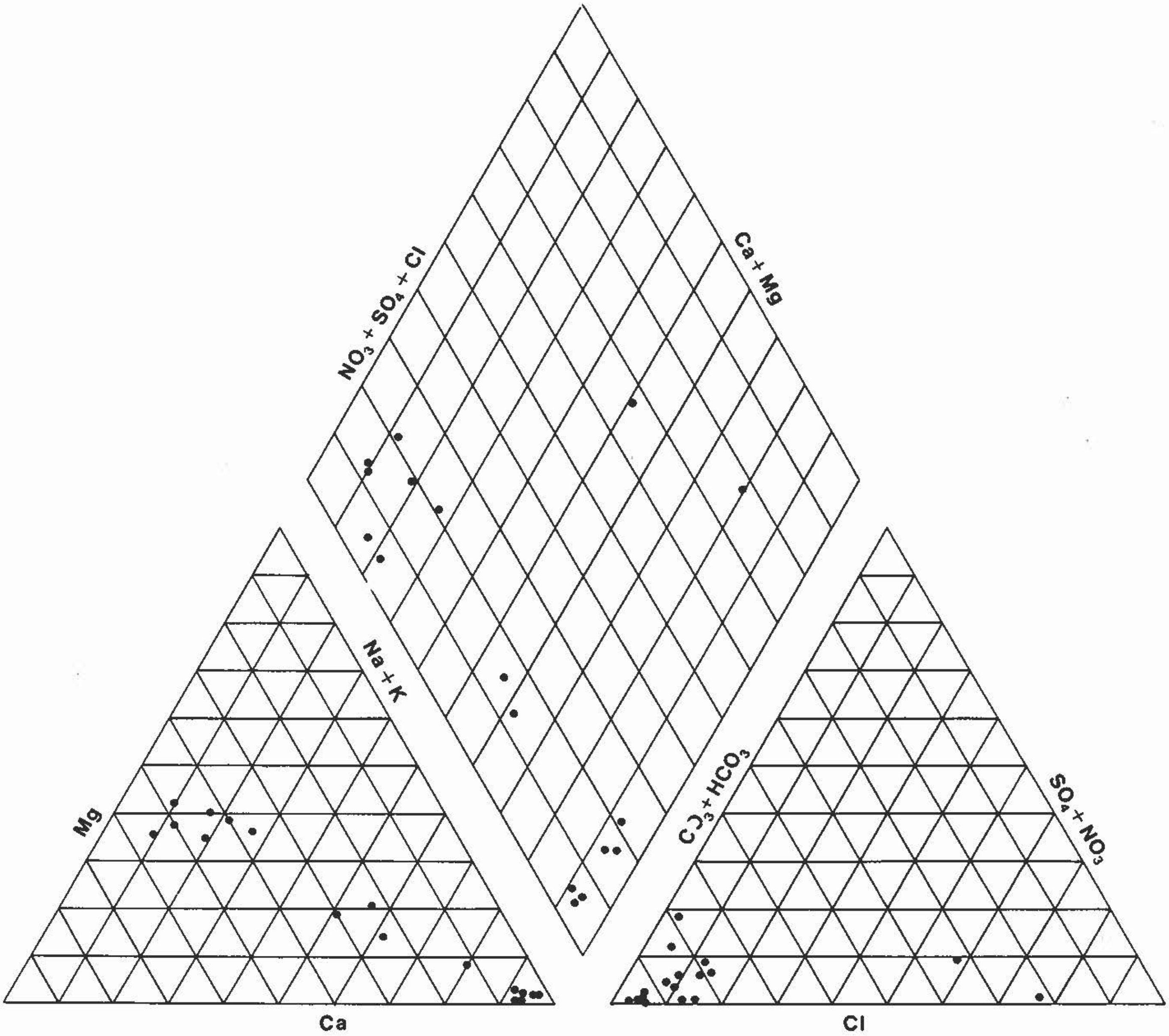


Figure 61. Piper plot [49] of inorganic chemistry, 150 m boreholes.

6.2 Environmental Isotopes

The isotopes of hydrogen and oxygen are useful tools in a variety of hydrologic investigations. Isotopes are atoms having one or more extra neutrons in their nuclei. In this study, tritium (^3H), deuterium (^2H), and Oxygen-18 (^{18}O) have been measured in selected groundwater and surface water samples to assist in the definition of groundwater residence times, flow system mapping, and confirmation of other geochemical interpretations. The results of an unpublished report on dissolved gases and radionuclides [53] in the basin will also be discussed.

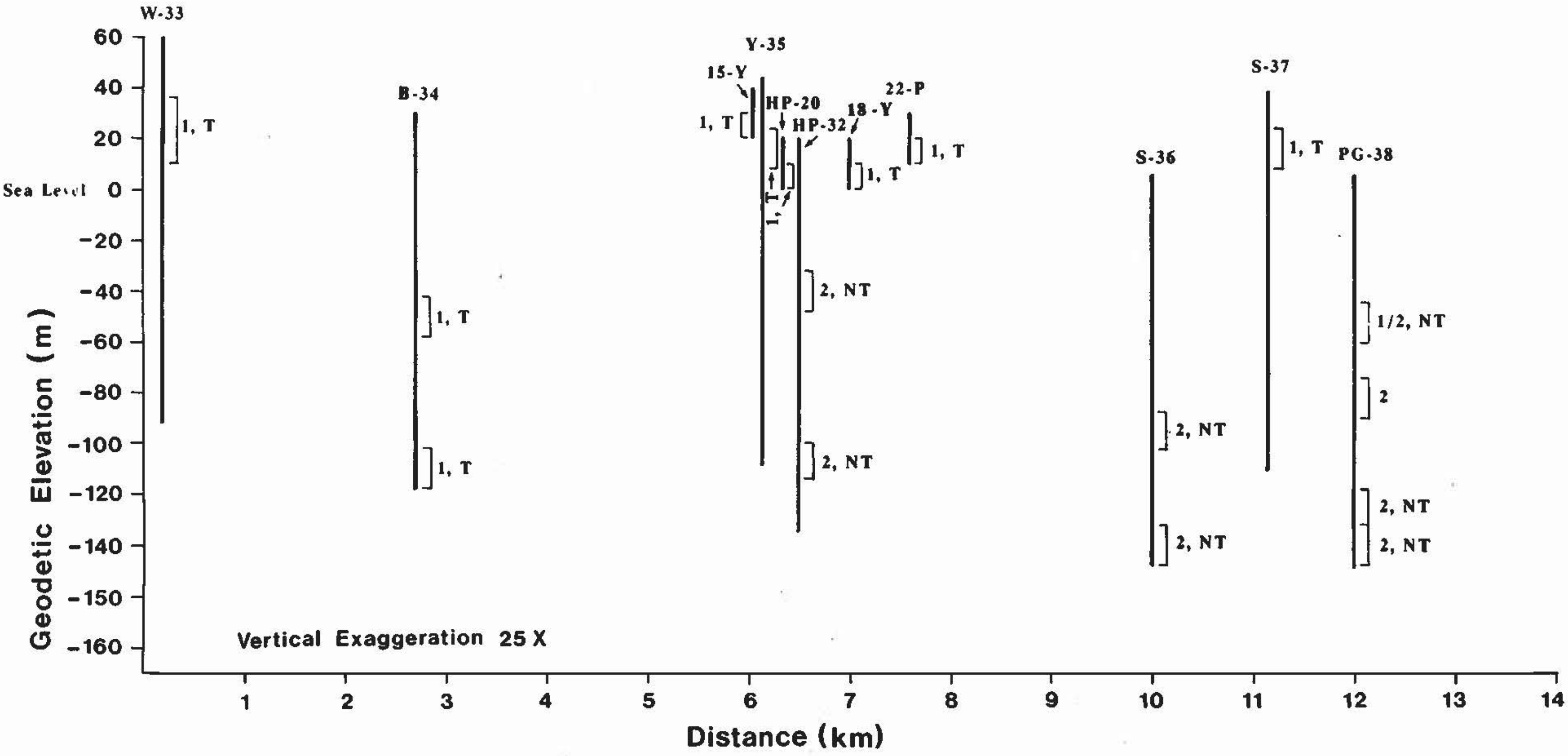


Figure 62. Relative positions of groundwater sampling zones, 150 m boreholes, shown on cross-section A-B (Figure 7).

Table 22. **Inorganic Chemistry, Representative Intervals of 150 m Boreholes and Shallow Piezometers.**

Parameter	W-33 24.3-50.2m	B-34 72.7-87.7m	B-34 132.7-147.7m	15Y	Y-35 top-35.2m	HP-20	HP-32 51.8-66.8m	HP-32 119-134m
Calcium	30.7	33.0	34.1	22.0	30.6	47.3	10.3	7.5
Magnesium	16.01	15.29	15.34	8.4	18.11	26.3	3.7	0.4
Sodium	6.5	7.0	8.4	41.3	11.2	10.7	29.6	112.0
Potassium	1.51	1.59	1.66	3.15	2.36	1.72	1.7	1.43
Phosphorus	0.10	0.14	0.12	0.02	0.18	0.06	0.09	0.14
Sulfate	5	6	9	10	6	6	—	—
Chloride	11	14	15	70	20	10	9	6
Nitrate(N)	1.0	3.0	3.5	6.0	6.2	0.3	0.2	<0.2
Alkalinity (as $CaCO_3$)	160	118	123	57	150	267	87	188
P.Alkalinity (as $CaCO_3$)	—	—	—	—	—	—	—	22
Hardness (as $CaCO_3$)	143.1	146.3	149.3	89.8	151.4	227.7	42.2	21.5
Specific Conductance	—	—	—	395	—	485	—	—
Temperature (°C)	—	—	—	6.5	—	7.0	—	—
pH	7.6	7.5	7.4	6.7	7.2	7.5	8.2	9.1
Diss. Iron	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1
Ext. Iron	< 0.1	< 0.1	< 0.1	0.2	< 0.1	0.2	< 0.1	< 0.1
Manganese	< 0.02	< 0.02	< 0.02	< 0.02	< 0.02	0.28	< 0.02	0.04
Lead	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1
Zinc	0.22	0.50	0.52	0.09	0.17	0.4	0.7	0.54
Copper	0.02	< 0.02	< 0.02	0.05	0.05	0.03	< 0.02	< 0.02
Ammonium (N)	< 0.1	—	—	< 0.01	< 0.1	< 0.1	—	—
Cadmium	< 0.02	—	—	—	< 0.02	—	—	—
Nickel	< 0.05	—	—	—	< 0.05	—	—	—

Table 22. (cont')

Parameter	18-Y	22-P	S-36 93.4-108.4m	S-36 138.6-153.6m	S-37 14.6-29.6m	PG-38 50-65m	PG-38 80.4-95.4m	PG-38 123.2-138.2m	PG-38 138.2-153.2m
Calcium	16.7	40.4	2.6	4.4	40.0	8.3	3.6	6.5	8.0
Magnesium	7.14	23.87	0.63	1.24	15.85	4.55	1.00	0.54	1.82
Sodium	129.0	23.7	112.0	190.0	7.6	22.7	74.0	117.0	131.0
Potassium	7.50	2.95	1.07	1.66	1.66	1.84	0.97	1.94	2.04
Phosphorus	0.12	0.12	0.14	0.12	0.14	0.1	0.08	0.12	0.11
Sulfate	—	—	30	70	5	—	7	—	—
Chloride	180	10	8	8	12	10	10	9	8
Nitrate(N)	0.8	0.7	0.3	< 0.2	< 0.2	0.4	< 0.2	0.2	0.2
Alkalinity (as $CaCO_3$)	73	243	202	321	153	82	132	197	219
P.Alkalinity (as $CaCO_3$)	—	—	19	13	—	—	17	23	13
Hardness (as $CaCO_3$)	78.4	199.6	9.6	16.9	165.9	40.1	13.9	19.6	28.5
Specific Conductance	—	—	—	—	—	—	—	—	—
Temperature (°C)	—	—	—	—	—	—	—	—	—
pH	7.4	8.0	9.0	8.6	7.5	7.7	9.0	9.0	8.8
Diss. Iron	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1
Ext. Iron	< 0.1	0.2	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1
Manganese	3.71	0.08	< 0.02	< 0.02	< 0.02	< 0.02	< 0.02	< 0.02	0.06
Lead	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1
Zinc	0.25	0.08	0.23	0.42	0.4.0	0.32	0.4	0.64	0.5
Copper	0.03	< 0.02	< 0.02	< 0.02	< 0.02	< 0.02	< 0.02	< 0.02	0.09
Ammonium (N)	—	—	—	—	—	—	< 0.1	—	—
Cadmium	—	—	—	—	—	—	< 0.02	—	—
Nickel	—	—	—	—	—	—	< 0.05	—	—

Tritium, a radioactive atom, occurs naturally in the atmosphere in small quantities but its abundance in the atmosphere at present is the result of thermonuclear tests conducted between 1952 and 1969. If water samples contain no detectable tritium, it is usually evidence that the sample has no post-1953 water in it [11].

Deuterium and Oxygen-18 are present in precipitation in amounts which depend on the condensation - precipitation history of the air mass. The concentrations are affected by evaporation and by temperature, and thus by elevation. The concentrations of oxygen-18 and deuterium are also inter-related globally in precipitation according to the globally derived function [11]:

$$\delta\ {}^{2}\mathrm{H}‰ = 8\,\delta^{18}\mathrm{O}‰ + 10$$

where δ is the difference between the isotopic ratio in the sample and in an arbitrary standard known as standard mean ocean water (SMOW), expressed in per mil relative to the standard. The above equation describes what is known as the meteoric water line. Deviation of water samples from the meteoric water line can sometimes be used to interpret the hydrologic history of the water.

Water samples collected for isotope analyses in this study included precipitation, surface water, shallow groundwater and deep groundwater. All analyses were conducted at the University of Waterloo's Environmental Isotope Laboratory. Monthly composite precipitation samples were collected from the Maypoint Road precipitation station (Figure 1). The results are summarized in Figure 63. These suggest a local meteoric water line represented by:

$$\delta\ {}^{2}\mathrm{H}_{\substack{\text{Monthly}\\ \text{Avg.}}}‰ = 6.9 \pm 0.23\ \delta^{18}\mathrm{O}_{\substack{\text{Monthly}\\ \text{Avg.}}}‰ - 6.2 \pm 5.5$$

This is very similar to the results from longer term (1975-83) precipitation analyses at a Truro, Nova Scotia station [54]:

(1) $\delta\ {}^{2}\mathrm{H}_{\substack{\text{Monthly}\\ \text{Avg.}}}‰ = 7.61 \pm 0.23 \bullet \delta\ {}^{18}\mathrm{O}_{\substack{\text{Monthly}\\ \text{Avg.}}}‰ + 7.06 \pm 1.05$

(2) $\delta^{18}\mathrm{O}_{\substack{\text{Monthly}\\ \text{Avg.}}}‰ = 0.26\ T_{\substack{\text{Monthly}\\ \text{Avg.}}} - 10.99‰$

(3) $\delta\ {}^{2}\mathrm{H}_{\substack{\text{Monthly}\\ \text{Avg.}}}‰ = 1.87\ T_{\substack{\text{Monthly}\\ \text{Avg.}}} - 75.24‰$

The results of surface water and shallow and deep groundwater analyses are presented in Table 23. Deuterium and ^{18}O compositions in surface water and shallow groundwater are more variable than in deep groundwaters. The former represent mixtures of recent seasonal precipitation. The deeper groundwaters have a very narrow range of isotopic composition, suggesting that they are a mixture of recharge integrated over long periods of time [11]. The ^{18}0 and deuterium data are plotted in Figure 64 with the meteoric water line from the Truro station. All groundwater data plot on or close to the meteoric water line. The deep groundwater data plot together, suggesting that all samples were recharged under similar, relatively recent climatic conditions. Groundwater recharge at the time of the last glaciation would be significantly depleted in ^{18}0 and deuterium (more negative values).

Use of the global ^{18}O temperature relationship yields a recharge temperature for the deep groundwater of 4.5°C. Rustico Deep Well results plot slightly above the meteoric water line,

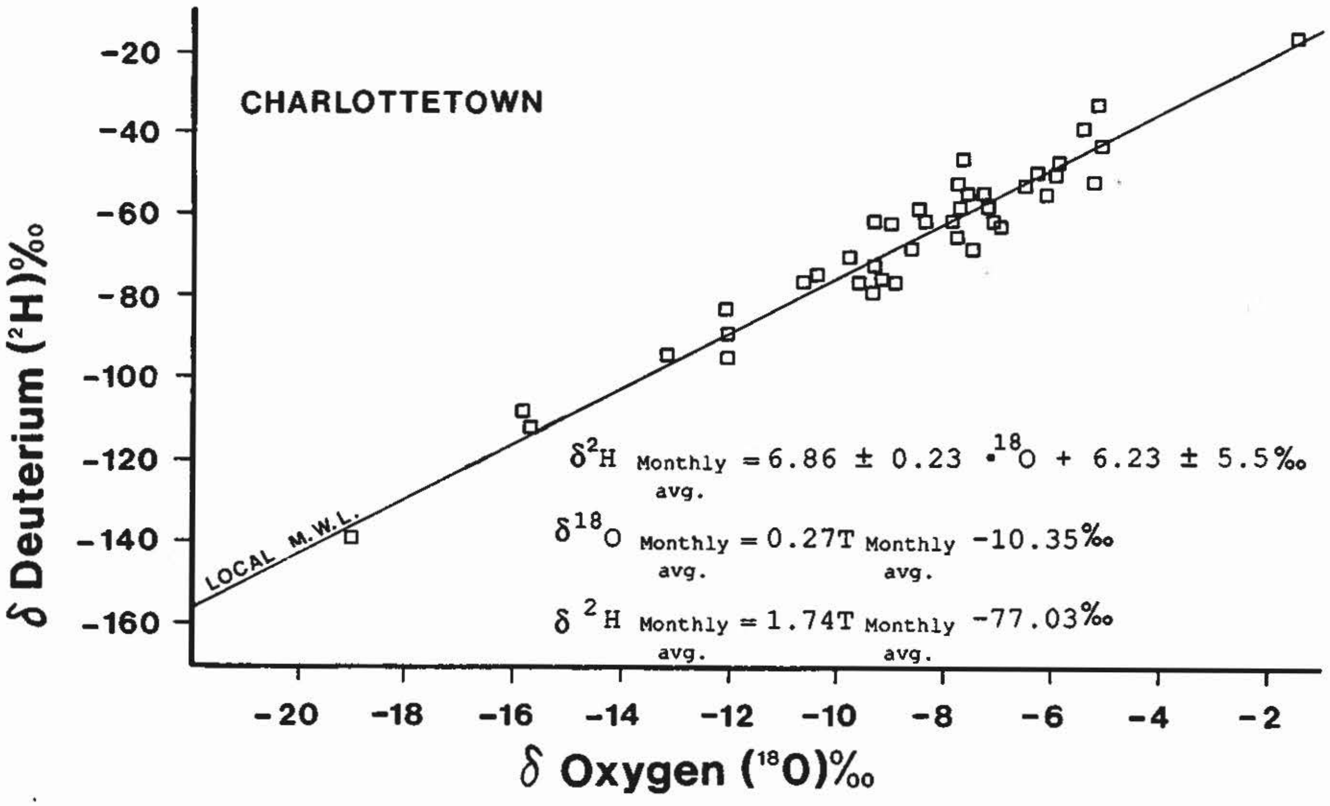


Figure 63. ^{18}O and ^{2}H in precipitation, Maypoint Road precipitation station. The equations for the local meteoric water line and isotope-temperature relationships are shown.

suggesting strongly reducing conditions and possible enrichment in deuterium due to formation of H_2S. The odour of H_2S has been detected in water from this borehole.

The tritium data in Table 23 show that shallow groundwater and surface water have measurable tritium concentrations, as expected. However, in samples collected from isolated test intervals, tritium is absent in the deeper intervals of all boreholes with upward gradients (HP-32, S-36, PG-38, Rustico Deep Well). It is notable that all of the zones without detectable tritium have Type 2 water. In boreholes W-33, B-34, Y-35, and S-37, the representative zones (Figure 62) all have measurable tritium concentrations. Groundwater in the deeper portion of the basin, away from the recharge areas, appears to have been recharged prior to 1953. Further implications of these results will be discussed in Section 7.

A study by Andrews on radioelements and dissolved gases in the bedrock aquifer [53] was conducted using samples from the Deep Groundwater (Composite) group on Table 21. Uranium isotope analyses showed that uranium mobilization by shallow groundwater is occurring throughout the basin and the uranium concentration increases with depth from about 0.11 mg/L at Y-35 to 12.02 mg/L at HP-32. Oxidizing conditions predominate in the basin. The low uranium concentrations in the Rustico Deep Well indicate reducing conditions exist at that location.

The radon (^{222}Rn) content of groundwaters range from about 750 to about 1000 pCi/kg, the highest value occurring at HP-32. The radon content of groundwater is determined by the uranium concentration and the porosity and permeability of the rock matrix. The radon values are somewhat high for sandstone formations, probably a result of significant

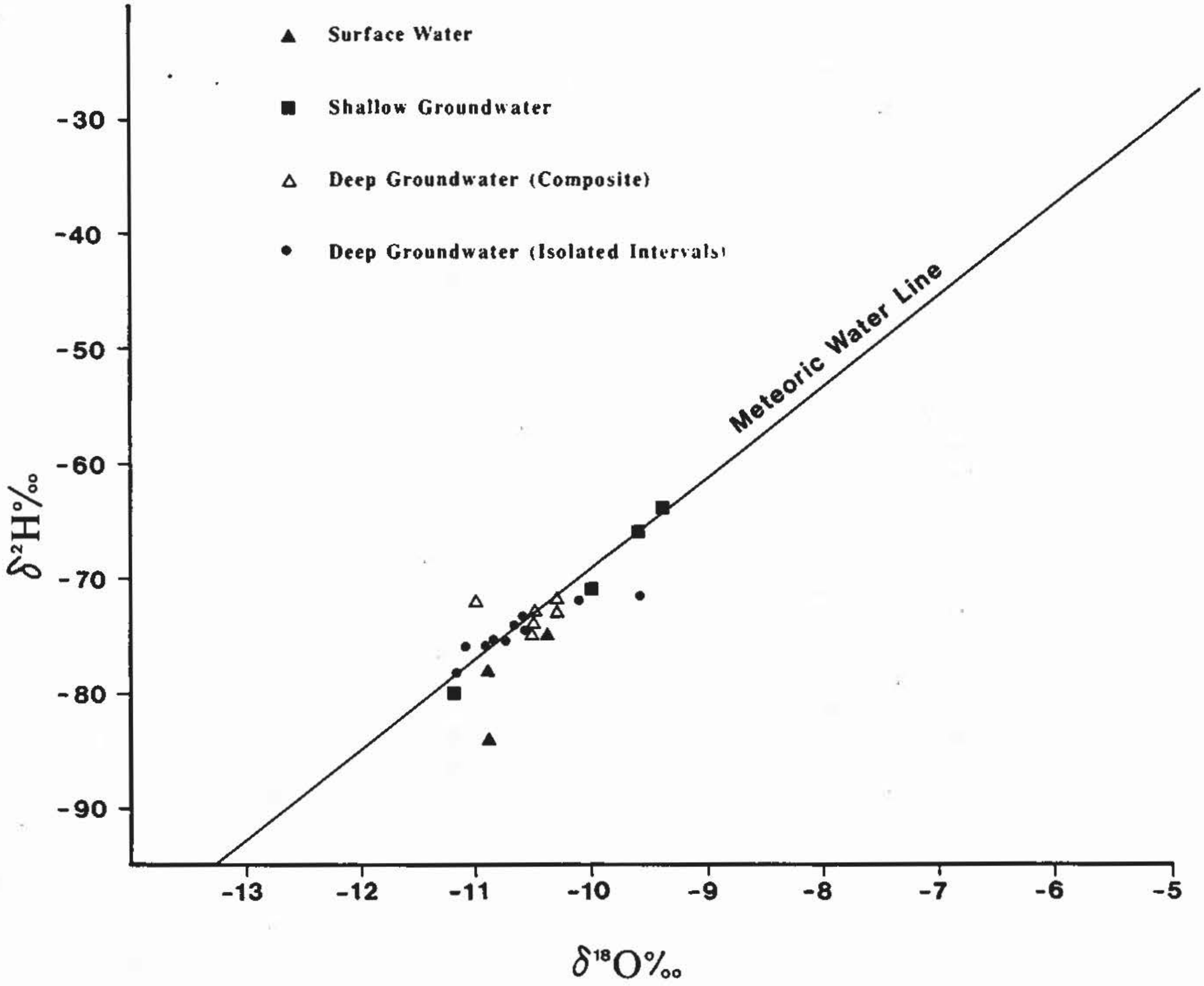


Figure 64. ^{18}O and ^2H in groundwater and surface samples, Winter River basin.

uranium concentrations and high intergranular permeabilities. The intergranular permeability and porosity of the bedrock does not appear to vary substantially, based on these results.

Helium concentrations in shallow to intermediate groundwater are not sufficiently high to be explained by in situ origin. Concentrations in deep intervals are higher than in shallow intervals which suggests that ^4He diffusion may be responsible for the concentrations in shallow groundwater. ^4He concentrations in the deep groundwater are too low to support the hypothesis of regional groundwater movement from the mainland through the lower red beds.

The noble gas (Neon, Argon, Krypton and Xenon) concentrations of the groundwater were used to derive groundwater recharge temperatures from the solubility/temperature relationships for the gases. All of the groundwater except that from W-33 have been recharged in a temperature range of 5.7 ±0.6°C. W-33 shows lower recharge temperatures, probably reflecting recent seasonal recharge at that location. The value of 5.7°C is in reasonable agreement with the recharge temperatures of 4.5°C derived from ^{18}O data and supports the conclusion that the groundwater has been recharged under modern climatic conditions.

Table 23. Stable Isotope and Tritium Data, Winter River Basin.

Source/Location	Date Sampled	^{18}O‰	^{2}H‰	^{3}H(T.U.)
Surface Water				
Winter River at Brackley Station	28/02/84	-10.4	-75	22
Winter River at Suffolk	28/02/84	-10.9	-78	36
Winter River at Pleasant Grove	10/12/84	-10.9	-84.2	
Shallow Groundwater				
20-HP	28/02/84	-9.4	-64	68
15-Y	28/02/84	-11.2	-80	16
18-Y	10/12/84	-9.6	-66.1	
22-P	10/12/84	-10.0	-71.1	
Deep Groundwater (Composite)				
HP-32	28/02/84	-10.5	-75	0
W-33	29/02/84	-10.3	-73	28
B-34	28/02/84	-10.5	-73	48
Y-35	28/02/84	-10.5	-74	43
Union #1	05/03/84	-10.3	-72	32
Brackley #9	06/03/84	-10.5	-73	48
Rustico Deep Well[1]	29/02/84	-11.0	-72	0
Deep Groundwater (Isolated Intervals)				
HP-32 (52-67m)	07/08/86	-10.91	-76.9	<6±8
HP-32 (119-134m)	06/08/86	-10.77	-75.4	<6±8
W-33 (24-50m)	10/09/85	-10.12	-72.2	23±8
B-34 (72-87m)	16/12/85	-10.59	-73.8	18±8
Y-35 (20-35)	26/09/85	-10.55	-74.5	10±8
S-36 (93-108m)	29/11/85	-10.85	-75.5	<6±8
S-36 (108-123m)	27/11/85	-10.93	-75.8	12±8
S-36 (138-153m)	27/11/85	-9.58	-71.6	<6±8
S-37 (88-103m)	12/11/85	-10.68	-74	28±8
PG-38 (138-153m)	24/07/86	-10.74	-75.3	<6±8
PG-38 (123-138m)	25/07/86	-11.08	-75.9	<6±8
PG-38 (50-68m)	01/08/86	-11.19	-78.2	<6±8

Note 1. Rustico Deep Well- Location on coast northwest of basin, well 150m deep, 119m casing.

7. THE GROUNDWATER FLOW SYSTEM

The direction and rate of groundwater flow in fractured aquifer systems is a transient three dimensional product of hydraulic gradients, hydraulic conductivities and fracture geometries and interconnections. In the Winter River basin, the degree of detail to which these variables have been described through these field and laboratory studies is sufficient to provide at least a first-level analysis of the groundwater flow system.

The current capabilities of numerical modeling is such that three-dimensional analyses of groundwater flow systems can best be addressed by computer based techniques. A project to this end is currently underway at Memorial University of Newfoundland, Earth Sciences Department, which will provide the ability to model both the steady state groundwater flow system in the Winter River Basin and a number of groundwater development and management options, utilizing the data contained in this report to define the model parameters.

In this section of the report a brief description of the groundwater flow system will be provided, based on two-dimensional analysis of the distributions of hydraulic head identified in Section 4.2.4, and other pertinent study results.

Cross section A-B (Figure 65) is a southwest to northeast profile from the highest elevations in the basin near Winsloe to sea level at the Winter River estuary and Winter Bay (Figure 7). The topographic profile is shown, along with the hydraulic head measurements along each of the 150 m boreholes on the line of section (Section 4.2.4). Data from B-34 has not been utilized in the analysis because of the effect of the well field at Brackley on hydraulic head distribution. The position of the water table has been derived from the borehole profiles, shallow piezometer data, and from the water table elevations in Figure 28. The equipotentials and lines of groundwater flow were determined from conventional flow net analysis, assuming a constant horizontal to vertical hydraulic conductivity ratio of about 500. While the data set is admittedly sparse, and some rather subjective interpretations have been made, it is instructive to consider the resulting groundwater flow system.

This fractured porous aquifer appears, on a macroscopic scale, to behave as a classical unconfined flow system having local, intermediate and regional components [55]. Local flow systems operate in the shallow, highly permeable upper portion of the aquifer to depths of less than about 40 m. Flow proceeds from local topographic (and water table) highs to discharge areas along the tributaries of the river. Figure 28 (Section 4.2) is a generalized view of this local flow system. Residence times are probably in the order of months to a few years. Water chemistry and isotopic composition reflect recent conditions.

Intermediate flow systems are created only at the higher elevations; in this cross section (1) recharging southwest of the Brackley well field and discharging at Hardy's Pond and (2) originating at the topographic high northwest of Officers Pond and discharging to the estuary area. This flow system description appears to support the evidence of a major discharge area at Hardy's Pond suggested by the groundwater-surface water interaction

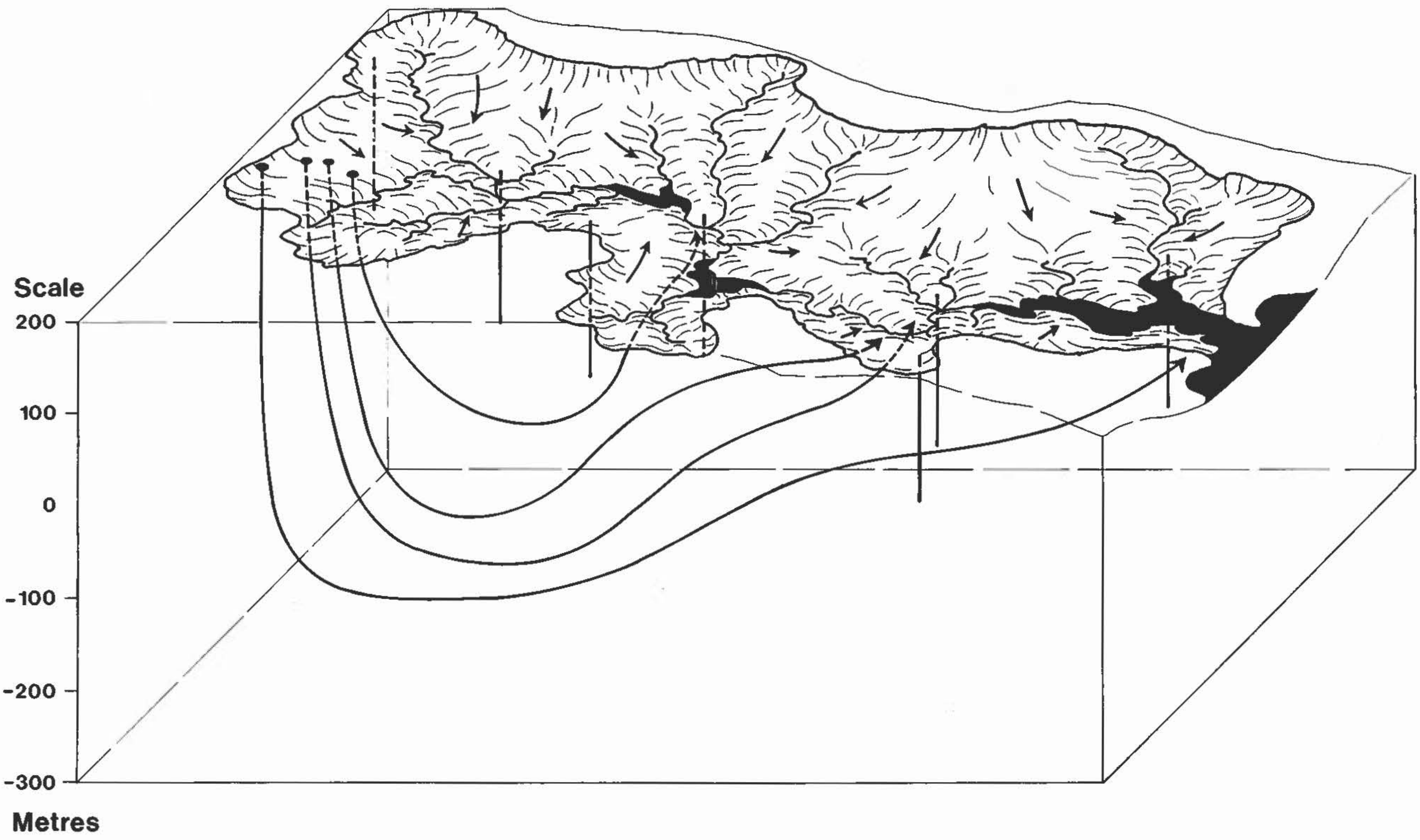


Figure 66. Three dimensional schematic of groundwater flow, Winter River basin.

8. SUMMARY AND RECOMMENDATIONS

8.1 Summary of Results

8.1.1 Basin Hydrogeology

The Winter River basin drains an area of about 63 km^2 in central Prince Edward Island. It is an area of farmland and forest which receives about 1200 mm of precipitation annually and a mean annual temperature of 5.4°C.

The geology of the basin consists of two to eight metres of sand phase till or sandy glaciofluvial deposits overlying Permo-Pennsylvanian red beds. The surficial deposits are somewhat thicker at lower elevations. The red beds are nearly horizontal, and consist primarily of red-brown fine- to medium-grained sandstone, with lesser amounts of siltstone and claystone lenses. Lithological continuity is difficult to establish because of the absence of marker beds.

Grain size analyses of the surficial deposits provided estimates of hydraulic conductivity ranging from about 10^{-7} m/s to 10^{-5} m/s, relatively high for this type of geological deposit. The water table is below the overburden-bedrock contact in upland areas. Perched water tables are uncommon. At lower elevations, near discharge areas, the overburden is saturated.

The red bed aquifer is a good example of a fractured porous aquifer; the fractures represent the primary flow paths, while the bulk of the fluid is stored in the rock blocks. At a test site in Union well field, horizontal bedding plane fractures comprised 82% of all natural fractures and sub-vertical fractures were infrequent below about 35 m. The fracture aperture distribution appears to be log-normal with a mean effective fracture aperture of 0.19 mm in the upper portion of the aquifer, determined from injection tests and fracture spacing analysis. Injection tests conducted on two metre intervals showed total rock mass hydraulic conductivity ranges from 10^{-7} m/s to 10^{-3} m/s. Fracture flow conditions predominate in the upper 35 to 50 m of the aquifer. Hydraulic conductivity decreases with depth due to decreased fracture frequency and decreased fracture apertures. Laboratory measurements on sandstone cores showed intergranular hydraulic conductivity values to range from 10^{-8} m/s to 5×10^{-7} m/s. Siltstone and claystone permeabilities were less than 5×10^{-10} m/s. Porosity values for the sandstone average 16%.

A study of the anisotropic characteristics of the shallow bedrock aquifer was conducted using the Papadopulos method. Three aquifer zones were found to have $T_{max}:T_{min}$ ratios of 9:1, 2:1 and 3:1. The orientation of the principal axes of the transmissivity ellipse averaged 147°. This coincides with the general trend of subvertical fractures observed in fracture mapping studies and borehole cores.

The three dimensional distribution of hydraulic head and hydraulic conductivity in the basin was obtained from field measurements in seven 150 m boreholes. Using a dual-packer assembly with 15 m packer spacings, hydraulic conductivity profiles gave values ranging from 10^{-3} m/s in the upper intervals to about 10^{-7} m/s in the lowest portions of several boreholes. The range of values is considered a function of fracture frequency and fracture aperture as opposed to lithological variations. Total rock mass hydraulic conductivity decreases by an order of magnitude for each 60 m depth. The distribution of hydraulic conductivity is truncated at about 10^{-7} m/s at depths over 100 m, indicating the matrix permeability's dominance there. The reduction in hydraulic conductivity with depth is related to the depth below surface rather than geodetic elevation.

Groundwater levels in both overburden and bedrock fluctuate seasonally, with major recharge events normally occuring in spring and fall, water table recession through the summer, and minor recharge events through the winter months. The magnitude of water level fluctuations in observation wells is a direct reflection of the elevation of the observation well - a wider range at higher elevations. Depth to water table ranges from zero to about 24 m. Annual fluctuations of less than one metre and more than six metres are observed. Mean annual groundwater levels over many years of record have varied by less than two metres, the variations being the result of variations in total annual precipitation. Calculations based on seasonal water table decline suggests that the specific yield of the bedrock aquifer is about 10%.

Well yield tests conducted at Union and Brackley well fields show that early-time response generally follows the Theis ideal response curve. Where the upper, highly fractured portion of the aquifer is saturated, the system responds as a 'porous medium'. Drawdowns are relatively less because of the permeability and porosity of the rock matrix. Late-time data suggests a 'leaky' unconfined aquifer response due to gravity drainage of the water table.

Well losses in pumping wells due to turbulent flow and entrance effects are very substantial. Although the average specific capacity for the well fields is high (10.7 L/s.m), specific capacities decrease markedly with increased pumping rates.

A study of groundwater-surface water interaction using seepage meters and mini-piezometers has shown that groundwater is naturally effluent to streams in all locations. Variations in seepage flux between locations are primarily due to differences in sub-stream hydraulic gradients. The data suggest that the Hardy's Pond area is a major groundwater discharge point and that seepage flux generally increases in a downstream direction.

The hydrologic budget for the basin was assessed in detail using available streamflow, precipitation and groundwater withdrawal data. Baseflow separation by a graphical method showed that it normally constitutes 60% to 70% of total annual streamflow. Baseflow as a proportion of total annual precipitation is lower at the Winter River gauging stations than in other watersheds due to groundwater withdrawals. Baseflow forms over 80% of streamflow in the late summer and fall months of many years. Average annual recharge for the Winter River basin is estimated at 42%.

Shallow groundwater in the basin is a Ca-Mg-HCO_3 type, the result of open-system dissolution of dolomite from the sandstone matrix. The natural groundwater quality very adequately meets current drinking water guidelines. Deep groundwater from the lower intervals of boreholes away from recharge areas is of the Na-HCO_3 type with very low hardness and high pH. The latter is attributed to the effects of cation exchange in strata with significant amounts of clay minerals and exchangeable sodium, which must occur at depths of more than 150 m.

Environmental isotope analyses were carried out on precipitation, surface water and shallow and deep groundwaters. The local meteoric water line was defined from the results of ^{18}O and ^{2}H analyses. All groundwater samples show isotopic characteristics which indicate recharge under relatively recent climatic conditions (less than 10,000 years). Tritium data show that shallow groundwater contains post-1953 water. The Na-HCO_3 groundwater has no detectable tritium. Analyses of radioelements and dissolved gases in the red bed aquifer were carried out. Helium (^{4}He) concentrations in deep groundwater are too low to support the hypothesis of regional groundwater movement from the mainland through the lower red beds. Noble gas concentrations reflected groundwater recharge temperatures of about 5.7°C.

This fractured porous aquifer appears, on a macroscopic scale, to behave as a classical, unconfined flow system having local, intermediate and regional components. The local systems probably have residence times in the order of months to a few years, the regional system, hundreds or thousands of years. The geochemical differences in the groundwater flow system support this analysis of groundwater flow. The active groundwater flow system is fully contained within the surface water drainage basin.

8.1.2 Effect of Groundwater Withdrawals

Well fields at Union and Brackley currently provide the City of Charlottetown and surrounding municipalities with about 5.0×10^6 m^3 of groundwater each year. This demand has doubled in the past 30 years and, while relatively constant for the last 10 years, demands on the Winter River well fields have continued to increase as the production from the 'Malpeque' systems has been reduced.

Analysis of the hydrologic budget for the Brackley and Suffolk sub-watersheds showed that groundwater withdrawals have reduced baseflow and total streamflow. In the Brackley sub-watershed, annual pumping is reducing streamflow by 53% and baseflow by 70%, in the Union sub-watershed by 39% and 54% respectively, and at Suffolk, 17% and 24%. However, in no part of the watershed is pumping exceeding annual recharge. No continual lowering of the water table should therefore occur, nor has it been observed at observation wells in and near the well fields.

Results of groundwater-surface water interaction studies show that, in close proximity to the well fields, baseflow is rapidly diverted toward pumping wells and away from the stream. Downward gradients beneath the streambed and reduced seepage flux were observed. Induced recharge may occur periodically. Streamflow's dependence on groundwater baseflow during the summer-fall months means that acceptable baseflow levels must be maintained. The residual baseflows (normal baseflow minus pumping) at Brackley are less than 10% during the August-September period, at Union, generally greater than 30% but only about 13% in September, and greater than 60% all year at Suffolk. The effects at Brackley and Union result in dry streambeds during the late summer of some years.

The extent of the drawdown cones around Union and Brackley well fields is limited by the effects of regular spring and fall recharge events and the natural slope of the water table toward the well fields. It is impossible to distinguish the gradient of the drawdown cones from the natural gradient of the water table beyond about 250 m from the well fields. The natural decline in the water table at intermediate and higher elevations occurs more rapidly and with more magnitude than the decline of the piezometric surface due to pumping. Therefore, the effects on private wells greater than 250 m away should be immeasurable.

8.2 Recommendations

8.2.1 Groundwater Supply and Development

Suitable aquifer characteristics, high yielding wells, good quality water and few conflicting land uses strongly support the continued use and development of the Winter River basin for municipal groundwater supply.

1. It is recommended that, in order to maintain baseflow and protect other surface water uses, withdrawals from the existing well fields at Union and Brackley be limited to 60% of average annual recharge, or 5.0 x 10^6 m^3/year. Further, this should be considered an interim maximum, reducing to 55% of recharge, or 4.6 x 10^6 m^3/year as soon as additional groundwater supplies are developed.

2. Good potential for future development of groundwater supplies exists farther down the Winter River watershed. Total annual groundwater withdrawals (all wells) in the recharge area, for any proposed well field, should be planned at 50% of average annual recharge, or about 2.5 x 10^5 m^3/year, for each km^2 of recharge area. Thus, the choice of well field location should be based on desired annual production, as well as local land use and well yield and water quality tests. For example, a well field developed in the Hardy's Pond - York Road area (recharge area 25.6 km^2) could withdraw about 2.0 x 10^6 m^3/year in addition to current pumping at Union and Brackley.

3. Production wells should be located in areas of near-surface water table, where the upper, more highly fractured portion of the aquifer is saturated. Locations in valleys would also benefit from the effect of the sloping water table.

4. In the development of sites for large scale withdrawal of groundwater, the safe yield of the well, the well field, and the watershed should each be determined through appropriate testing methods. Detailed assessment of step-drawdown tests should be utilized to optimize the pumping rate and reduce pumping costs.

5. Groundwater protection zones should be established around existing and proposed well field locations in the Winter River basin. On properties owned by the Charlottetown Water Commission, activities should be limited to those involving provision of water supply. Within a radius of 250 m of production wells, no commercial, industrial or residential development should occur and restrictions should be placed on agricultural activities. Within a radius of 500 m of each well field (60 day protection zone) the storage and handling of hazardous materials, including petroleum products, should be prohibited, and all development proposals should be subjected to an environmental impact assessment. In the remainder of the recharge area for the well fields, major development proposals should be subjected to an environmental impact assessment.

6. An assessment of the most appropriate means of establishing the above groundwater protection zones must be carried out. Possible legislative instruments include the Planning Act, Environmental Protection Act, Greater Charlottetown Environmental District Act, and municipal official plans and bylaws.

7. Observation wells at Harrington, Airport #7, and Union and Brackley well fields should be maintained. The stream gauging station at Brackley should be considered for relocation to Union well field.

8. The pond at Brackley pumping station does not serve a useful purpose and should be released. There is potential for anoxic bottom sediments to detrimentally affect groundwater quality.

8.2.2 Future Research

1. The effective porosity of fractured porous aquifers and thus estimates of average linear groundwater velocity should be measured through field scale tracer tests. This would allow better definition of groundwater protection zones in the Winter River basin.
2. The numerical model for the Winter River basin, being completed at Memorial University of Newfoundland, should be utilized to predict the effects of possible one-, or two-year drought events on water levels in the basin, especially in the well field areas.
3. Geochemical and isotope methods should be utilized to further clarify the contribution of groundwater baseflow to streams, especially during the spring recharge event.

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APPENDIX I

Borehole No. Brackley #12

Location:	Brackley Well Field
Drilled:	May 10, 1976
Logged By:	R. N. Betcher
Equipment:	Cable Tool

Ref. Map: 11L/6E Easting 494885.5 Northing 5128900

Elevation (Top of Well Pit) 31.32 m

Depth (m)		Lithology
0 -	1.6	Mainly silt and clay, less than 25% fine sand.
1.6 -	3.1	as above
3.1 -	4.7	as above; slightly more very fine sand; a few fragments of very fine grained sandstone (bedrock?)
4.7 -	6.2	as in 3.1 - 4.7 m
6.2 -	7.7	Fine grained white flecked red silty sandstone.
7.7 -	9.2	Red siltstone; well cemented calcareous fine grained red sandstone.
9.2 -	10.7	Reddish brown clayey siltstone
10.7 -	12.3	Dark red clayey siltstone
12.3 -	13.8	Reddish brown fine clayey siltstone
13.8 -	15.3	as above
15.3 -	16.8	Reddish brown siltstone
16.8 -	18.3	Reddish brown clayey siltstone
18.3 -	19.9	Dark red fine grained to very fine grained sandstone
19.9 -	21.4	Fine reddish-brown siltstone
21.4 -	22.9	Calcareous well cemented brown siltstone with a few green reduced zones
22.9 -	24.4	Brown siltstone
24.4 -	25.9	Red claystone; brownish-red siltstone; green reduced siltstone
25.9 -	27.5	Reddish-brown clayey siltstone
27.5 -	29.0	Reddish-brown siltstone; a few fragments of fine grained sandstone
29.0 -	30.5	Reddish-brown siltstone
30.5 -	32.0	Dark red claystone, at times as a hard shale; reddish-brown hard siltstone
32.0 -	33.6	Red mudstone; claystone; hard siltstone with a few green siltstone zones
33.6 -	35.2	Red and green claystone
35.2 -	36.7	Reddish-brown siltstone; fine grained sandstone
36.7 -	38.2	Siltstone; fine grained sandstone
38.2 -	39.7	Reddish-brown siltstone

39.7 -	41.2	Reddish-brown siltstone; fine grained sandstone
41.2 -	42.8	Red fine grained sandstone; reddish siltstone; probably significant claystone
42.8 -	44.2	as above
44.2 -	45.8	Reddish-brown siltstone; fine grained sandstone
45.8 -	47.3	as above
47.3 -	48.8	Fine grained clayey sandstone; red mudstone
48.8 -	50.4	Reddish-brown siltstone, red claystone with a few green zones
50.4 -	51.9	no sample
51.9 -	53.4	Reddish-brown siltstone; fine grained sandstone
53.4 -	54.9	Red mudstone; fine grained sandstone
54.9 -	56.4	Reddish-brown siltstone
56.4 -	58.0	as above
58.0 -	59.5	Red siltstone; shale
59.5 -	61.0	Reddish-brown siltstone; fine grained sandstone
61.0 -	62.5	Red clayey siltstone, slightly micaceous
62.5 -	64.0	Fine grained reddish-brown sandstone; hard red shale
64.0 -	65.6	Fine grained reddish-brown sandstone
65.6 -	67.1	as above; reddish-brown siltstone
67.1 -	68.6	Reddish-brown siltstone
68.6 -	70.1	Calcareous reddish-brown siltstone; fine grained calcareous sandstone
70.1 -	71.7	Brownish-red siltstone, somewhat clayey
71.7 -	73.2	Brownish-red mudstone
73.2 -	74.7	Red clayey siltstone
74.7 -	76.2	Sample missing
76.2 -	77.7	Red silty claystone
77.7 -	79.3	Red claystone; clayey siltstone to clayey fine grained sandstone
79.3 -	80.8	Red claystone; red mudstone
80.8 -	82.3	Reddish-brown silty fine grained sandstone
82.3 -	83.9	Reddish-brown siltstone
83.9 -	85.4	Reddish-brown clayey siltstone; a few fragments of purplish-red claystone
85.4 -	86.9	Dark purplish-red claystone
86.9 -	88.4	Fragments of above but mainly reddish-brown mudstone with considerable green zonations, calcareous.
88.4 -	89.9	Reddish-brown clayey siltstone; small amounts of purplish-red shale
89.9 -	91.5	Reddish-brown siltstone; red mudstone
91.5 -	93.0	Red mudstone

93.0 -	94.5	Reddish-brown clayey siltstone
94.5 -	96.1	as above
96.1 -	97.6	Red mudstone; red claystone
97.6 -	99.1	Reddish-brown siltstone
99.1 -	100.6	Reddish-brown siltstone; fine grained sandstone
100.6 -	102.1	Siltstone, very hard, purplish-red shale
102.1 -	103.7	Red clayey siltstone; red claystone
103.7 -	105.2	Brownish-red claystone; purplish-red shale
105.2 -	106.7	Red to dard red claystone and mudstone
106.7 -	108.2	Reddish-brown mudstone to clayey siltstone
108.2 -	109.7	Redish-brown clayey siltstone
109.7 -	111.3	as above; some red claystone
111.3 -	112.8	Red mudstone; red claystone
112.8 -	114.3	as above
114.3 -	115.8	Hard purplish-red shale; red claystone; reddish-brown siltstone
115.8 -	117.3	Red mudstone
117.3 -	118.9	Dark red shale; reddish-brown siltstone
118.9 -	120.4	Dark red claystone; brownish-red siltstone; some green silty zones
120.4 -	121.9	Red mudstone; clayey fine grained sandstone
121.9 -	123.4	as above
123.4 -	124.9	Brown siltstone; green siltstone; hard purplish-red shale
124.9 -	126.5	Reddish-brown clayey siltstone
126.5 -	128.0	as above
128.0 -	129.5	as above but somewhat more clay
129.5 -	131.1	Dark red claystone
131.1 -	132.6	Reddish-brown and grey-green mudstone
132.6 -	134.1	Red claystone; red mudstone
134.1 -	135.6	Reddish-brown siltstone; fine grained sandstone
135.6 -	137.1	Reddish-brown siltstone
137.1 -	138.7	as above
138.7 -	140.2	Purplish-red claystone, orangy tint in places; some blue-green clay
140.2 -	141.7	Red claystone
141.7 -	143.2	Red claystone; reddish-brown clayey siltstone
143.2 -	144.7	Reddish-brown siltstone; purplish-red claystone
144.7 -	146.3	Dark red to purplish-red shale
146.3 -	147.8	Sample missing

147.8 -	149.3	Red shale
149.3 -	150.8	Fragments of orangy-red mudstone in a mainly calcareous siltstone to fine grained sandstone
150.8 -	152.3	as above
152.3 -	154.3	No sample

Borehole No. B-34

Location: Charlottetown Water Commission Brackley Well Field, Brackley, P.E.I. Date Drilled: Aug. 2, 1983
Logged By: Don Jardine and Mary Gill Equipment: Air Rotary and Cable Tool
Ref. Map: 11L/6E Easting: 488410 Northing: 5128880
Elevation (Top of Casing):
Elevation (Top of Ground): 30 m

Depth (m)	Lithology
0 - 6.1	Silty fine grain sand, less than 10% fine grain sandstone fragments.
6.1 - 7.9	Fractured silty fine grain sandstone interbedded with 10% claystone, some quartz and volcanic pebbles.
7.9 - 9.1	Highly fractured fine grain sandstone, 10% claystone, green and brown siltstone.
9.1 - 11.0	Silty fine grain sandstone, 30-40% siltstone, 10% green siltstone.
11.0 - 11.9	Shaley, silty fine grain sandstone.
11.9 - 13.1	Silty, fine grain sandstone, 20% claystone, 10% siltstone.
13.1 - 14.9	Fine to medium grain sandstone, 20% claystone, 5-10% green and brown siltstone.
14.9 - 16.5	Silty fine grain sandstone, 20% siltstone, 5% claystone.
16.5 - 18.0	Claystone, 20-50% green and brown siltstone.
18.0 - 18.6	Shaley siltstone, 20% claystone, some green siltstone.
18.6 - 18.9	Fine grain sandstone, 25% siltstone.
18.9 - 19.5	Shaley siltstone, 10% claystone.
19.5 - 20.4	Shaley, silty, fine grain sandstone, 10-20% siltstone.
20.4 - 22.9	Green and brown siltstone, up to 20% silty fine grain sandstone, 5-50% claystone.
22.9 - 25.9	Silty fine green micaceous sandstone, 5-10% siltstone and claystone, some green claystone.
25.9 - 31.1	Silty fine grain sandstone, 5-10% siltstone and claystone.
31.1 - 32.9	Silty fine grain sandstone, 5% claystone, 10-25% siltstone.
32.9 - 35.7	Green and brown siltstone, 20-30% silty fine grain sandstone, 5% claystone.
35.7 - 43.9	Soft and highly fractured silty fine grain sandstone, 15-50% green and brown siltstone, 5-10% claystone.
43.9 - 44.2	Claystone
44.2 - 44.8	Silty fine to medium grain sandstone, 10% siltstone.
44.8 - 55.8	Silty fine grain sandstone, 15-50% siltstone, 5-10% claystone, green siltstone lense at 50.6 m.
55.8 - 74.1	Fine grain sandstone, 10-50% siltstone, 5% claystone, green sandstone between 59.4 and 61.3 m, some volcanic
74.1 - 76.8	Silty fine grain sandstone, 5-10% siltstone, 5-10% claystone.
76.8 - 82.3	Fine to medium grain sandstone, some softer lenses, 5-30% siltstone, 10-15% claystone.

82.3 - 150 Not Available

Notes:

1. Water occurrences at 1.8, 6.1, 7.9, 9.8,. 64-68.6 metres below surface. Water occurrences at 7.9 metres had a yield of approximately 1100-1350 L/m.
2. Depth to bedrock = 6.1 below surface.
3. Casing: 15.1 metres of 12.7 cm.
4. A possible fracture between 64 - 68.6 m. 5. Hole diameter - 12.7 cm from 0 - 15.1 m 12.1 cm from 15.1 - 82.3 pebbles.

Borehole No. S-37

Location:	Boswell Property, Suffolk (Mill Cove Road) P.E.I.
Drilled:	August, 1985
Logged By:	Don Jardine, Jamie Mutch and F. Cruckshanks
Equipment:	Air Rotary and Cable Tool

Ref. Map: 11L/6E Easting: 496430 Northing: 5132350

Elevation: 39.6 m

Depth (m)	Lithology
0 - 1.5	Fine sand
1.5 - 6.1	Fine sand and clay
6.1 - 10.6	Fine sandstone
10.6 - 11.1	Siltstone
11.1 - 20.2	Fine sandstone interbedded with some siltstone.
20.2 - 23.0	Coarse sandstone
23.0 - 25.7	Brown and green sandstone with some siltstone and claystone.
25.7 - 28.8	Fine sandstone with minor siltstone.
28.8 - 29.3	Siltstone
29.3 - 30.5	Coarse sandstone
30.5 - 32.6	Coarse sandstone with 25% siltstone and claystone.
32.6 - 38.0	Fine sandstone with minor siltstone.
38.0 - 39.5	Claystone and siltstone with mainly green sandstone.
39.5 - 48.2	Sandstone with minor siltstone.
48.2 - 52.4	Claystone and siltstone with 30% sandstone.
52.4 - 75.3	Fine sandstone with minor siltstone and claystone.
75.3 - 76.3	Coarse sandstone with 25% siltstone and claystone.
76.3 - 89.0	Fine sandstone with up to 10% siltstone and claystone.
89.0 - 90.5	Fine sandstone with 25% siltstone and claystone.
90.5 - 97.5	Fine sandstone with up to 10% siltstone and claystone.
97.5 - 99.7	Silty claystone
99.7 - 107.9	Fine sandstone
107.9 - 109.7	Siltstone
109.7 - 118.0	Silty claystone with minor sandstone
118.0 - 125.0	Silty sandstone
125.0 - 132.2	Fine sandstone with minor siltstone
132.2 - 135.6	Clayey siltstone

135.6 -	138.4	Silty claystone with minor sandstone
138.4 -	140.2	Clayey siltstone
140.2 -	142.6	Silty sandstone
142.6 -	146.3	Siltstone interbedded with silty claystone.
146.3 -	147.8	Clayey siltstone interbedded with hard siltstone.

Notes:

1. Depth to bedrock = 6.1 m
2. Water occurrences at 8.2, 18.3, 22.9, 29.6, 35.1, 46.6, 72.5 m.
3. Possible fracture zone at 72.5 and 90.2 m.
4. Hole deepened from 97.5 to 152.4 m via the cable tool method in November, 1985.
5. Casing length 7.0 m.

Borehole No. HP-32

Location: Hardy Pond Road, York, P.E.I.
Drilled: July 26, 1983
Logged by: Alan Robison & Don Jardine
Equipment: Air Rotary & Cable Tool
Ref. Map: 11L/6E Easting: 491310 Northing: 5131030
Elevation (Top of Casing): 21.8 m
Elevation (Top of Ground): 21.3 m

Depth (m)	Lithology
0 - 0.6	Silty fine grain white sand.
0.6 - 8.5	Reddish brown silty fine grain sand, up to 20% fine grain sandstone fragments.
8.5 - 12.8	Soft and fractured fine to medium grain sandstone.
12.8 - 17.7	Soft and fractured fine to medium grain sandstone, 5-20% claystone and siltstone.
17.7 - 20.7	Soft and fractured medium grain sandstone.
20.7 - 23.7	Hard fine grain sandstone with some soft lenses, 5-10% claystone and siltstone. Thin band of siltstone between 21.3 - 22.9 metres, traces of mica.
23.7 - 27.4	Hard medium grain sandstone, 10-25% claystone and siltstone, 10% green sandstone.
27.4 - 28.3	Claystone and siltstone with 40% fine grain sandstone.
28.3 - 32.9	Hard fine to medium grain sandstone, 40-50% claystone and siltstone (some green lenses).
32.9 - 34.7	Medium grain sandstone, 10-40% claystone and siltstone.
34.7 - 35.7	Fine to medium grain sandstone, 50% claystone and siltstone.
35.7 - 39.3	Hard medium grain sandstone, 10-30% claystone (some soft lenses).
39.3 - 41.1	Fine to medium grain sandstone, 10% claystone.
41.1 - 46.6	Medium grain sandstone, 5-30% reddish and greenish claystone, some softer lenses between 42.1 - 43.0 metres.
46.6 - 48.5	Fine to medium grain sandstone, slightly conglomeratic, 10-25% claystone and siltstone.
48.5 - 48.8	Claystone and siltstone.
48.8 - 50.3	Medium grain sandstone, slightly conglomeratic, 30-40% claystone and siltstone interbedded.
50.3 - 51.8	Hard siltstone interbedded with fine grain green and brown sandstone.
51.8 - 56.4	Soft medium grain sandstone interbedded with reddish and greenish claystone and siltstone.
56.4 - 64.0	Fine to medium grain sandstone, some reddish and greenish siltstone, traces of mica.
64.0 - 71.6	Fine grain sandstone, very little siltstone.
71.6 - 78.3	Medium grain micaceous sandstone, 10-20% reddish and greenish siltstone and claystone.
78.3 - 96.6	Fine to medium grain micaceous sandstone, 5-40% siltstone and claystone, some green siltstone.

96.6 -	105.2	Medium grained micaceous sandstone, 20-30% siltstone and claystone, some green sandstone and siltstone.
105.2 -	118.9	Fine to medium grain sandstone, 5-30% sandstone and siltstone, traces of mica.
118.9 -	121.9	Medium to coarse grained sandstone, 20-30% siltstone and claystone.
121.9 -	125.0	Sandstone
125.0 -	128.0	Sandstone
125.0 -	131.1	Claystone
131.1 -	134.1	Sandstone, Minor Siltstone
134.1 -	137.2	Sandstone
137.2 -	140.2	Sandstone
140.2 -	143.3	Sandstone
143.3 -	146.3	Siltstone
146.3 -	149.4	Sandstone
149.4 -	152.4	Siltstone
152.4 -	154.5	Siltstone, Minor Sandstone

Notes

1. Water occurrences were observed at 1.7, 8.8, 9.8, 10.7-13.7, 17.1, 37.2, 83.9-86.9, and 88.1-88.4 metres below surface. The static water level upon completion was 1.1 metres. The anticipated yield from this well is high, based on a drawdown of 15 cm at a pumping rate of 3L/s.
2. Hard lenses were observed at 23.8-24.7 and 41.1-42.1 metres below surface. The depth to bedrock is 8.5 metres. A partial loss of circulation was observed at 40.2-41.1 metres. A washout occurred at 9.4 metres.
3. Hole diameter 12.7 cm from 0 - 10.7 metres
   12.1 cm from 10.7 - 50.3 metres
   10.2 cm from 50.3 - 121.9 metres
4. Casing: 10.7 metres of 12.7 cm.

Borehole No. PG-38

Location: Dept. of Transportation Right of Way, Grand Tracadie, P.E.I.
Drilled: August, 1985
Logged By: Don Jardine and Jamie Mutch
Equipment: Air Rotary
Ref. Map: 11L/6E Easting: 494810 Northing: 5136120
Elevation: 7.6 m geodetic

Depth (m)		Lithology
0 -	3.0	Silty sand
3.0 -	7.6	Sandstone
7.6 -	13.0	Sandstone interbedded with minor siltstone.
13.0 -	14.2	Claystone
14.2 -	29.2	Fine sandstone interbedded with minor claystone.
29.2 -	34.0	Claystone interbedded with sandstone.
34.0 -	37.3	Sandstone interbedded with siltstone.
37.3 -	38.6	Claystone
38.6 -	43.6	Sandstone interbedded with claystone and siltstone.
43.6 -	46.0	Claystone and siltstone interbedded with sandstone.
46.0 -	49.4	Fine sandstone interbedded with minor claystone and siltstone.
49.4 -	50.5	Claystone and siltstone
50.5 -	56.0	Fine sandstone interbedded with minor siltstone and claystone.
56.0 -	58.0	Claystone and siltstone
58.0 -	67.0	Fine sandstone interbedded with minor siltstone and claystone.
67.0 -	73.3	Claystone interbedded with sandstone.
73.3 -	88.4	Coarse sandstone interbedded with minor siltstone and claystone.
88.4 -	94.5	Coarse sandstone interbedded with 20% siltstone and claystone.
94.5 -	96.0	Coarse sandstone interbedded with claystone.
96.0 -	99.1	Siltstone
99.1 -	102.1	Siltstone
102.1 -	105.2	Siltstone
105.2 -	108.2	Sandstone
108.2 -	111.3	Sandstone
111.3 -	114.3	Sandstone
114.3 -	117.3	Sandstone
117.3 -	120.4	Sandstone

120.4 -	123.4	Sandstone, Minor Claystone
123.4 -	126.5	Sandstone
126.5 -	130.0	Sandstone
130.0 -	132.5	Sandstone
132.5 -	135.5	Sandstone
135.5 -	138.7	Sandstone
138.7 -	141.7	Sandstone
141.7 -	144.8	Sandstone
144.8 -	147.8	Sandstone
147.8 -	150.9	Sandstone
150.9 -	152.4	Sandstone
152.4 -	154.8	Sandstone

Notes:

1. Borehole lithology compiled from point resistance and natural gamma logs and notes taken during the drilling by J. Mutch.
2. Depth to bedrock = 3.0 m below surface.
3. A major water occurrence was detected at 6.7 m below surface.
4. Static water level upon completion was 2.4 m below surface.
5. Casing: 6.5 m

Borehole No. S-36

Location: Lewis Bros. Property, Suffolk, P.E.I.
Drilled: August, 1985
Logged By: Don Jardine and Jamie Mutch
Equipment: Air Rotary
Ref. Map: 11L/6E Easting: 494420 Northing: 5132830
Elevation (Top of Casing): 6.5 m
Elevation (Top of Ground): 6 m

Depth (m)	Lithology
0 - 3.7	Fine sand
3.7 - 4.4	Sandstone
4.4 - 4.6	Sandstone and Claystone
4.6 - 6.7	Sandstone
6.7 - 8.3	Sandstone and Siltstone
8.3 - 9.3	Sandstone
9.3 - 10.3	Sandstone and Siltstone
10.3 - 12.7	Sandstone
12.7 - 14.0	Sandstone and Siltstone
14.0 - 18.4	Sandstone
18.4 - 20.0	Sandstone and Siltstone
20.0 - 23.6	Sandstone
23.6 - 27.0	Sandstone and Siltstone
27.0 - 29.8	Sandstone
29.8 - 32.2	Sandstone and Claystone
32.2 - 34.7	Sandstone with minor Claystone
34.7 - 35.7	Claystone or Siltstone
35.7 - 44.0	Sandstone with minor Siltstone
44.0 - 45.5	Siltstone
45.5 - 53.8	Sandstone with minor Siltstone
53.8 - 55.8	Siltstone and Sandstone
55.8 - 57.8	Sandstone with Siltstone
57.8 - 58.7	Claystone
58.7 - 64.7	Sandstone with Siltstone
64.7 - 68.2	Siltstone with Sandstone
68.2 - 70.6	Sandstone with Siltstone

70.6 -	76.0	Claystone, Siltstone and Sandstone
76.0 -	79.4	Sandstone and Siltstone
79.4 -	80.5	Siltstone
80.5 -	89.0	Sandstone and Siltstone
89.0 -	90.6	Claystone and Sandstone
90.6 -	96.5	Sandstone and Siltstone
96.5 -	150	Not Available

Notes:

1. Hole lithology compiled from point resistance and natural gamma logs and notes taken during the drilling by J. Mutch.
2. Depth to bedrock = 3.7 metres below surface.
3. Casing: 6.3 metres of 12.7 cm steel casing was installed.
4. Water occurrences were observed at 8.2 and 11.0 to 11.6 metres below surface.
5. The static water level upon completion was 4.6 metres below surface.

Borehole No: Union #1

Location: Union Well Field
Drilled: 1971
Logged By: R. N. Betcher
Equipment: Cable Tool
Ref. Map: 11L/6E Easting: Northing:
Elevation (Top of Well Pit) 27.24 m

Depth (m)	Lithology
0 - 1.6	Clay
1.6 - 3.1	Clay, fine sand
3.1 - 4.7	Silt, clay, sandstone fragments
4.7 - 6.2	Clay, sandstone fragments
6.2 - 9.2	Clay, pebbles
9.2 - 10.7	Coarse sand, clay
10.7 - 12.3	Medium sand
12.3 - 15.3	Fine sand
15.3 - 16.8	Medium sand
16.8 - 18.3	Medium - coarse sand
18.3 - 21.4	Silt, clay
21.4 - 22.9	Silt
22.9 - 24.4	Medium sand
24.4 - 25.9	Silt, clay, fine sand
25.9 - 27.5	Fine sand, silt, sandstone fragments
27.5 - 29.0	Silt, clay, sandstone fragments
29.0 - 30.5	Medium sand, silt
30.5 - 32.0	Clay, silt
32.0 - 35.1	Silt, clay
35.1 - 36.6	Medium sand
36.6 - 38.1	Clay, silt
38.1 - 39.6	Clay, pebbles
39.6 - 41.2	Clay
41.2 - 42.7	Silt, clay
42.7 - 44.2	Clay, pebbles
44.2 - 53.4	Clay
53.4 - 54.9	Clay, pebbles

54.9 -	58.0	Clay, silt
58.0 -	59.5	Fine sand
59.5 -	61.0	Clay, silt
61.0 -	62.5	Clay, sand, rock fragments
62.5 -	64.0	Clay
64.0 -	67.1	Clay, silt
67.1 -	70.1	Clay
70.1 -	71.6	Clay, silt
71.6 -	73.2	Missing
73.2 -	74.7	Clay, sand
74.7 -	76.2	Fine sand, silt
76.2 -	77.7	Clay, silt
77.7 -	79.3	Fine sand, clay, pebbles
79.3 -	82.3	Fine sand
82.3 -	83.9	Fine sand, silt
83.9 -	90.0	fine sand
90.0 -	91.5	Clay, silt
91.5 -	93.0	Fine sand, clay
93.0 -	94.6	Fine sand
94.6 -	96.1	Fine sand, silt
96.1 -	100.6	Silt, clay, fine sand
100.6 -	102.2	Fine sand, clay
102.2 -	103.7	Fine sand, silt
103.7 -	105.2	Sand, silt
105.2 -	106.7	Sand, clay
106.7 -	108.2	Silt, fine sand
108.2 -	109.8	Fine sand, clay
109.8 -	114.3	Fine sand, silt
114.3 -	117.3	Clay, fine sand
117.3 -	125.0	Clay
125.0 -	126.5	Fine sand, silt
126.5 -	129.6	Clay, silt
129.6 -	131.1	Clay, silt
131.1 -	132.6	Silt, fine sand

Borehole No. Y-35

Location: Lewis Bros, Property, York, P.E.I.
Date Drilled: Aug. 2, 1983
Logged By: Don Jardine and Alan Robison
Equipment: Air Rotary
Ref. Map: 11L/6E Easting: 492610 Northing: 5128920
Elevation (Top of Casing):
Elevation (Top of Ground): 43 m

Depth (m)	Lithology
0 - 0.3	Silty fine sand loam.
0.3 - 4.6	Shaley fine grain sandstone interbedded with 25% siltstone.
4.6 - 7.9	Shaley fine grain sandstone.
7.9 - 9.8	Fine grain sandstone, 10% siltstone and claystone.
9.8 - 10.7	Green and brown siltstone, 25% silty fine grain sandstone.
10.7 - 11.3	Fine grain sandstone, 10% claystone and siltstone.
11.3 - 12.5	Green and brown medium grain andstone less than 5% siltstone.
12.5 - 27.4	Fine to medium grain sandstone, up to 10% siltstone.
27.4 - 29.3	Medium grain sandstone, 50% siltstone and claystone.
29.3 - 45.7	Fine to medium grain sandstone.
45.7 - 48.2	Medium grain micaceous, green and brown sandstone, some quartzite present.
48.2 - 56.4	Medium grain sandstone, up to 20% siltstone.
56.4 - 61.0	Medium grain micaceous sandstone, 5% siltstone.
61.0 - 67.1	Medium grain green sandstone, 10-20% siltstone.
67.1 - 71.6	Medium grain brown and green sandstone, 10-40% siltstone.
71.6 - 75.3	Medium grain sandstone, 10-25% siltstone.
75.3 - 76.2	Very fine grain sandstone.
76.2 - 79.2	Fine to medium grain sandstone, up to 40% green and brown siltstone.
79.2 - 87.5	Medium grain sandstone, 5-30% green and brown siltstone.
87.5 - 89.6	Fine grain sandstone, 10% siltstone.
89.6 - 93.3	Fine to medium grain sandstone, 20-30% green and brown siltstone.
93.3 - 96.0	Fine to medium grain sandstone up to 20% siltstone.
96.0 - 99.1	Sandstone
99.1 - 102.1	Siltstone
102.1 - 106.7	Claystone
106.7 - 108.2	Claystone

108.2 -	114.3	Claystone
114.3 -	121.9	Siltstone
121.9 -	126.5	Siltstone
126.5 -	131.1	Siltstone
131.1 -	134.1	Claystone
134.1 -	137.2	Sandstone and Minor Siltstone
137.2 -	140.2	Siltstone
140.2 -	143.3	Siltstone
143.3 -	146.3	Siltstone
146.3 -	149.4	Siltstone

Notes:

1. Water occurrences at: 10.7, 27.4, 35.7, 41.1, and 64.0 metres below surface. Static water level upon completion = 14.9 m.
2. Hard drilling between: 16.8 - 18.3, 45.7 - 46.6 and 50.6 - 51.8 metres. 3. Depth to bedrock: 0.3 metres (located on the perimeter of a borrow pit). 4. Casing: 12.8 metres of 12.7 cm diameter.

Borehole No. W33

Location: Don Jardine property, Winsloe Road
Date Drilled: July 29, 1983
Logged By: Don Jardine
Equipment: Air Rotary
Ref. Map: 11L/6E Easting: 486420 Northing: 5127300
Elevation (Top of Casing):
Elevation (Top of Ground): 60.0 m

Depth m	Lithology
0 - 5.2	Silty clayey fine grain sandstone, 10% fine grain sandstone fragments.
5.2 - 10.1	Shaley silty fine grain sandstone, interbedded with 30-50% claystone.
10.1 - 10.7	Claystone
10.7 - 11.0	Green calciferous very fine grain silty sandstone thinly bedded.
11.0 - 12.2	Claystone, interbedded with very fine grain green sandstone.
12.2 - 13.1	Shaley silty very fine grain green and brown sandstone.
13.1 - 14.9	Siltstone and claystone, 30-40% very fine grain sandstone.
14.9 - 18.9	Soft green and brown fine grain sandstone, 10% siltstone.
18.9 - 20.7	Claystone and siltstone.
20.7 - 28.0	Soft very fine to fine grain sandstone, up to 5% siltstone.
28.0 - 30.5	Very hard fine to medium grain sandstone with some softer lenses, up tp 50% claystone and siltstone.
30.5 - 40.2	Soft fine grain sandstone, 5-10% green and brown siltstone.
40.2 - 40.8	Siltstone and claystone.
40.8 - 48.8	Soft fine to medium grain sandstone, 10% green sandstone, 5% siltstone, 20-30% claystone.
48.8 - 49.7	Siltstone and claystone.
49.7 - 54.3	Soft fine to medium grain sandstone with 5% siltstone.
54.3 - 55.5	Brown green and purple siltstone, 10% fine grain sandstone.
55.5 - 58.5	Very fine to fine grain silty sandstone, 10% siltstone.
58.5 - 60.4	Soft fine to medium grain micaceous sandstone, 5-10% siltstone.
60.4 - 61.9	Soft fine grain sandstone, 50% siltstone, green and brown claystone.
61.9 - 67.1	Soft fine grain micaceous sandstone, 5-20% siltstone.
67.1 - 68.6	Siltstone and claystone, 30% fine grain sandstone.
68.6 - 71.6	Medium to coarse grain sandstone, some highly micaceous sandstone lenses, some quartz pebbles.

APPENDIX II

WINTER RIVER OVERBURDEN DRILLING PROGRAM

BOREHOLE LOG

BOREHOLE NO: 1W

LOCATION: Don Jardine Property, Winsloe Road, P.E.I.

DATE DRILLED: July 26, 1982 LOGGED BY: Don Jardine

EQUIPMENT: Air Rotary Drilling Machine

REF. MAP: 11L/6 EASTING: 486420 NORTHING: 5127250

Elevation (Metres, Geodetic) Top of Casing: 60.20 m

Top of Ground: 60.00 m (Ortho)

Depth (m)	Lithology
0 - 0.46	Clayey sand fill with concrete
0.46 - 0.91	Clayey very fine sand with 10% fine grained sandstone fragments
0.91 - 2.44	Very fine sandy clay with 10% fine grained sandstone fragments
2.44 - 5.18	Very fine grained silty sandstone.

OTHER NOTES:

1. Split spoon sample collected at 0.9 - 1.5 meters below surface.
2. Hole moister after 2.4 meters.
3. Water occurrence between 4.6 - 5.2 meters with a static water level - 4.4 meters
4. Depth to bedrock = 2.44 meters
5. Gravel pack between 0.6 to 2.4 meters
6. Piezometer opening between 0.9 and 2.4 meters.

WINTER RIVER OVERBURDEN DRILLING PROGRAM

BOREHOLE LOG

BOREHOLE NO: 2 HC

LOCATION: Horne Cross Road, Winsloe at edge of Russell Diamond Property

DATE DRILLED: July 26, 1982 LOGGED BY: Don Jardine

EQUIPMENT: Air Rotary Drilling Machine

REF. MAP: 11L/6 EASTING: 486800 NORTHING: 5128850

Elevation (Metres, Geodetic) Top of Casing: 64.32 m

Top of Ground: 64.07 m

Depth (m)	Lithology
0 - 2.9	Silty very fine sand with up to 20% fine grained sandstone and claystone fragments.
2.9 - 4.4	Medium hard very fine sand with less than 10% silt and clay and approx. 15% fine grained sandstone and claystone fragments.
4.4 - 5.2	Hard greenish,reddish claystone.
5.2 - 5.5	Fine grained sandstone interbedded with claystone.

OTHER NOTES:

1. No water occurrences or seepage
2. Three split spoon samples were collected as follows: 0.91 m to 1.37 m, 2.9 m to 3.51 m, 4.57 m to 5.18 m.
3. Depth to bedrock = 4.4 m
4. Gravel pack between 1.4 m and 4.4 m.
5. Piezometer opening between 1.4 m and 4.4 m.

WINTER RIVER OVERBURDEN DRILLING PROGRAM

BOREHOLE LOG

BOREHOLE NO: *3B*

LOCATION: Brackley Point Rd., Brackley at Dalziel Auto Body

DATE DRILLED: July 19, 1982 *LOGGED BY: Don Jardine*

EQUIPMENT: Air Rotary Drilling Machine

REF. MAP: 11L/6 *EASTING:* 489090 *NORTHING:* 5126640

Elevation (Metres, Geodetic) *Top of Casing: 50.729 m*

Top of Ground: 50.159 m

Depth(m)	*Lithology*
0 - 0.3	*Greyish clayey very fine sand*
0.3 - 3.5	*Clayey very fine sand with fine grained sandstone cobbles and boulders*
3.5 - 5.5	*Fine grained sandstone*

OTHER NOTES:

1. *Two split spoon samples were collected at 0.9m to 1.5m and 3.35 m to 3.51m below surface.*
2. *Some water seepage at 3.35 m below surface. Static water level upon hole completion= 3.28, below surface.*
3. *Depth to bedrock = 3.5m*
4. *Gravel pack between 2.1m and 5.5m*
5. *Piezometer opening between 2.4m and 5.5m.*

WINTER RIVER OVERBURDEN DRILLING PROGRAM

BOREHOLE LOG

BOREHOLE NO: 4B

LOCATION: East off Brackley Point Road on Subdivision Road in Brackley.

DATE DRILLED: July 19, 1982 *LOGGED BY:* Don Jardine

EQUIPMENT: *Air Rotary Drilling Machine*

REF. MAP: 11L/6 *EASTING:* 488950 *NORTHING:* 5127750

Elevation (Metres, Geodetic) Top of Casing: 46.59 m

Top of Ground: 46.41 m

Depth	*Lithology*
0 - 2.7	Silty very fine sand with 20% very fine grained sandstone fragments.
2.7 - 5.2	Very fine grained silty sandstone.
5.2 - 5.8	Very fine grained silty sandstone interbedded with 5% claystone.

OTHER NOTES

1) A split spoon sample was collected at 0.91 m to 1.52 m below ground surface.
2) Depth to bedrock = 2.7 meters.
3) Higher moisture content from 5.0 - 5.8 m but no water occurrences.
4) Gravel pack between 0.61 m and 2.7 m.
5) Piezometer opening between 0 m and 2.7 m.

WINTER RIVER OVERBURDEN DRILLING PROGRAM

BOREHOLE LOG

BOREHOLE NO: 5B

LOCATION: Brackley Pt. Road at City Water Pumping Station in Brackley.

DATE DRILLED: July 19, 1982 *LOGGED BY:* Don Jardine

EQUIPMENT: *Air Rotary Drilling Machine*

REF. MAP: 11L/6 *EASTING:* 488470 *NORTHING:* 5128620

Elevation (Metres, Geodetic) Top of Casing: 30.81 m

Top of Ground: 30.46 m

Depth	*Lithology*
0 - 0.30	Fine grained sandstone fill.
0.30 - 5.79	Clayey very fine silty sand with fine grained and silty sandstone pebbles, cobbles and boulders.
5.79 - 6.10	Silty very fine grained sandstone interbedded with fine to medium grained sandstone.

OTHER NOTES

1) Two split spoon samples were collected at
0.91 m to 1.52 m
4.57 m to 5.18 m.

2) Water occurrence between 3.05 m and 4.57 m with a static water level of 1.98 m below surface.

3) Depth to bedrock = 5.79 meters.

4) Gravel pack between 2.44 and 5.79 meters.

5) Piezometer opening between 2.74 and 5.79 meters.

WINTER RIVER OVERBURDEN DRILLING PROGRAM

BOREHOLE LOG

BOREHOLE NO: 6B

LOCATION: Horne Cross Road, Brackley, 100 m west of Brackley Pt. Road

DATE DRILLED: July 19, 1982 *LOGGED BY:* Don Jardine

EQUIPMENT: *Air Rotary Drilling Machine*

REF. MAP: 11L/6 *EASTING:* 488050 *NORTHING:* 5129300

Elevation (Metres, Geodetic) Top of Casing: 50.10 m

Top of Ground: 50.00 m (Ortho)

Depth	*Lithology*
0 - 0.91	Very fine sand with less than 10% clay and silt
0.91 - 2.90	Clayey very fine sand with 25 to 30% fine grained sandstone pebbles and cobbles.
2.90 - 4.57	Very fine grained sandstone.

OTHER NOTES

1) Two split spoon samples were collected at
0.91 m to 1.52 m
2.74 to 3.05 m below ground surface.

2) Hole dry.

3) Depth to bedrock = 2.90 meters.

4) Gravel pack between 0.61 and 3.05 m.

5) Piezometer opening between 0.61 and 3.05 m.

WINTER RIVER OVERBURDEN DRILLING PROGRAM

BOREHOLE LOG

BOREHOLE NO: 7HC

LOCATION: Horne Cross Road, Brackley at bend in road

DATE DRILLED: July 19, 1982 *LOGGED BY:* Don Jardine

EQUIPMENT: *Air Rotary Drilling Machine*

REF. MAP: 11L/6 *EASTING:* 489050 *NORTHING:* 5129500

Elevation (Metres, Geodetic) Top of Casing: 46.12 m

Top of Ground: 45.78 m

Depth	*Lithology*
0 - 1.52	Clayey fine sand with approximately 10% fine grained sandstone fragments
1.52 - 4.73	Fine sand with less than 5% clay and 10-20% fine grained sandstone fragments
4.73 - 6.10	Soft fine grained sandstone interbedded with less than 5% claystone

OTHER NOTES

1) Three split spoon samples collected at
    1.91 to 1.52 m
    2.74 to 3.35 m
    4.57 to 5.03 m.

2) High moisture content from 4.6 - 6.1 m below ground surface but no static water level detectable.

3) Depth to bedrock = 4.73 meters.

4) Gravel pack between 0.61 and 4.73 m.

5) Piezometer opening between 1.68 and 4.73 m.

WINTER RIVER OVERBURDEN DRILLING PROGRAM

BOREHOLE LOG

BOREHOLE NO: 8U

LOCATION: Union Road near end of airport main runway.

DATE DRILLED: July 14, 1982 *LOGGED BY:* Don Jardine

EQUIPMENT: *Air Rotary Drilling Machine*

REF. MAP: 11L/6. *EASTING:* 490400 *NORTHING:* 5127750

Elevation (Metres, Geodetic) Top of Casing: 49.73 m

Top of Ground: 49.63 m

Depth	*Lithology*
0 - 2.74	Fine to medium sand with fine to medium grained sandstone fragments.
2.74 - 5.49	Clayey fine sand with fine to medium grained sandstone fragments.
5.49 - 10.37	Fine to medium grained sandstone.
10.37 - 11.59	Green and orange claystone.
11.59 - 14.94	Fine to medium grained sandstone.
14.94 - 15.55	Green and orange claystone.
15.55 - 16.16	Fine to medium grained sandstone.
16.16 - 16.46	Reddish claystone.
16.46 - 17.68	Fine grained sandstone interbedded with siltstone and claystone.

OTHER NOTES

1) Two split spoon samples collected at 2.44 to 3.05 m and 4.27 to 4.57 meters.

2) One sample of soil cuttings collected at 1.22 to 2.44 m.

3) Water occurrence at 17.99 m with a static water level of 13.5 m below ground surface.

4) Depth to bedrock = 5.49 meters below surface.

5) Piezometer opening between 14.63 and 17.68 meters.

6) Gravel pack between 13.38 and 17.68 meters.

7) Very high moisture content between 2.44 m and 5.49 m.

WINTER RIVER OVERBURDEN DRILLING PROGRAM

BOREHOLE LOG

BOREHOLE NO: 9U

LOCATION: Union Road near Union Well Field.

DATE DRILLED: July 15, 1982 *LOGGED BY:* Don Jardine

EQUIPMENT: *Air Rotary Drilling Machine*

REF. MAP: 11L/6 *EASTING:* 490130 *NORTHING:* 5128820

Elevation (Metres, Geodetic) Top of Casing: 27.49 m
Top of Ground: 27.46 m

Depth	*Lithology*
0 - 2.74	Very fine sand with less than 10% clay and 15-20% fine grained sandstone fragments.
2.74 - 3.96	Soft and hard fine sandstone.
3.96 - 4.57	Fine sandstone interbedded with claystone.

OTHER NOTES

1) Two split spoon samples collected at 0.91 to 1.22 meters and 2.74 to 3.05 meters below ground surface.

2) Water occurrence between 4.0 and 4.57 meters with a static water level of 2.2 meters below surface.

3) Gravel pack between 2.13 and 4.57 meters.

4) Piezometer opening between 1.52 and 4.57 meters.

5) Depth to bedrock = 2.74 meters.

WINTER RIVER OVERBURDEN DRILLING PROGRAM

BOREHOLE LOG

BOREHOLE NO: 10U

LOCATION: Union Road at Access To Pit Owned by Howard Coles.

DATE DRILLED: July 15, 1982 *LOGGED BY:* Don Jardine

EQUIPMENT: *Air Rotary Drilling Machine*

REF. MAP: 11L/6 *EASTING:* 489820 *NORTHING:* 5129880

Elevation (Metres, Geodetic) Top of Casing: 41.69 m
Top of Ground: 41.59 m

Depth	*Lithology*
0 - 5.18	Clayey fine sand with up to 35% fine to medium grained sandstone fragments.
5.18 - 7.01	Very soft fine grained sandstone.
7.01 - 8.54	Hard fine grained sandstone.
8.54 - 12.50	Hard fine to medium grained sandstone interbedded with claystone.
12.50 - 12.80	Claystone
12.80 - 14.02	Hard fine to medium grained sandstone interbedded with claystone.
14.02 - 16.46	Fine to medium grained sandstone .
16.46 - 17.07	As above but interbedded with claystone.
17.07 - 17.38	Siltstone interbedded with claystone.
17.38 - 18.29	Siltstone interbedded with very fine grained sandstone.

OTHER NOTES

1) Three split spoon samples collected at
0.91 m to 1.52 m
2.74 m to 3.05 m
4.57 to 5.18 m.

2) Hole appeared saturated from 4.57 to 5.18 m below surface and at 17.68 m to 18.29 m.

3) Depth to bedrock = 5.18 m below surface.

4) Piezometer opening between 2.13 and 5.18 m.

WINTER RIVER OVERBURDEN DRILLING PROGRAM

BOREHOLE LOG

BOREHOLE NO: 11U

LOCATION: Union Road at Intersection of Hardy's Pond Road.

DATE DRILLED: July 15, 1982 *LOGGED BY:* Don Jardine

EQUIPMENT: *Air Rotary Drilling Machine*

REF. MAP: 11L/6 *EASTING:*489620 *NORTHING:* 5130630

Elevation (Metres, Geodetic) Top of Casing: 40.35 m

Top of Ground: 40.17 m

Depth	*Lithology*
0 - 4.27	Clayey fine sand with fine to medium grained sandstone fragments.
4.27 - 10.37	Soft and hard fine sandstone.
10.37 - 12.20	Fine sandstone interbedded with siltstone and claystone.
12.20 - 17.68	Soft and hard,fine to medium sandstone.
17.68 - 18.29	Fine sandstone interbedded with claystone.

OTHER NOTES

1) Two split spoon samples collected at 0.91 to 1.52 meters and 2.74 to 3.35 meters below surface.

2) Water occurrence between 11.89 - 12.20 meters below surface with a static water level of 14.3 meters below surface.

3) Depth to bedrock = 4.27 meters.

4) Gravel pack between 15.34 meters and 18.29 meters.

5) Piezometer opening between 15.24 and 18.29 meters.

WINTER RIVER OVERBURDEN DRILLING PROGRAM

BOREHOLE LOG

BOREHOLE NO: 12U

LOCATION: Union Road at Edge of Farmer's Field

DATE DRILLED: July 15, 1982 *LOGGED BY:* Don Jardine

EQUIPMENT: *Air Rotary Drilling Machine*

REF. MAP: 11L/6 *EASTING:* 489380 *NORTHING:* 5131690

Elevation (Metres, Geodetic) Top of Casing: 53.25 m

Top of Ground: 53.03 m

Depth	*Lithology*
0 - 4.27	Clayey fine sand with fine grained sandstone fragments.
4.27 - 8.23	Hard and soft fine grained sandstone.
8.23 - 8.38	Claystone.
8.38 - 8.84	Very hard fine grained sandstone.
8.84 - 12.80	Soft and hard fine grained sandstone interbedded with claystone and siltstone.
12.80 - 14.02	Hard fine grained sandstone.
14.02 - 14.94	Fine grained sandstone interbedded with claystone.
14.94 - 18.29	Hard fine grained sandstone interbedded with silty fine grained sandstone.
18.29 - 20.43	Hard fine to medium grained sandstone interbedded with siltstone and claystone.

OTHER NOTES

1) Two split spoon samples collected at 0.91 to 1.52 and 2.74 to 3.35 meters below ground surface.

2) A major water occurrence between 18.29 and 20.43 meters with a static water level = 14.9 meters below surface.

3) Depth to bedrock = 4.27 meters.

4) Gravel pack between 17.38 and 20.43 meters.

5) Piezometer opening between 17.38 and 20.43 meters.

WINTER RIVER OVERBURDEN DRILLING PROGRAM

BOREHOLE LOG

BOREHOLE NO: 13HP

LOCATION: Hardy's Pond Road about 1 km East of Union Road

DATE DRILLED: July 19, 1982 *LOGGED BY:* Don Jardine

EQUIPMENT: Air Rotary Drilling Machine

REF. MAP: 11L/6 *EASTING:* 490200 *NORTHING:* 5130730

Elevation (Metres, Geodetic) Top of Casing: 28.165 m

Top of Ground: 27.765 m

Depth	*Lithology*
0 - 0.30	Orangy fine loamy sand.
0.30 - 5.34	Clayey very fine sand with very fine grained sandstone and claystone fragments.
5.34 - 5.95	Fine grained sandstone interbedded with claystone.

OTHER NOTES

1) Three split spoon samples collected at 0.91 to 1.52, 2.74 to 3.35 and 4.57 to 5.34 meters below surface.

2) High moisture content between 2.7 and 3.3 meters. Water occurrence between 4.0 and 5.9 meters with a static water level of 4.0 meters below surface.

3) Depth to bedrock = 5.34 meters.

4) Gravel pack between 1.98 and 5.34 meters.

5) Piezometer opening between 2.29 and 5.34 meters.

WINTER RIVER OVERBURDEN DRILLING PROGRAM

BOREHOLE LOG

BOREHOLE NO: 14HP

LOCATION: Hardy's Pond Road about 1.5 to 2.0 km east of Union Road

DATE DRILLED: July 20, 1982 *LOGGED BY:* Don Jardine

EQUIPMENT: *Air Rotary Drilling Machine*

REF. MAP: 11L/6 *EASTING:* 490700 *NORTHING:* 5130880

Elevation (Metres, Geodetic) Top of Casing: 23.49 m

Top of Ground: 23.24 m

Depth	*Lithology*
0 - 0.91	Clayey fine sand with 10% fine grained sandstone fragments.
0.91 - 2.13	Very fine sand with less than 5% silt and clay and 20% fine grained sandstone fragments.
2.13 - 3.05	Clayey fine sand with 10% fine grained sandstone fragments.
3.05 - 3.20	Very fine sand with minor silt and clay and 20% fine grained sandstone fragments.
3.20 - 4.27	Clayey fine sand with 10% fine grained sandstone fragments.
4.27 - 5.34	Very soft silty very fine grained sandstone.
5.34 - 5.79	Hard fine grained sandstone.

OTHER NOTES

1) Two split spoon samples collected at 0.91 to 1.52 meters and 3.05 to 3.66 meters below ground surface.

2) Some water seepage at 0.91 to 1.52 meters. Static water upon hole completion = 1.5 meters below surface.

3) Depth to bedrock = 4.27 meters

4) Gravel pack between 0.91 and 4.27 meters.

5) Piezometer opening between 1.22 and 4.27 meters.

WINTER RIVER OVERBURDEN DRILLING PROGRAM

BOREHOLE LOG

BOREHOLE NO: 15Y

LOCATION: York Road, 2 Meters North of CNR Tracks

DATE DRILLED: July 23, 1982 *LOGGED BY:* Don Jardine

EQUIPMENT: *Air Rotary Drilling Machine*

REF. MAP: 11L/6 *EASTING:* 492500 *NORTHING:* 5128930

Elevation (Metres, Geodetic) Top of Casing: 40.417 m

Top of Ground: 40.207 m

Depth	*Lithology*
0 - 1.07	Soft silty very fine sand.
1.07 - 2.74	Hard silty and clayey very fine sand with 20% fine grained sandstone and silty very fine grained sandstone fragments.
2.74 - 3.05	Very fine sandy clay with less than 5% sandstone fragments.
3.05 - 3.35	Very fine sandy silt with 15% fine grained sandstone.
3.35 - 4.57	Hard silty and clayey very fine sand with 20% sandstone fragments.
4.57 - 5.03	Very fine sandy clay with less than 5% sandstone fragments.
5.03 - 5.95	Claystone with thin lenses of very fine grained sandstone.
5.95 - 6.10	Very fine grained sandstone.

OTHER NOTES

1) Three split spoon samples collected at 0.91 to 1.37 m, 2.74 to 3.35m and 4.57 to 5.18 m below surface.

2) Some water seepage at 4.6 m below surface but no static water level.

3) Depth to bedrock = 5.03 meters.

4) Gravel pack between 0.46 and 5.03 meters.

5) Piezometer opening between 2.67 and 5.03 meters.

WINTER RIVER OVERBURDEN DRILLING PROGRAM

BOREHOLE LOG

BOREHOLE NO: 16Y

LOCATION: East of York Road, on lawn of Claude Lewis

DATE DRILLED: July 20, 1982 *LOGGED BY:* Don Jardine

EQUIPMENT: *Air Rotary Drilling Machine*

REF. MAP: 11L/6 *EASTING:* 492220 *NORTHING:* 5129920

Elevation (Metres, Geodetic) Top of Casing: 49.20 m

Top of Ground: 49.20 m

Depth	*Lithology*
0 - 2.74	Silty fine sand with 15% fine grained, semi-rounded sandstone pebbles.
2.74 - 4.42	Fine to medium sand.
4.42 - 6.10	Soft to medium hard fine to medium grained sandstone interbedded with 20% siltstone.

OTHER NOTES

1) Two split spoon samples collected at 0.91 to 1.52 and 2.74 to 3.35 meters below surface.

2) No water seepage.

3) Depth to bedrock = 4.42 meters below surface.

4) Gravel pack between 1.07 and 4.42 meters.

5) Piezometer opening between 1.37 and 4.42 meters.

WINTER RIVER OVERBURDEN DRILLING PROGRAM

BOREHOLE LOG

BOREHOLE NO: 17Y

LOCATION: West of York Road on Ross Lewis property.

DATE DRILLED: July 22, 1982 *LOGGED BY:* Don Jardine

EQUIPMENT: *Air Rotary Drilling Machine*

REF. MAP: 11L/6 *EASTING:* 491930 *NORTHING:* 5130350

Elevation (Metres, Geodetic) Top of Casing: 41.379 m

Top of Ground: 41.099 m

Depth	*Lithology*
0 - 1.07	Soft very fine sand with less than 5% clay and silt and 10-15% fine grained sandstone fragments.
1.07 - 3.51	Hard and soft fine sand with 10% fine grained sandstone and claystone fragments.
3.51 - 5.49	Fine grained sandstone.

OTHER NOTES

1) Two split spoon samples collected at 0.91 to 1.22 m and 3.05 to 3.51 meters below surface.

2) No water seepage.

3) Depth to bedrock = 3.51 meters.

4) Gravel pack between 1.07 and 3.20 meters.

5) Piezometer opening between 1.68 and 3.20 meters.

WINTER RIVER OVERBURDEN DRILLING PROGRAM

BOREHOLE LOG

BOREHOLE NO: 18Y
LOCATION: Pleasant Grove Road at Junction of York Road
DATE DRILLED: July 20, 1982 *LOGGED BY:* Don Jardine
EQUIPMENT: Air Rotary Drilling Machine
REF. MAP: 11L/6 *EASTING:* 491830 *NORTHING:* 5131390
Elevation (Metres, Geodetic) Top of Casing: 18.40 m
Top of Ground: 18.30 m

Depth	*Lithology*
0 - 1.37	Fine to medium sand.
1.37 - 1.98	Organic silty very fine sand.
1.98 - 2.90	Silty very fine sand.
2.90 - 4.57	Silty fine sand with 10-20% fine grained sandstone cobbles.
4.57 - 5.03	Fine to medium sand.
5.03 - 5.18	Silty fine sand.
5.18 - 8.23	Fine to medium sand with less than 5% silt and less than 10% fine to medium grained sandstone fragments.
8.23 - 10.37	Very soft and medium hard fine to medium grained sandstone.

OTHER NOTES

1) Three split spoon samples collected at 0.91 to 1.52, 2.90 to 3.51 and 4.57 to 5.18 meters below surface. A loose soil sample was collected between 7.32 to 7.62 meters.

2) Hole very moist at 1.83 to 2.13 meters. Water seepage noted at 4.57 meters. Static water level = 2.3 meters below surface. Hole caving below 2.4 meters.

3) Depth to bedrock = 8.23 meters.

4) Gravel pack between 0.6 and 2.4 meters.

5) Piezometer opening between 2.4 and 5.5 meters.

WINTER RIVER OVERBURDEN DRILLING PROGRAM

BOREHOLE LOG

BOREHOLE NO: 19Y

LOCATION: Covehead Road on Fred Morrison Property

DATE DRILLED: July 22, 1982 *LOGGED BY:* Don Jardine

EQUIPMENT: *Air Rotary Drilling Machine*

REF. MAP: 11L/6 *EASTING:* 491600 *NORTHING:* 5132080

Elevation (Metres, Geodetic) Top of Casing: 42.24 m
Top of Ground: 42.04 m

Depth	*Lithology*
0 - 1.07	Soft very fine sand with less then 10% clay and silt and approximately 10% fine grained sandstone fragments.
1.07 - 3.20	Silty very fine sand with 10-15% fine grained sandstone pebbles, semi-rounded.
3.20 - 5.95	Fine to medium sand interbedded with silty sand.
5.95 - 7.62	Fine to medium grained sandstone.

OTHER NOTES

1) Three split spoon samples collected at 0.91 to 1.52, 3.05 to 3.66 and 4.88 to 5.49 meters below ground surface.

2) High moisture content between 4.9 and 5.5 meters but no static water level

3) Depth ot bedrock = 5.95 meters.

4) Gravel pack between 2.9 and 6.0 meters.

5) Piezometer opening between 2.9 and 6.0 meters.

WINTER RIVER OVERBURDEN DRILLING PROGRAM

BOREHOLE LOG

BOREHOLE NO: 20HP

LOCATION: Hardy's Pond Road approximately 1 km west of York Road

DATE DRILLED: July 20, 1982 *LOGGED BY:* Don Jardine

EQUIPMENT: *Air Rotary Drilling Machine*

REF. MAP: 11L/6 *EASTING:* 491300 *NORTHING:* 5131050

Elevation: (Metres, Geodetic) Top of Casing: 20.629 m

Top of Ground: 20.329 m

Depth	*Lithology*
0 - 1.07	Very fine sandy silt.
1.07 - 1.37	Very fine sand with less than 5% silt.
1.37 - 1.68	Very fine sandy silt.
1.68 - 2.90	Very fine sand with less than 5% silt.
2.90 - 3.51	Very fine sandy silt with sub-rounded and rounded very fine grained sandstone pebbles.
3.51 - 4.88	Very fine silty sand with less than 5% clay and 25 to 30% very fine grained sandstone fragments.
4.88 - 7.01	Very fine sandy clay with 10% fine grained sandstone fragments.
7.01 - 7.93	Soft clayey fine grained sandstone.

OTHER NOTES

1) Three split spoon samples collected at 0.91 to 1.52, 2.90 to 3.51 and 4.88 to 5.49 meters below surface.

2) High moisture content from 1.0 m to bottom of hole. Major water occurrence at 7.6 m with a static water level of 1.07 m below surface.

3) Depth to bedrock = 7.01 meters below surface.

4) Gravel pack between 3.6 and 7.0 meters.

5) Piezometer opening between 4.0 and 7.0 meters.

WINTER RIVER OVERBURDEN DRILLING PROGRAM

BOREHOLE LOG

BOREHOLE NO: 21WR

LOCATION: York at NE corner of Claude Lewis pasture field about 20 m south of Winter River

DATE DRILLED: July 20, 1982 *LOGGED BY:* Don Jardine

EQUIPMENT: *Air Rotary Drilling Machine*

REF. MAP: 11L/6 *EASTING:* 493200 *NORTHING:* 5130320

Elevation (Metres, Geodetic) Top of Casing: 18.27 m

Top of Ground: 18.00 m (Ortho)

Depth	*Lithology*
0 - 0.91	Clayey fine sand
0.91 - 3.05	Silty fine sand with up to 20% fine to medium grained sandstone pebbles.
3.05 - 3.81	Clayey, sandy silt with very fine grained sandstone and siltstone pebbles.
3.81 - 5.49	Fine to medium grained sandstone interbedded with claystone and siltstone.

OTHER NOTES

1) Two split spoon samples collected at 0.91 to 1.52 and 2.74 to 3.35 meters below surface.

2) Higher moisture content from 1.5 meters to bottom. Water occurrence at 4.0 meters below surface with a static water level of 2.1 m below surface.

3) Depth to bedrock = 3.8 meters.

4) Gravel pack between 2.1 and 3.8 meters.

5) Piezometer opening between 2.3 and 3.8 meters.

WINTER RIVER OVERBURDEN DRILLING PROGRAM

BOREHOLE LOG

BOREHOLE NO:	22P
LOCATION:	Pleasant Grove Road near access to Joe Ready Pit
DATE DRILLED:	July 22, 1982
LOGGED BY:	Don Jardine
EQUIPMENT:	*Air Rotary Drilling Machine*
REF. MAP:	11L/6
EASTING:	492150
NORTHING:	5131840

Elevation (Metres, Geodetic)

Top of Casing: 30.76 m

Top of Ground: 30.52 m

Depth	*Lithology*
0 - 3.66	Fine to medium sand with less than 10% clay and silt with up to 20% fine grained sandstone fragments some semi rounded.
3.66 - 4.57	Clayey very fine sand with 15-20% fine grained semi rounded sandstone pebbles.
4.57 - 5.18	Silty very fine sand with semi rounded fine grained sandstone pebbles.
5.18 - 5.49	Very fine sand, slightly silty.
5.49 - 7.32	Clayey very fine sand with fine grained sandstone fragments.
7.32 - 8.23	Very soft, clayey, very fine sand.

OTHER NOTES

1) Two split spoon samples collected at 0.91 to 1.83 and 2.74 to 3.66 meters below ground surface.

2) High moisture content from 1.8 meters to bottom - static water level = 2.4 meters below ground surface.

3) Bedrock was not encountered. Hole caving below 0.9 meters and would not remain open.

4) No gravel pack installed.

5) Piezometer opening between 2.4 and 5.5 meters below surface. Some sand in bottom portion of piezometer.

WINTER RIVER OVERBURDEN DRILLING PROGRAM

BOREHOLE LOG

BOREHOLE NO: 23S

LOCATION: Suffolk Road on Saw Mill property

DATE DRILLED: July 22, 1982 *LOGGED BY:* Don Jardine

EQUIPMENT: Air Rotary Drilling Machine

REF. MAP: 11L/6 *EASTING:* 494980 *NORTHING:* 5130750

Elevation (Metres, Geodetic) Top of Casing: 18.947 m

Top of Ground: 18.697 m

Depth	*Lithology*
0 - 3.20	*Fine to medium sand with up to 30% fine grained sandstone pebbles.*
3.20 - 3.26	*Clayey fine sand*
3.26 - 5.00	*Fine to medium sand with up to 30% fine grained sandstone pebbles and cobbles.*
5.00 - 5.11	*Clayey very fine sand with fine grained sandstone and sandstone and claystone pebbles.*
5.11 - 5.79	*Fine to medium sand with less than 50% silt and clay.*
5.79 - 7.01	*Hard fine to medium grained sandstone.*

NOTES:

1. *Three split spoon samples collected at 0.9 to 1.5, 2.7 to 3.4, and 4.6 to 5.2 meters below ground surface.*
2. *High moisture content at 3.6 meters with a static water level upon completion of 3.8 meters below ground surface.*
3. *Depth to bedrock = 5.79 meters.*
4. *Gravel pack between 2.29 and 5.79 meters.*
5. *Piezometer opening between 2.74 and 5.79 meters but piezometer plugged at 5.03 meters.*

WINTER RIVER OVERBURDEN DRILLING PROGRAM

BOREHOLE LOG

BOREHOLE NO: 24S

LOCATION: Suffolk Road on S. Wheatley Property

DATE DRILLED: July 23, 1982 LOGGED BY: Don Jardine

EQUIPMENT: Air Rotary Drilling Machine

REF. MAP: 11L/6 EASTING: 495610 NORTHING: 5129610

Elevation (Metres, Geodetic) Top of Casing: 27.97 m

Top of Ground: 27.80 m

Depth	Lithology
0 - 0.91	Silty very fine sand with 10% fine grained sandstone and claystone fragments.
0. 91 - 2.74	Clayey, silty very fine sand with 15% soft fine grained semi-rounded sandstone and claystone fragments.
2.74 - 5.64	Very fine sandy clay with semirounded fine grained sandstone and claystone fragments.
5.64 - 7.01	Very fine grained sandstone interbedded with claystone.

NOTES:

1. Three split spoon samples collected at 0.9 to 1.5, 2.7 to 3.4 and 4.6 to 5.2 meters below ground surface.
2. Water occurrence at 6.1 meters below ground surface with a static water level of 4.4 meters below surface.
3. Depth to bedrock = 5.64 meters.
4. Piezometer opening between 2.59 and 5.64 meters.
5. Gravel pack between 2.29 and 5.64 meters.

WINTER RIVER OVERBURDEN DRILLING PROGRAM

BOREHOLE LOG

BOREHOLE NO: 25S

LOCATION: Suffolk Road on N.E. side of CNR Tracks

DATE DRILLED: July 23, 1982 LOGGED BY: Don Jardine

EQUIPMENT: Air Rotary Drilling Machine

REF. MAP: 11L/6 EASTING: 495780 NORTHING: 5129080

Elevation (Metres, Geodetic) Top of Casing: 47.522 m

Top of Ground: 47.122 m

Depth	Lithology
0 - 0.91	Fine sand with less than 5 % clay and silt and 10-20% fine grained sandstone fragments (fill).
0.91 - 1.52	Silty very fine sand with 25 to 30% fine grained sandstone fragments.
1.52 - 3.35	Very fine sand with less than 10% silt & clay and 25% fine grained sandstone and claystone fragments.
3.35 - 3.96	Fine sand with fine grained sandstone and claystone fragments.
3.96 - 6.10	Fine grained sandstone interbedded with claystone.

NOTES

1. Two split spoon samples collected at 0.9 to 1.5 and 2.7 to 3.4 meters below ground surface.
2. No water occurrences.
3. Depth to bedrock = 3.96 meters.
4. Gravel pack between 1.83 and 3.96 meters.
5. Piezometer opening between 2.44 and 3.96 meters.

WINTER RIVER OVERBURDEN DRILLING PROGRAM

BOREHOLE LOG

BOREHOLE NO: 26S

LOCATION: Ira Lewis Property approx. 1 km. west of Suffolk Rd.

DATE DRILLED: July 22, 1982 LOGGED BY: Don Jardine

EQUIPMENT: Air Rotary Drilling Machine

REF. MAP: 11L/6 EASTING: 493830 NORTHING: 5132030

Elevation (Metres, Geodetic) Top of Casing: 30.50 m

Top of Ground: 30.00 m (Ortho)

Depth	Lithology
0 - 1.52	Silty very fine sand with 10-20% fine grained sandstone fragments.
1.52 - 3.69	Hard fine sand with less than 10% silt & clay and approx. 25% semi-round fine grained sandstone pebbles, cobbles and boulders.
3.69 - 5.49	Hard fine grained sandstone.

NOTES:

1. Two split spoon samples collected at 0.9 to 1.5 and 2.7 to 3.2 meters below ground surface.
2. High moisture content near bottom but not saturated.
3. Depth to bedrock= 3.69 meters
4. Gravel pack between 0.61 and 3.69 meters.
5. Piezometer opening between 0.61 and 3.69 meters.

WINTER RIVER OVERBURDEN DRILLING PROGRAM

BOREHOLE LOG

BOREHOLE NO: 27Y

LOCATION: Frank Vessey Property, York - 1 km. west of the York Rd.

DATE DRILLED: July 23, 1982 LOGGED BY: Don Jardine

EQUIPMENT: Air Rotary Drilling Machine

REF. MAP: 11L/6 EASTING: 491700 NORTHING: 5128100

Elevation (Metres, Geodetic) Top of Casing: 50.83 m

Top of Ground: 50.50 m (Ortho)

Depth	Lithology
0 - 0.30	Organic material (tree roots).
0.30 - 0.91	Silty very fine sand.
0.91 - 1.83	Hard very fine sandy, clayey silt with 20% fine grained sandstone pebbles and cobbles.
1.83 - 3.05	Clayey, silty, very fine sand with up to 20% very fine grained sandstone pebbles and cobbles.
3.05 - 3.35	Hard very fine sand.
3.35 - 6.10	Moderately hard very fine grained sandstone interbedded with claystone.
6.10 - 6.55	Dark organic claystone.
6.55 - 7.01	Moderately hard very fine grained sandstone.

NOTES:

1. Three split spoon samples collected at 0.9 to 1.20, 2.7 to 3.4, and 6.1 to 6.5 meters below surface.
2. Water occurrence between 4.6 and 6.1 meters with a static water level = 5.9 meters below surface.
3. Depth to bedrock = 3.35 meters.
4. Gravel pack between 1.83 and 3.35 meters.
5. Piezometer opening between 1.83 and 3.35 meters.

WINTER RIVER OVERBURDEN DRILLING PROGRAM

BOREHOLE LOG

BOREHOLE NO: 28Y

LOCATION: Property of Bill Crockett - 1 km. west of York Rd.

DATE DRILLED: July 23, 1982 LOGGED BY: Don Jardine

EQUIPMENT: Air Rotary Drilling Machine

REF. MAP: 11L/6 EASTING: 491200 NORTHING: 5129500

Elevation (Metres, Geodetic) Top of Casing: 26.0 m

Top of Ground: 26.0 m (Ortho)

Depth	Lithology
0 - 2.90	Silty very fine sand with up to 40% fine grained sandstone fragments.
2.90 - 3.66	Very fine sandy, silty clay with 25% semi-round fine grained sandstone pebbles.
3.66 - 5.18	Very fine grained sandstone, interbedded with siltstone and claystone.

NOTES:

1. Two split spoon samples collected at 0.9 to 1.5 and 2.7 to 3.5 meters below surface.
2. Water occurrence between 4.6 and 5.2 meters with a static water level = 2.0 meters below ground surface. High moisture content at 1.0 meters.
3. Depth to bedrock = 3.66 meters.
4. Gravel pack between 0.61 and 3.66 meters.
5. Piezometer opening between 0.61 and 3.66 meters.

WINTER RIVER OVERBURDEN DRILLING PROGRAM

BOREHOLE LOG

BOREHOLE NO: *29Y*

LOCATION: *Joe Ready Property - 1 km. west of York Rd.*

DATE DRILLED: *July 26, 1982* *LOGGED BY:* *Don Jardine*

EQUIPMENT: *Air Rotary Drilling Machine*

REF. MAP: *11L/6* *EASTING:* *490400* *NORTHING:* *5131800*

Elevation (Metres, Geodetic) Top of Casing: 37.30 m

Top of Ground: 37.00 m (Ortho)

Depth	*Lithology*
0 - 0.91	*Silty very fine sand with approximately 10% fine grained sandstone fragments.*
0.91 - 1.52	*Clayey very fine sand with approximately 20% fine grained sandstone fragments.*
1.52 - 2.74	*Silty very fine sand with approximately 20% fine grained sandstone fragments.*
2.74 - 4.57	*Hard fine to medium grained sandstone interbedded with claystone.*

NOTES:

1. *Two split spoon samples collected at 0.9 to 1.5 and 2.7 to 3.0 meters below ground surface.*
2. *No water occurrences.*
3. *Depth to bedrock = 2.74 meters.*
4. *Gravel pack between 1.07 and 2.74 meters.*
5. *Piezometer opening between 1.22 and 2.74 meters.*

WINTER RIVER OVERBURDEN DRILLING PROGRAM

BOREHOLE LOG

BOREHOLE NO: 30B

LOCATION: Wendell Barbour Property west of Brackley Pt. Rd.

DATE DRILLED: July 26, 1982 LOGGED BY: Don Jardine

EQUIPMENT: Air Rotary Drilling Machine

REF. MAP: 11L/6 EASTING: 487960 NORTHING: 5127250

Elevation (Metres, Geodetic) Top of Casing: 45.68 m

Top of Ground: 45.40 m (Ortho)

Depth	Lithology
0 - 0.91	Silty very fine sand with 25% very fine grained sandstone gragments.
0.91 - 2.13	Hard clayey fine sand with 25% very fine grained sandstone and claystone fragments.
2.13 - 4.57	Soft fine sand with less than 5% clay and silt.
4.57 - 4.82	Soft clayey very fine sand with 20% very fine grained sandstone and claystone fragments.
4.82 - 6.04	Soft fine grained sandstone interbedded with claystone.
6.04 - 6.71	Hard fine grained sandstone.

NOTES:

1. Three split spoon samples collected at 0.9 to 1.5, 2.7 to 3.4, 4.6 to 4.9 meters below ground surface.
2. No water occurrences.
3. Depth to bedrock = 4.82 meters below surface.
4. Gravel pack between 1.55 and 4.82 meters.
5. Piezometer opening between 1.77 and 4.82 meters.

WINTER RIVER OVERBURDEN DRILLING PROGRAM

BOREHOLE LOG

BOREHOLE NO: *31W*

LOCATION: *L.D.C. Property - 1 km south of Winsloe Road*

DATE DRILLED: *July 26, 1982* *LOGGED BY:* *Don Jardine*

EQUIPMENT: *Air Rotary Drilling Machine*

REF. MAP: *11L/6* *EASTING:* *486900* *NORTHING:* *5128100*

Elevation (Metres, Geodetic) Top of Casing: 36.20 m

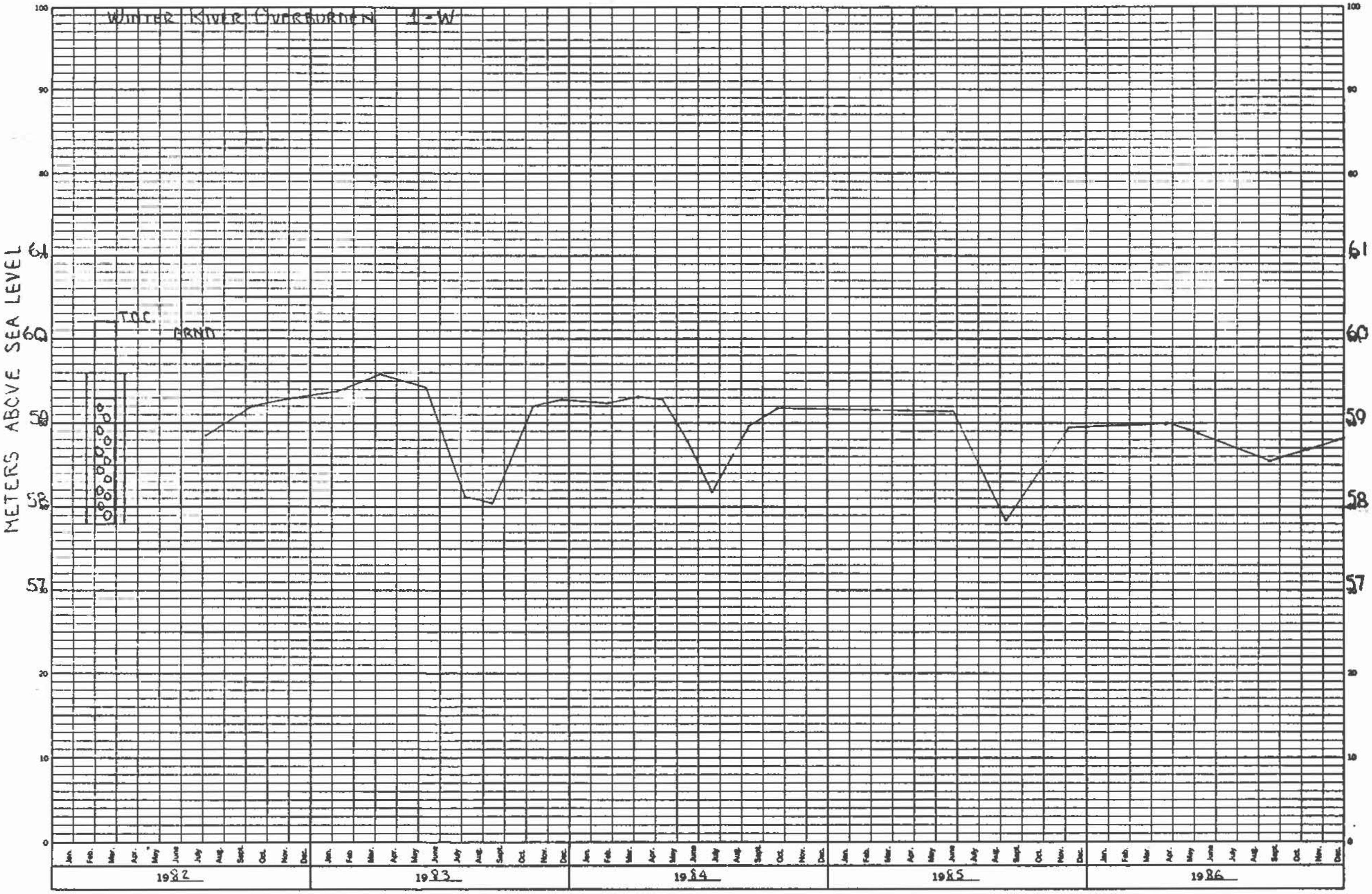
Top of Ground: 36.00 m (Ortho)

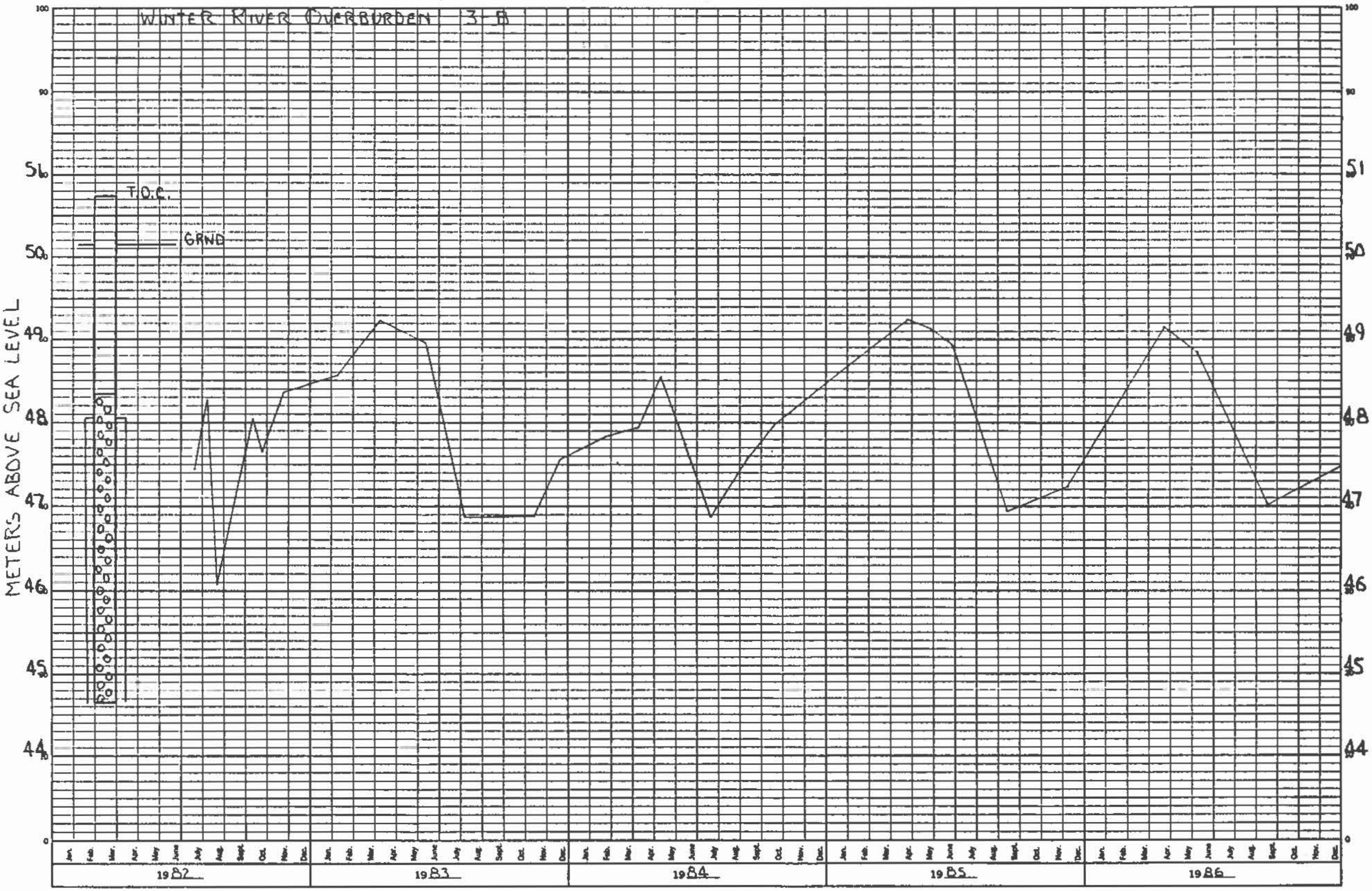
Depth	*Lithology*
0 - 0.91	*Clayey very fine sand with less than 10% fine grained sandstone fragments.*
0.91 - 5.18	*Sandy clay with approximately 10% fine grained sandstone, silty fine grained sandstone and claystone pebble, cobble and boulders.*
5.18 - 5.95	*Clayey very fine sand with approximately 20% silty very fine grained sandstone fragments.*
5.95 - 7.01	*Silty very fine grained sandstone.*

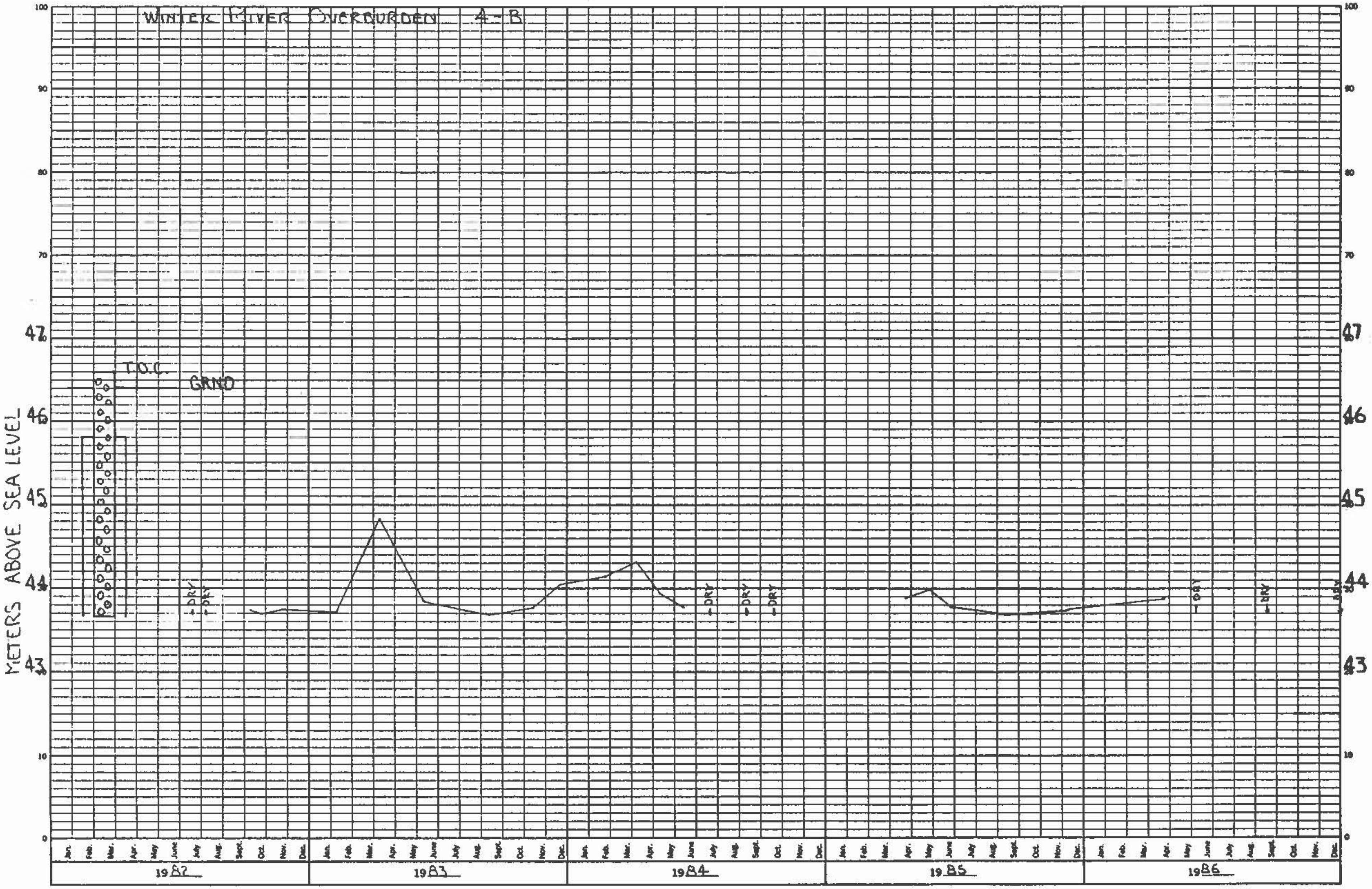
NOTES:

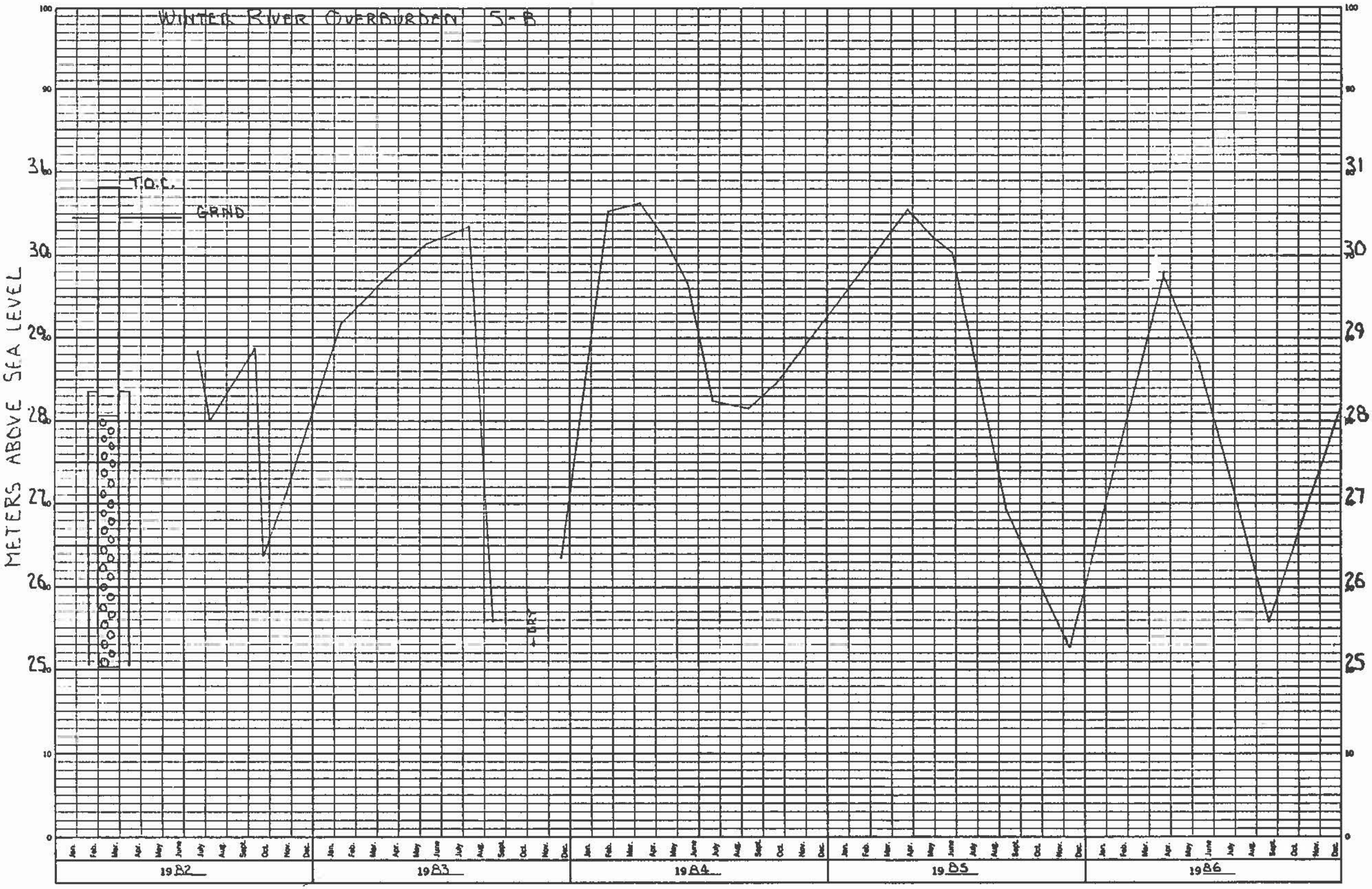
1. *Three split spoon samples collected at 0.9 to 1.5, 2.7 to 3.5 and 4.6 to 5.2 meters below ground surface.*
2. *High moisture content at 2.4 meters with a water occurrence at 5.9 to 6.1 meters. Static water level upon completion = 5.0 meters.*
3. *Depth to bedrock = 5.95 meters below surface.*
4. *Gravel pack between 2.59 and 5. 95 meters.*
5. *Piezometer opening between 2.90 and 5.95 meters.*

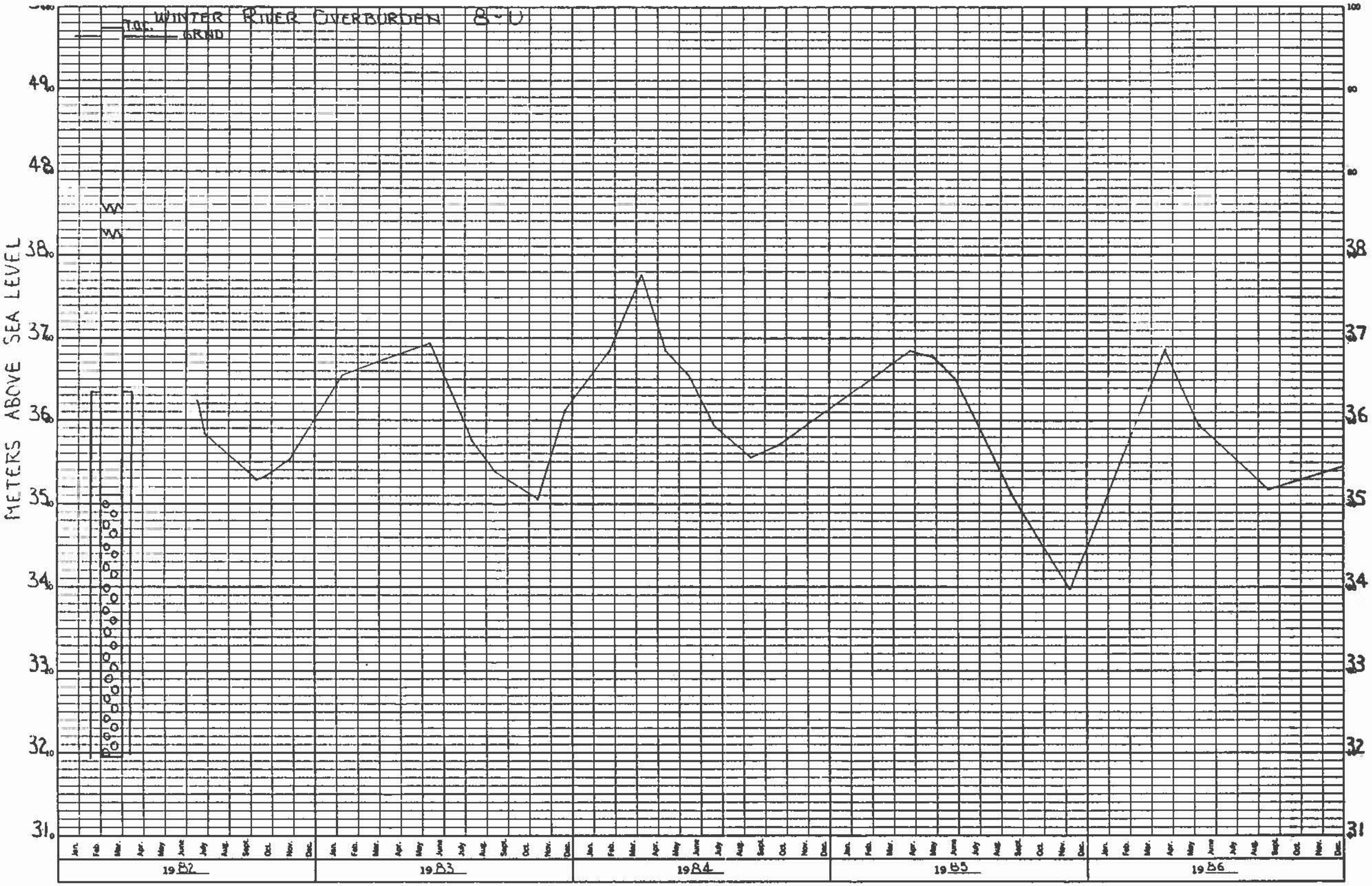
APPENDIX III

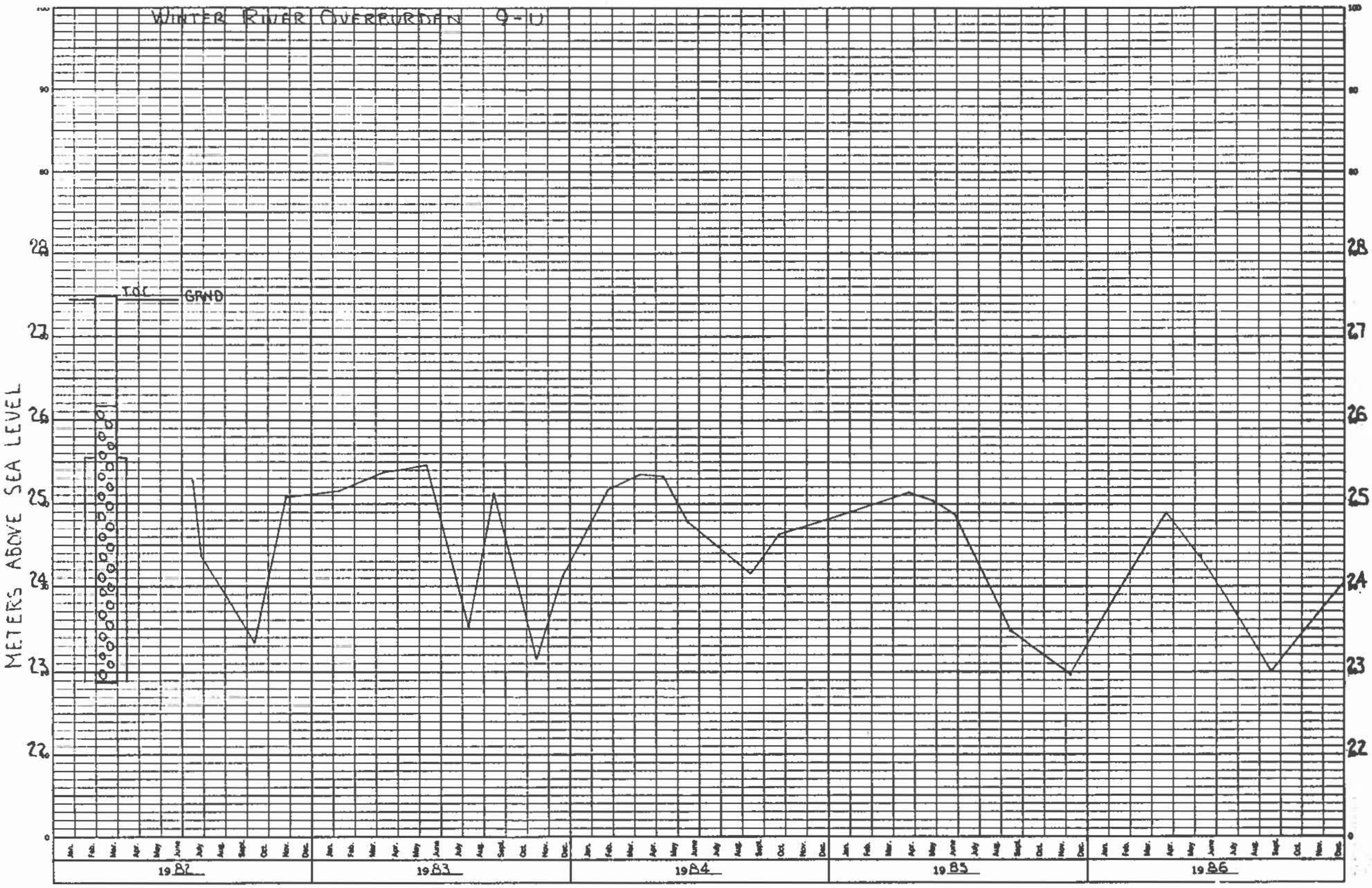

WINTER RIVER OVERBURDEN 1-W
T.O.C.
GRND
METERS ABOVE SEA LEVEL
61
60
59
58
57
1982
1983
1984
1985
1986

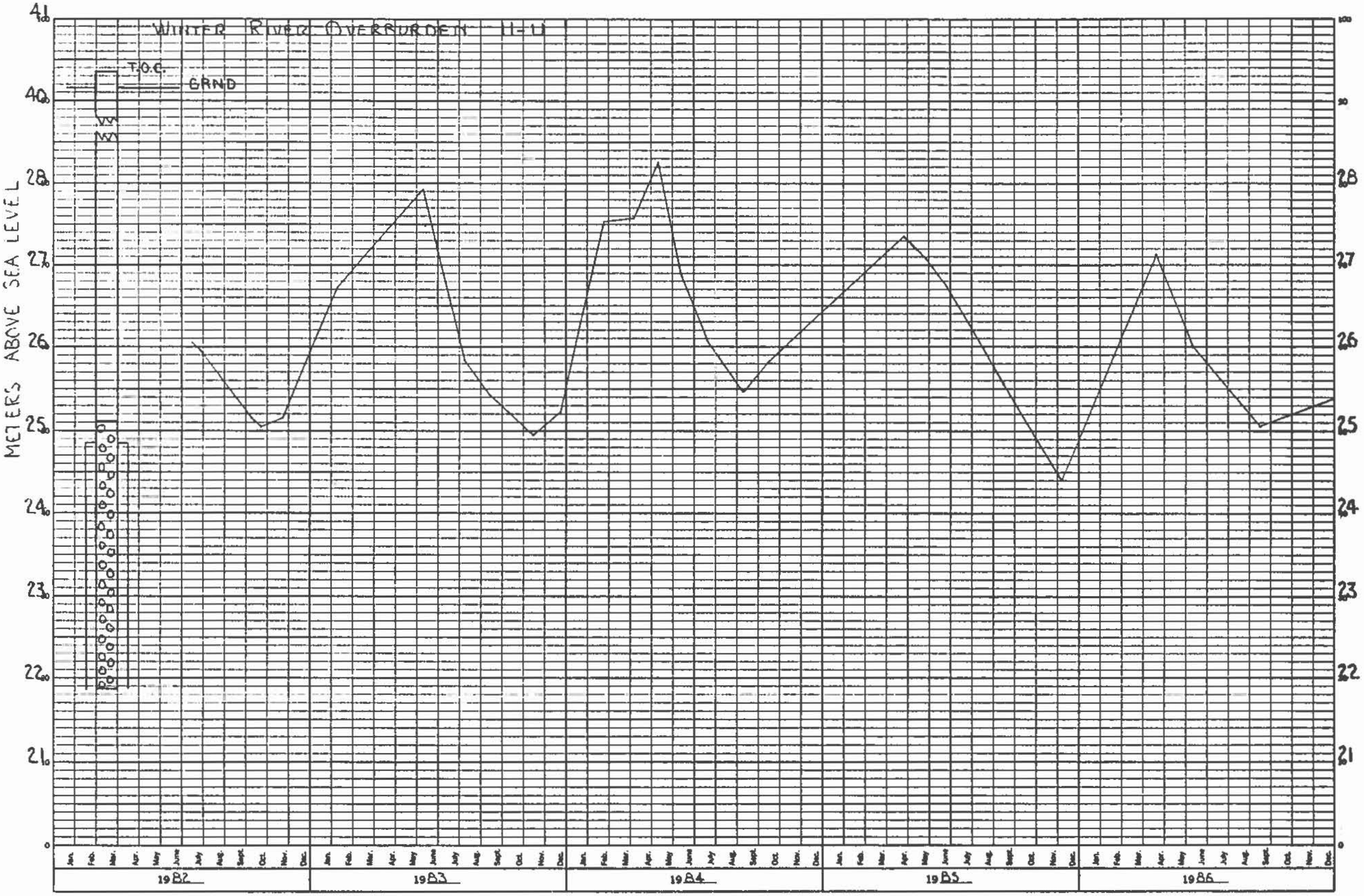

WINTER RIVER OVERBURDEN 3-B
T.O.C.
GRND
METERS ABOVE SEA LEVEL
51
50
49
48
47
46
45
44
Jan. Feb. Mar. Apr. May June July Aug. Sept. Oct. Nov. Dec.
1982
1983
1984
1985
1986

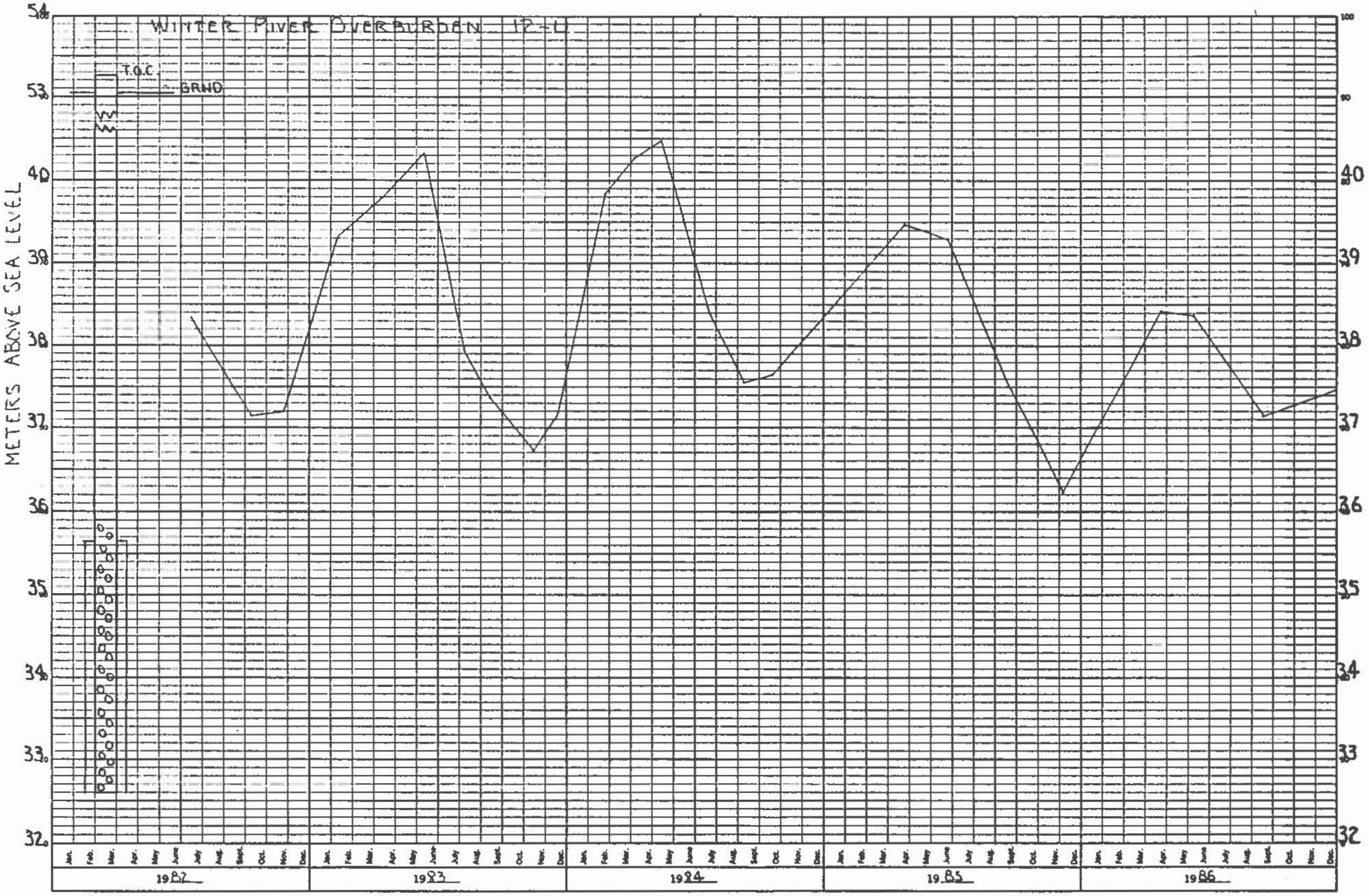

WINTER RIVER OVERBURDEN 4-B

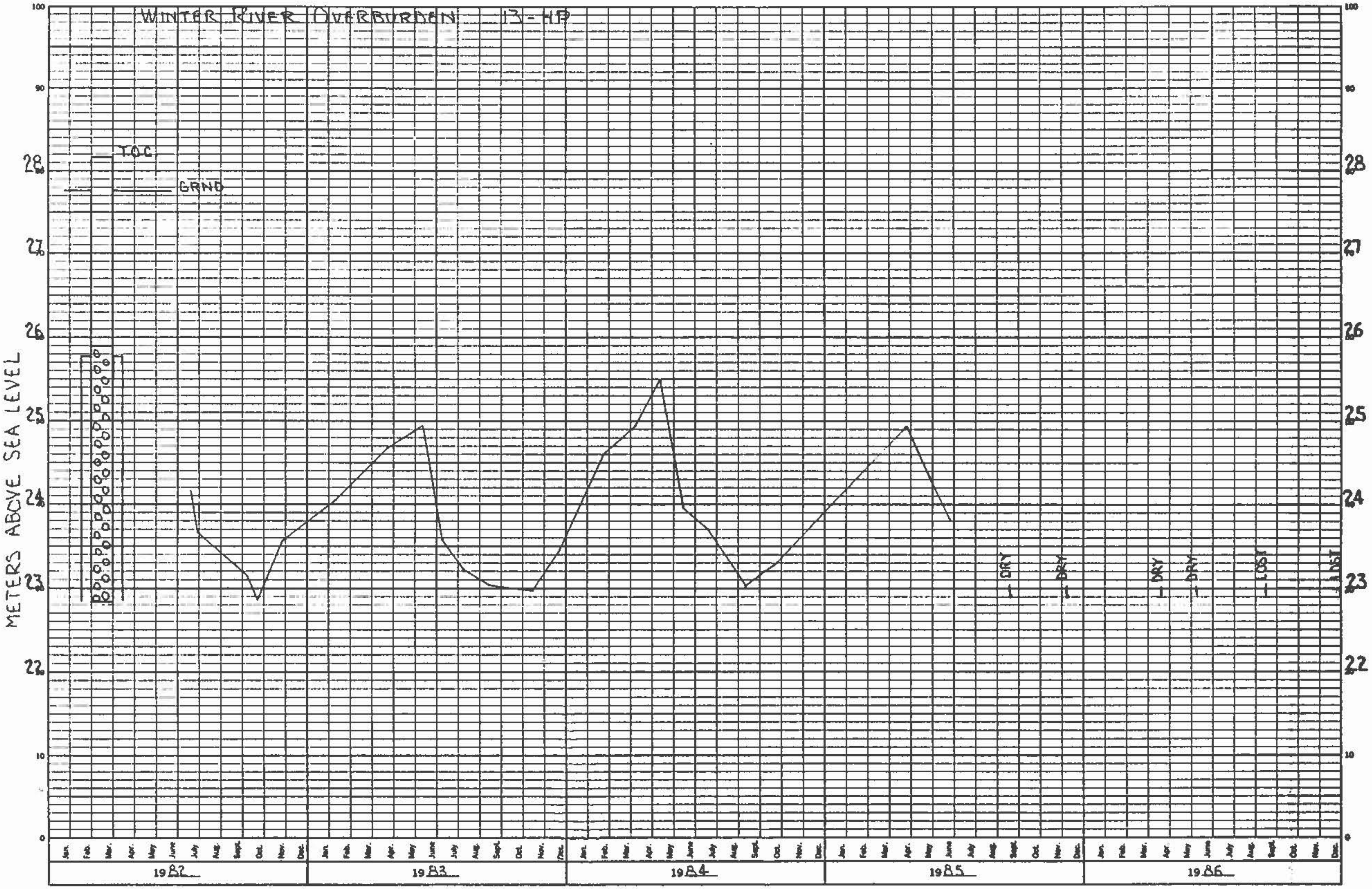

WINTER RIVER OVERBURDAN 5-B
METERS ABOVE SEA LEVEL
31
30
29
28
27
26
25
T.O.C.
GRND
DRY
Jan. Feb. Mar. Apr. May June July Aug. Sept. Oct. Nov. Dec.
1982
1983
1984
1985
1986

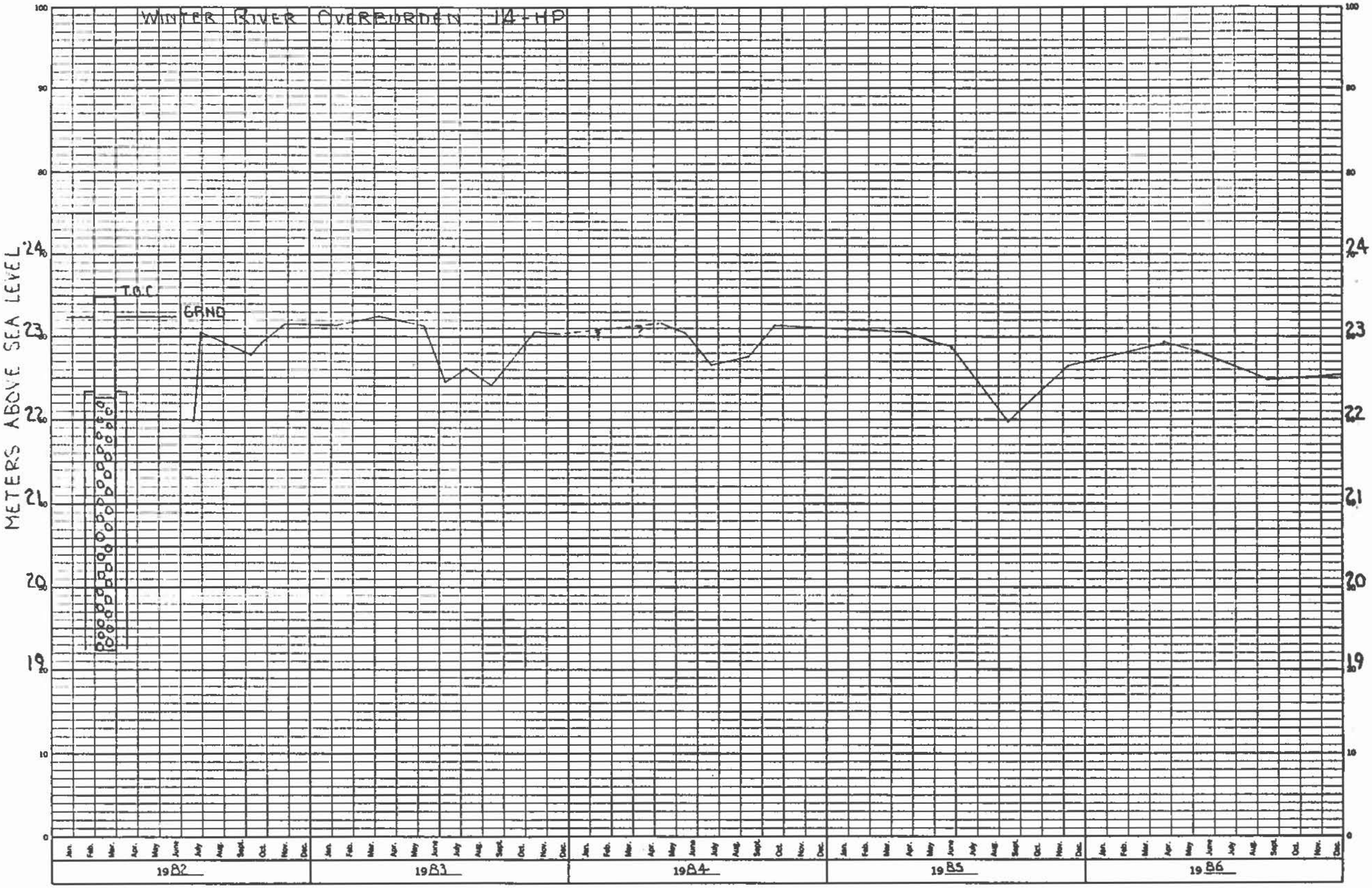
WINTER RIVER OVERBURDEN 8-U
T.O.C.
GRND
METERS ABOVE SEA LEVEL
49.0
48.0
38.0
37.0
36.0
35.0
34.0
33.0
32.0
31.0
38
37
36
35
34
33
32
31
Jan.
Feb.
Mar.
Apr.
May
June
July
Aug.
Sept.
Oct.
Nov.
Dec.
1982
1983
1984
1985
1986

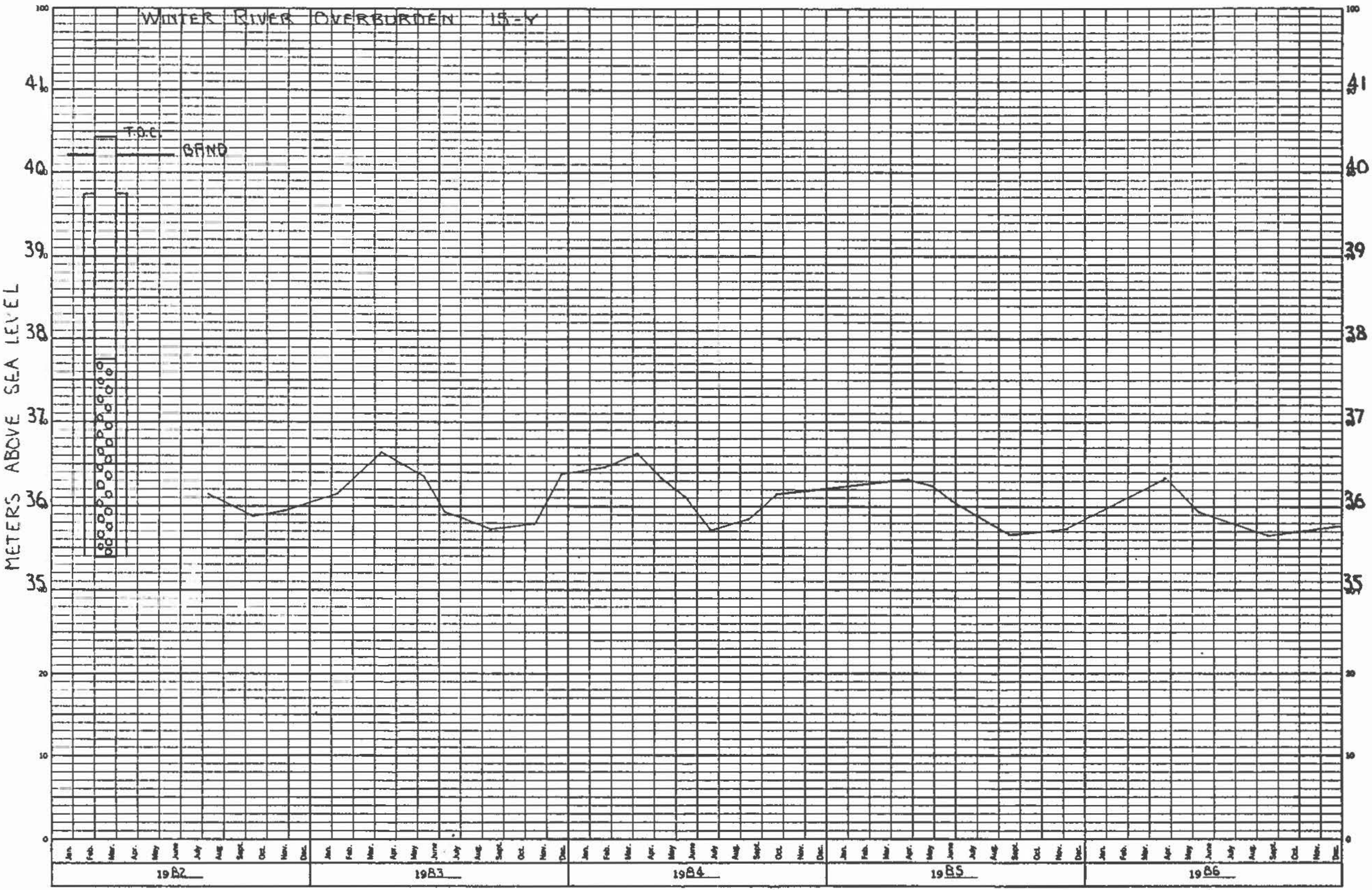

WINTER RIVER OVERBURDEN 9-U
METERS ABOVE SEA LEVEL
28
27
26
25
24
23
22
T.O.C.
GRND
Jan. Feb. Mar. Apr. May June July Aug. Sept. Oct. Nov. Dec.
1982
1983
1984
1985
1986

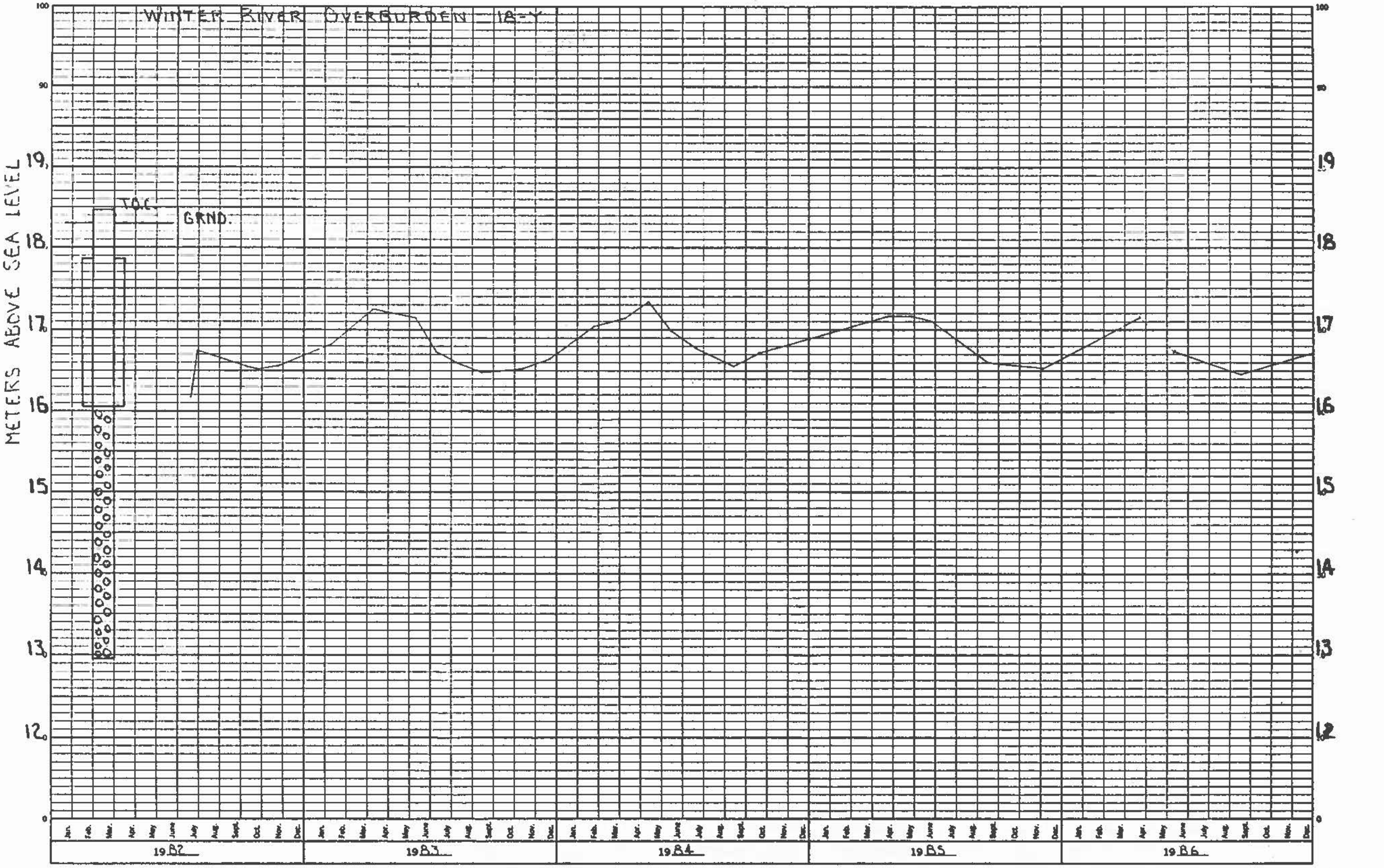

WINTER RIVER OVERBURDEN 11-U
T.O.C.
GRND
METERS ABOVE SEA LEVEL
41
40
28
27
26
25
24
23
22
21
0
100
90
Jan.
Feb.
Mar.
Apr.
May
June
July
Aug.
Sept.
Oct.
Nov.
Dec.
1982
1983
1984
1985
1986

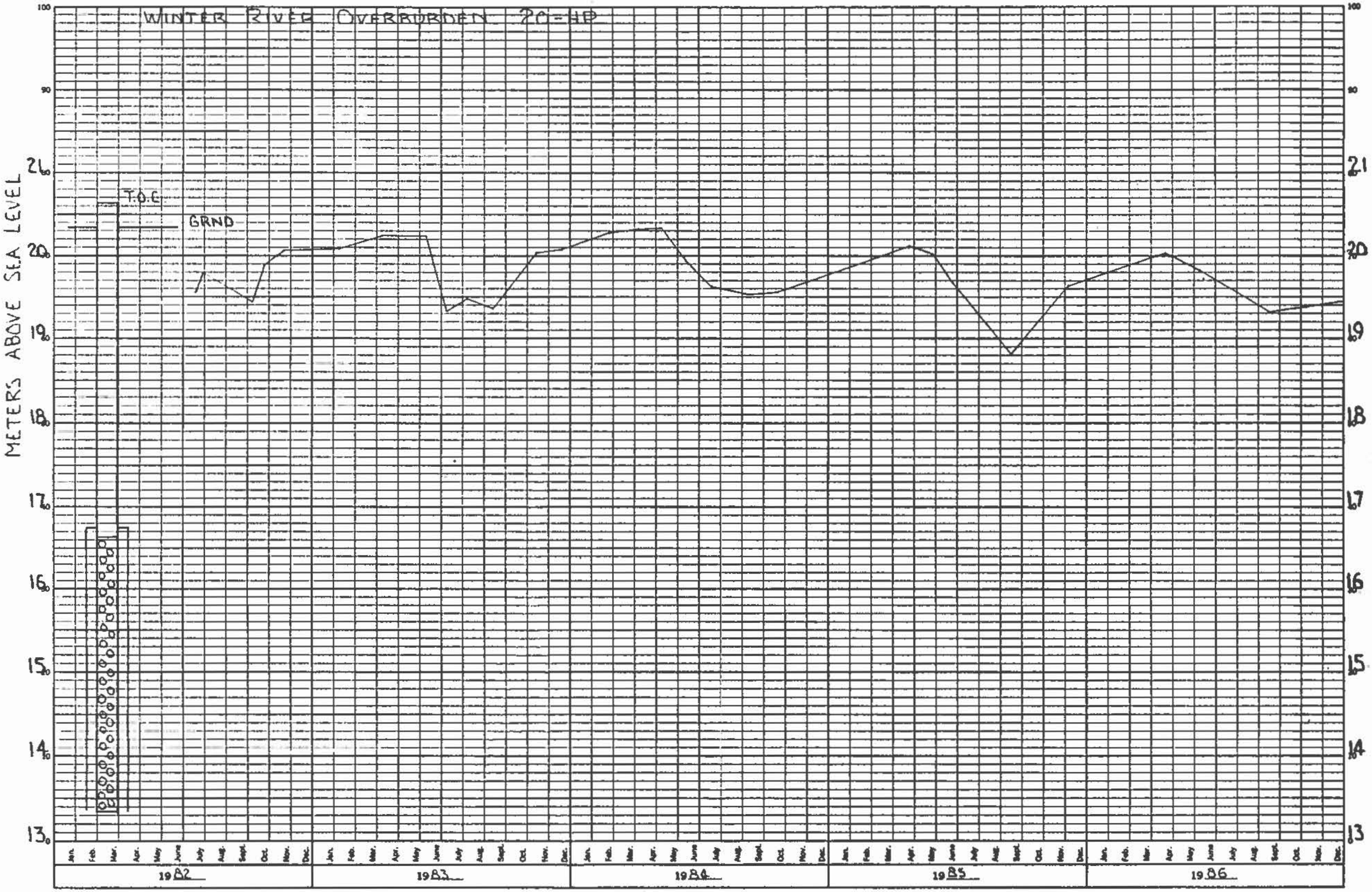

WINTER RIVER OVERBURDEN 12-U
T.O.C.
GRND
METERS ABOVE SEA LEVEL
54
53
40
39
38
37
36
35
34
33
32
Jan. Feb. Mar. Apr. May June July Aug. Sept. Oct. Nov. Dec.
1982
1983
1984
1985
1986

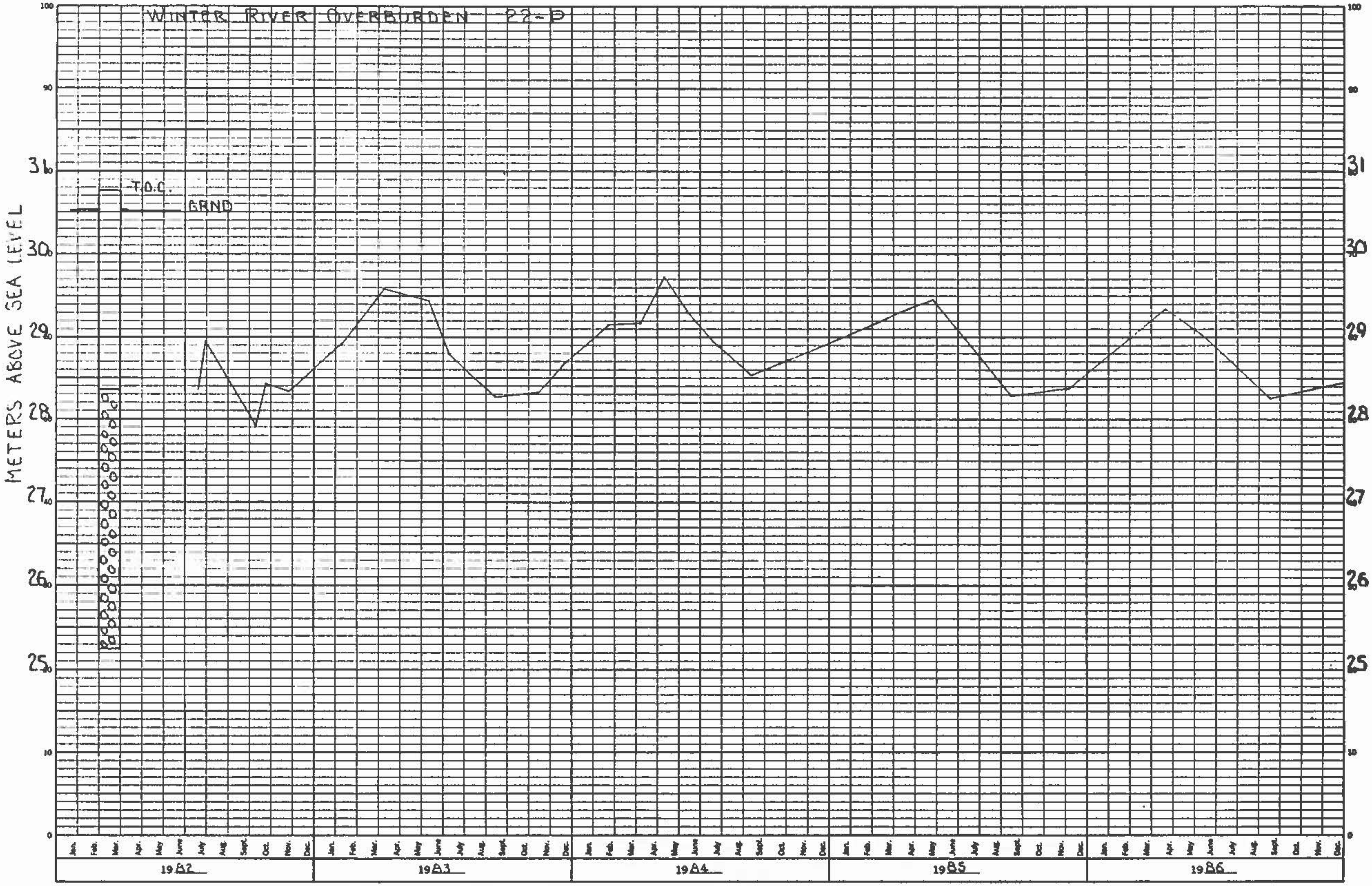

WINTER RIVER OVERBURDEN 13-HP
TOC
GRND
METERS ABOVE SEA LEVEL
28
27
26
25
24
23
22
100
90
10
0
DRY
DRY
DRY
DRY
LOST
LOST
Jan. Feb. Mar. Apr. May June July Aug. Sept. Oct. Nov. Dec.
1982
1983
1984
1985
1986

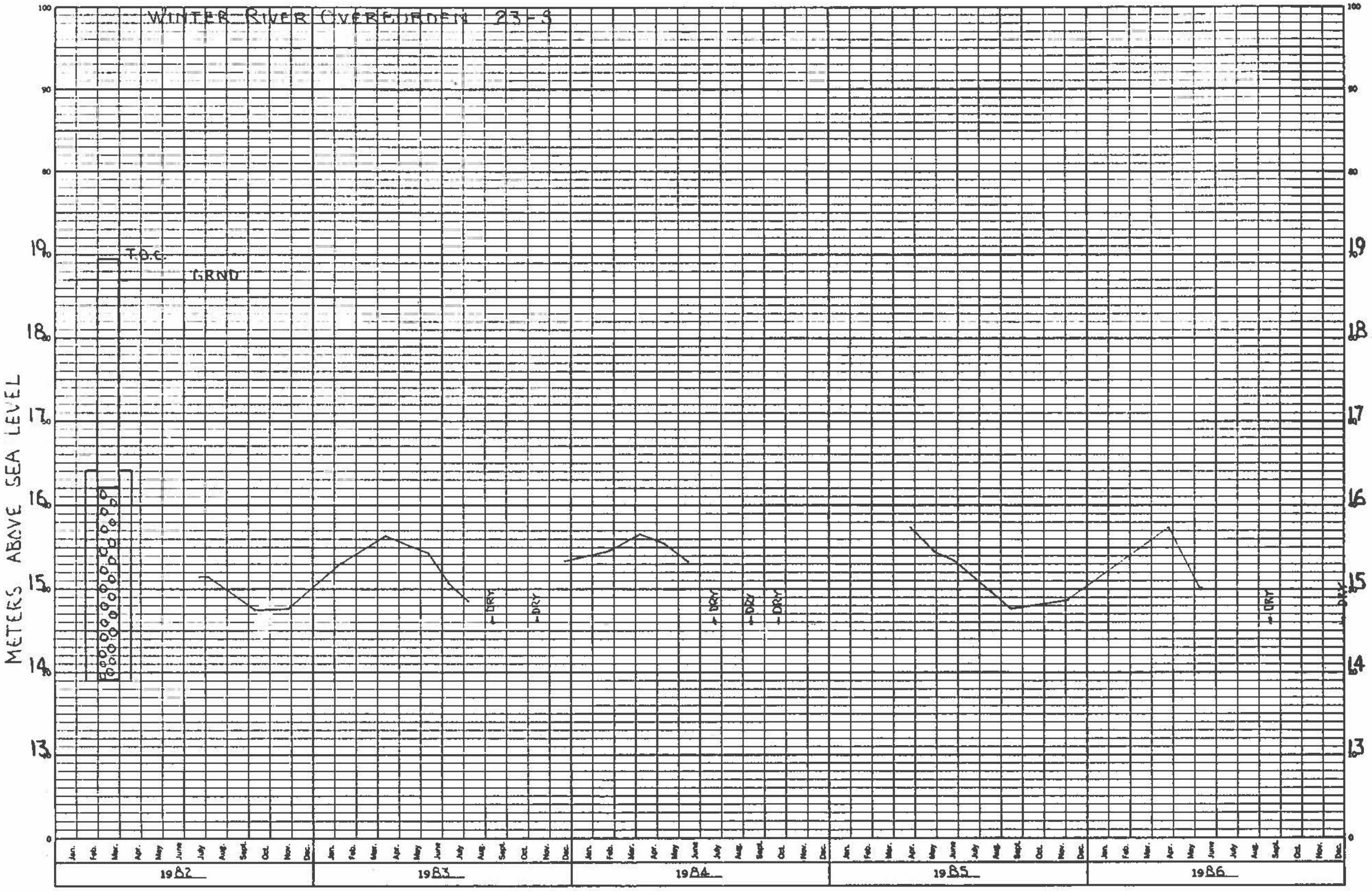

WINTER RIVER OVERBURDEN 14-HP
T.O.C
GRND
METERS ABOVE SEA LEVEL
24
23
22
21
20
19
100
90
80
10
0
Jan.
Feb.
Mar.
Apr.
May
June
July
Aug.
Sept.
Oct.
Nov.
Dec.
1982
1983
1984
1985
1986

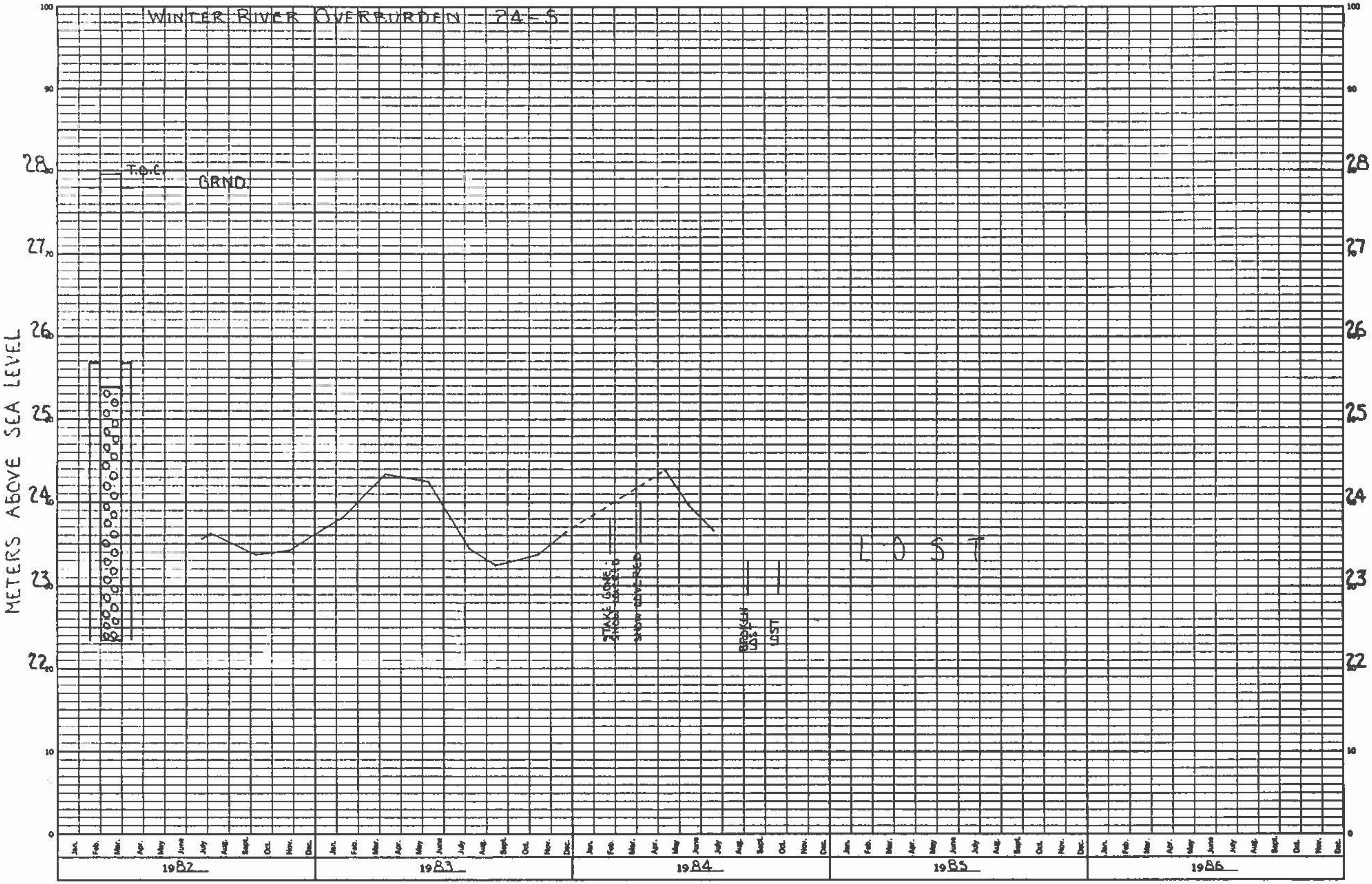

WINTER RIVER OVERBURDEN 15-Y

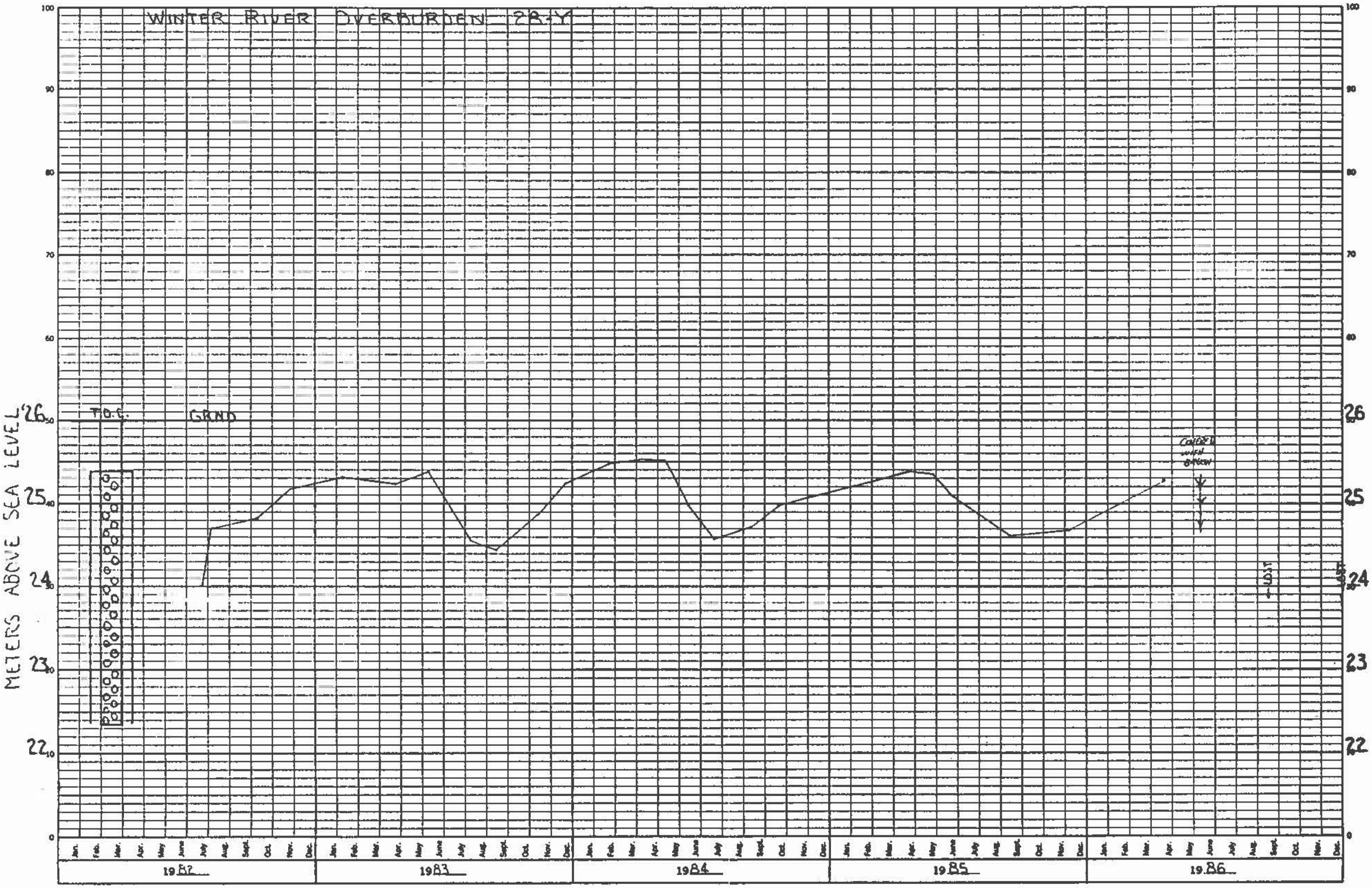

WINTER RIVER OVERBURDEN 1B-Y
METERS ABOVE SEA LEVEL
100
90
19
18
17
16
15
14
13
12
0
T.O.C.
GRND.
Jan. Feb. Mar. Apr. May June July Aug. Sept. Oct. Nov. Dec.
1982
1983
1984
1985
1986


WINTER RIVER OVERBURDEN 20-HP
T.O.C.
GRND
METERS ABOVE SEA LEVEL
100
90
21
20
19
18
17
16
15
14
13
Jan. Feb. Mar. Apr. May June July Aug. Sept. Oct. Nov. Dec.
1982
1983
1984
1985
1986


WINTER RIVER OVERBURDEN 22-P
T.O.C.
GRND
METERS ABOVE SEA LEVEL
31
30
29
28
27
26
25
100
90
10
0
Jan. Feb. Mar. Apr. May June July Aug. Sept. Oct. Nov. Dec.
1982
1983
1984
1985
1986


WINTER RIVER OVERBURDEN 23-3
METERS ABOVE SEA LEVEL
T.O.C.
GRND
13
14
15
16
17
18
19
DRY
DRY
DRY
DRY
DRY
DRY
DRY
Jan.
Feb.
Mar.
Apr.
May
June
July
Aug.
Sept.
Oct.
Nov.
Dec.
1982
1983
1984
1985
1986


WINTER RIVER OVERBURDEN 24-S
METERS ABOVE SEA LEVEL
28
27
26
25
24
23
22
T.O.C.
GRND.
STAKE GONE - SNOW COVERED
SNOW COVERED
BROKEN LOST
LOST
L O S T
1982
1983
1984
1985
1986


WINTER RIVER OVERBURDEN 28-Y
METERS ABOVE SEA LEVEL
100
90
80
70
60
50
40
30
20
10
0
26
25
24
23
22
T.O.C.
GRND
CAPPED when broken
LOST
Jan.
Feb.
Mar.
Apr.
May
June
July
Aug.
Sept.
Oct.
Nov.
Dec.
1982
1983
1984
1985
1986

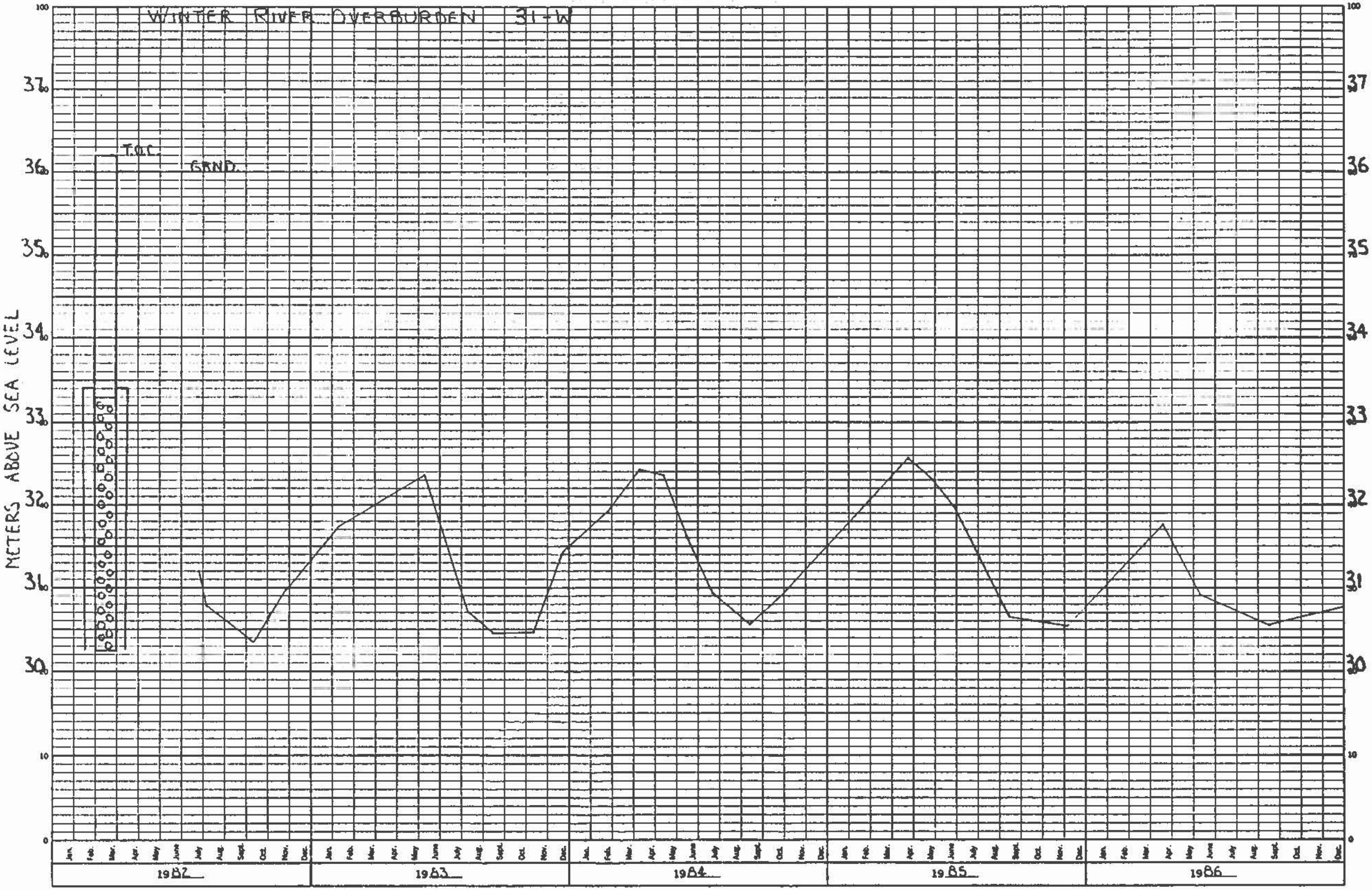
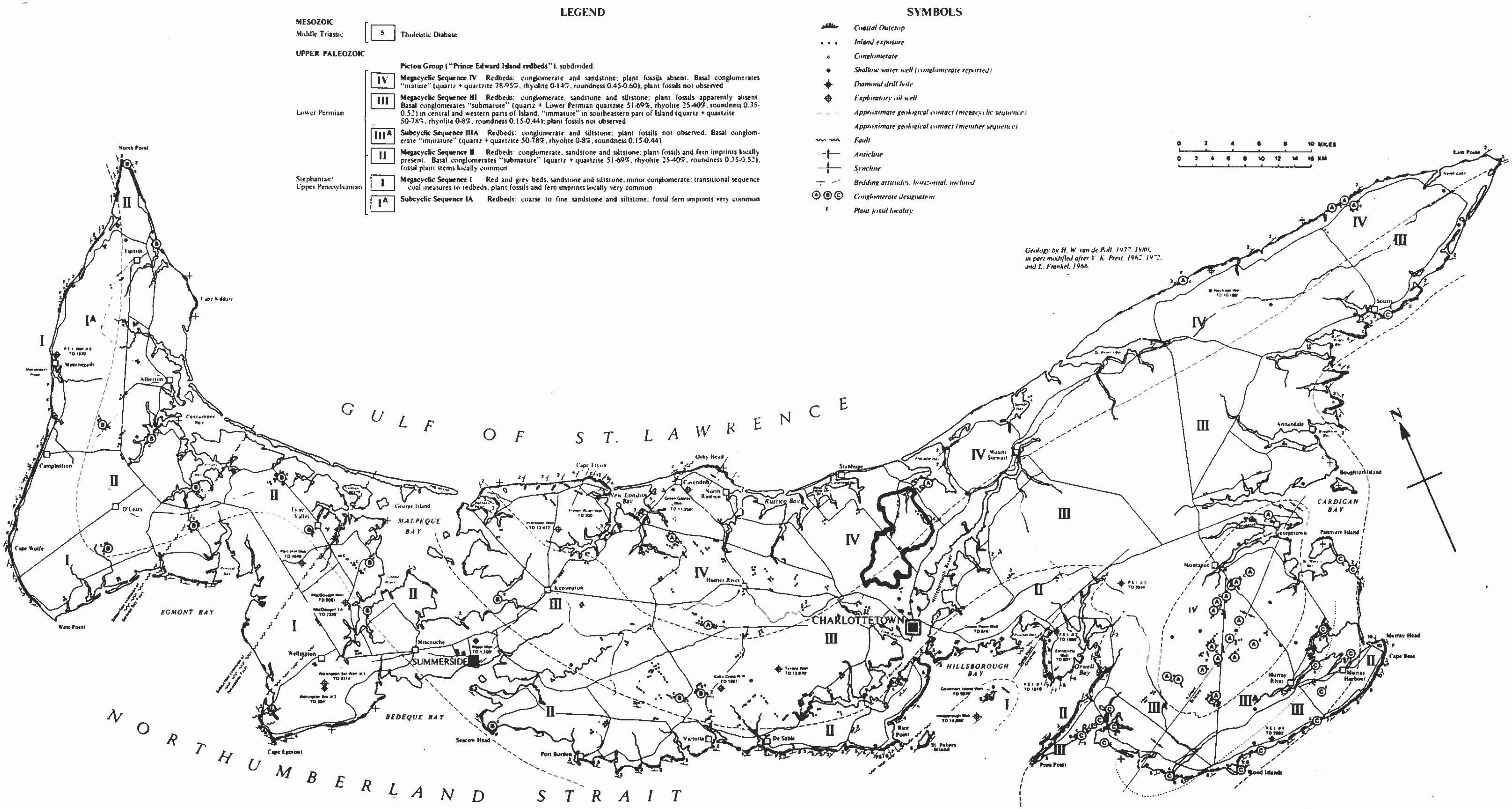

WINTER RIVER OVERBURDEN 31-W
T.O.C.
GRND.
METERS ABOVE SEA LEVEL
37
36
35
34
33
32
31
30
Jan. Feb. Mar. Apr. May June July Aug. Sept. Oct. Nov. Dec.
1982
1983
1984
1985
1986

Figure 5

GEOLOGICAL MAP OF PRINCE EDWARD ISLAND



LEGEND

MESOZOIC

Middle Triassic	5	Tholeiitic Diabase

UPPER PALEOZOIC

Pictou Group ("Prince Edward Island redbeds"), subdivided:

Lower Permian	IV	**Megacyclic Sequence IV** Redbeds: conglomerate and sandstone; plant fossils absent. Basal conglomerates "mature" (quartz + quartzite 78-95%, rhyolite 0-14%, roundness 0.45-0.60); plant fossils not observed
	III	**Megacyclic Sequence III** Redbeds: conglomerate, sandstone and siltstone; plant fossils apparently absent. Basal conglomerates "submature" (quartz + Lower Permian quartzite 51-69%, rhyolite 25-40%, roundness 0.35-0.52) in central and western parts of Island, "immature" in southeastern part of Island (quartz + quartzite 50-78%, rhyolite 0-8%, roundness 0.15-0.44); plant fossils not observed
	IIIA	**Subcyclic Sequence IIIA** Redbeds: conglomerate and siltstone; plant fossils not observed. Basal conglomerate "immature" (quartz + quartzite 50-78%, rhyolite 0-8%, roundness 0.15-0.44)
	II	**Megacyclic Sequence II** Redbeds: conglomerate, sandstone and siltstone; plant fossils and fern imprints locally present. Basal conglomerates "submature" (quartz + quartzite 51-69%, rhyolite 25-40%, roundness 0.35-0.52), fossil plant stems locally common
Stephanian/ Upper Pennsylvanian	I	**Megacyclic Sequence I** Red and grey beds, sandstone and siltstone, minor conglomerate; transitional sequence coal measures to redbeds; plant fossils and fern imprints locally very common
	IA	**Subcyclic Sequence IA** Redbeds: coarse to fine sandstone and siltstone; fossil fern imprints very common

SYMBOLS

	Coastal Outcrop
• • •	*Inland exposure*
c	*Conglomerate*
●	*Shallow water well (conglomerate reported)*
◆	*Diamond drill hole*
⊕	*Exploratory oil well*
– – –	*Approximate geological contact (megacyclic sequence)*
	Approximate geological contact (member sequence)
〰 〰	*Fault*
	Anticline
	Syncline
	Bedding attitudes, horizontal, inclined
Ⓐ Ⓑ Ⓒ	*Conglomerate designation*
F	*Plant fossil locality*

Geology by H. W. van de Poll, 1977, 1980, in part modified after V. K. Prest, 1962, 1972, and L. Frankel, 1966.

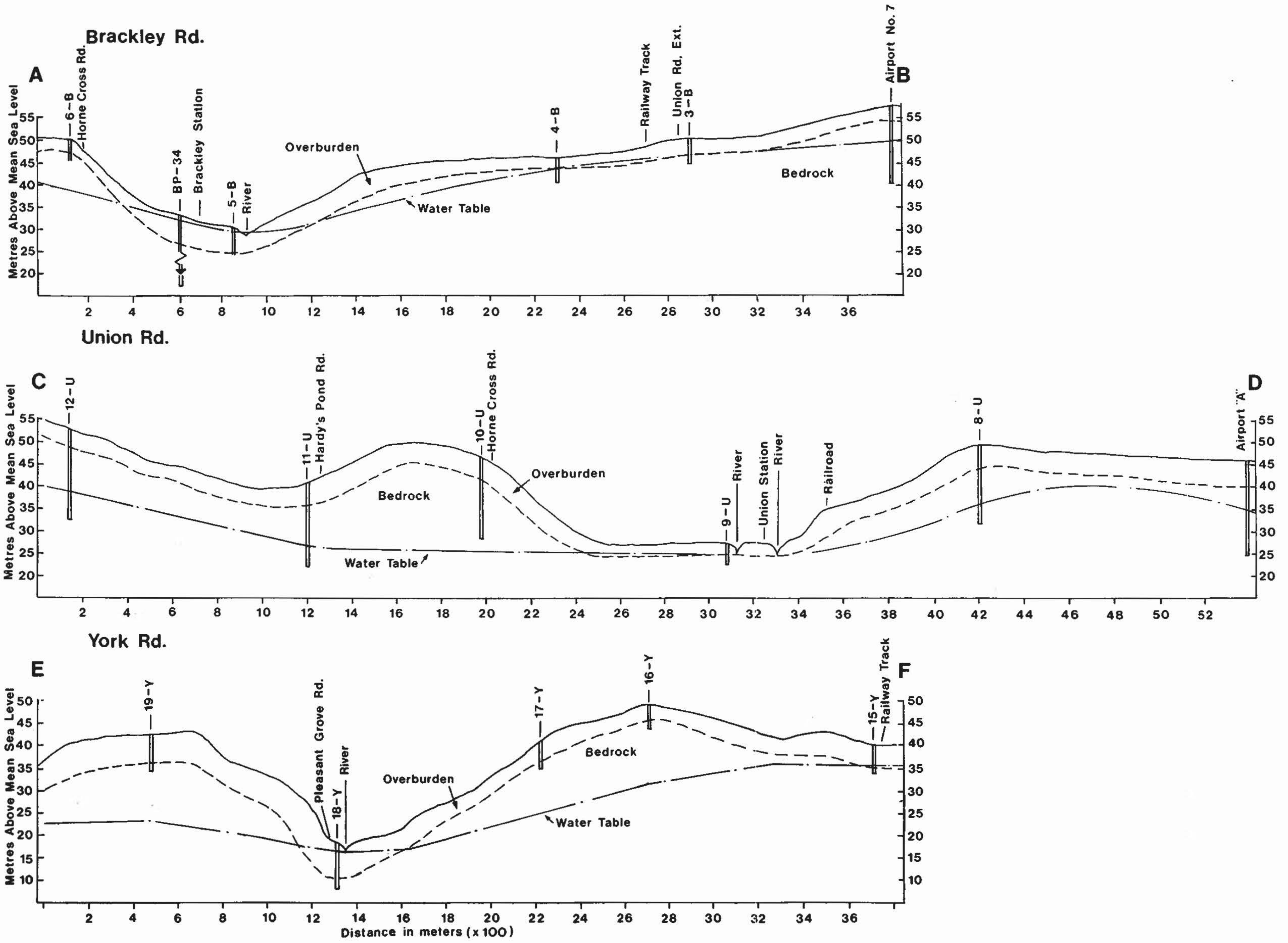


Figure 16. Cross sections A-B, C-D, and E-F (Figure 11) showing overburden, bedrock and water table positions.

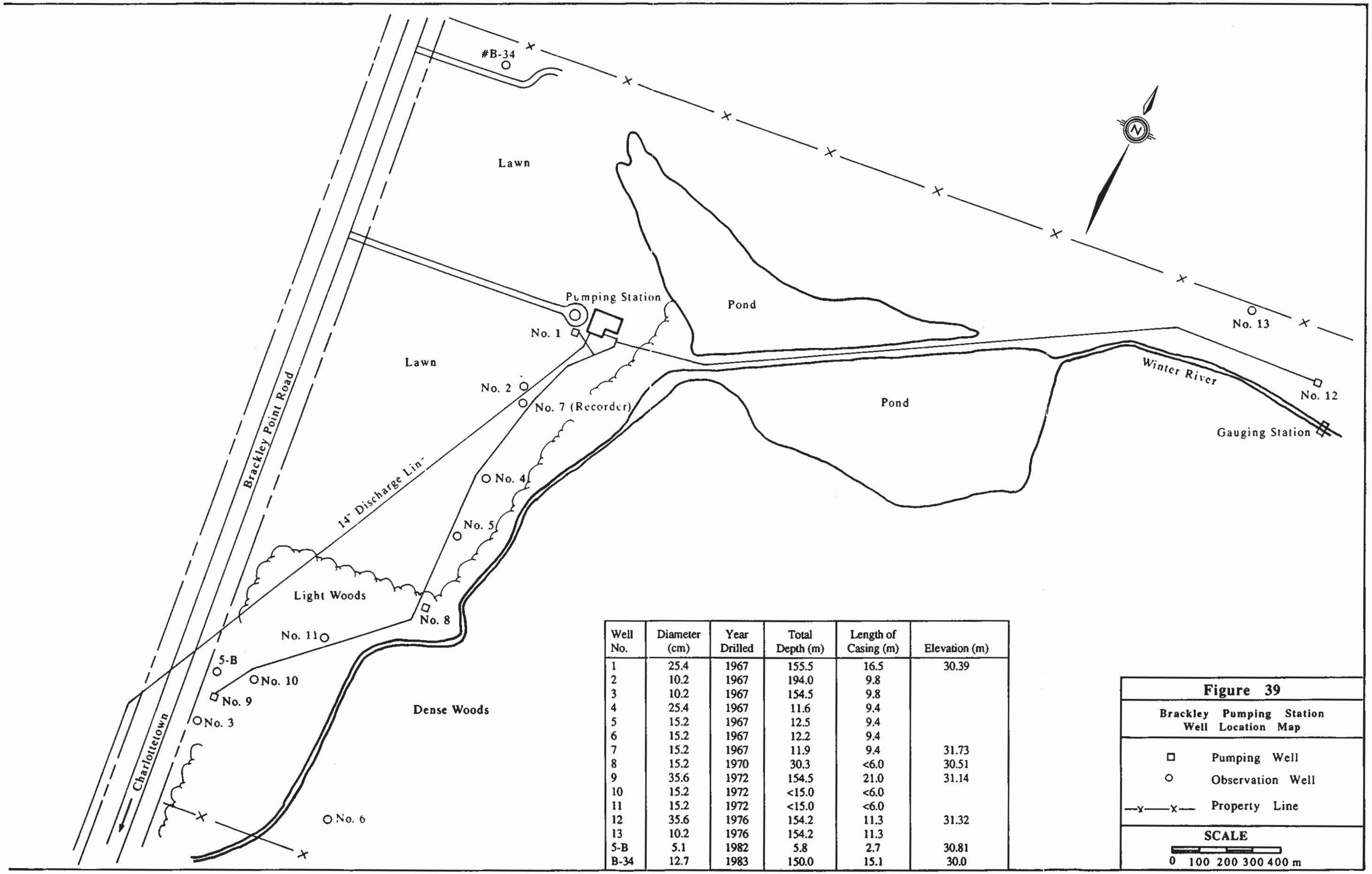
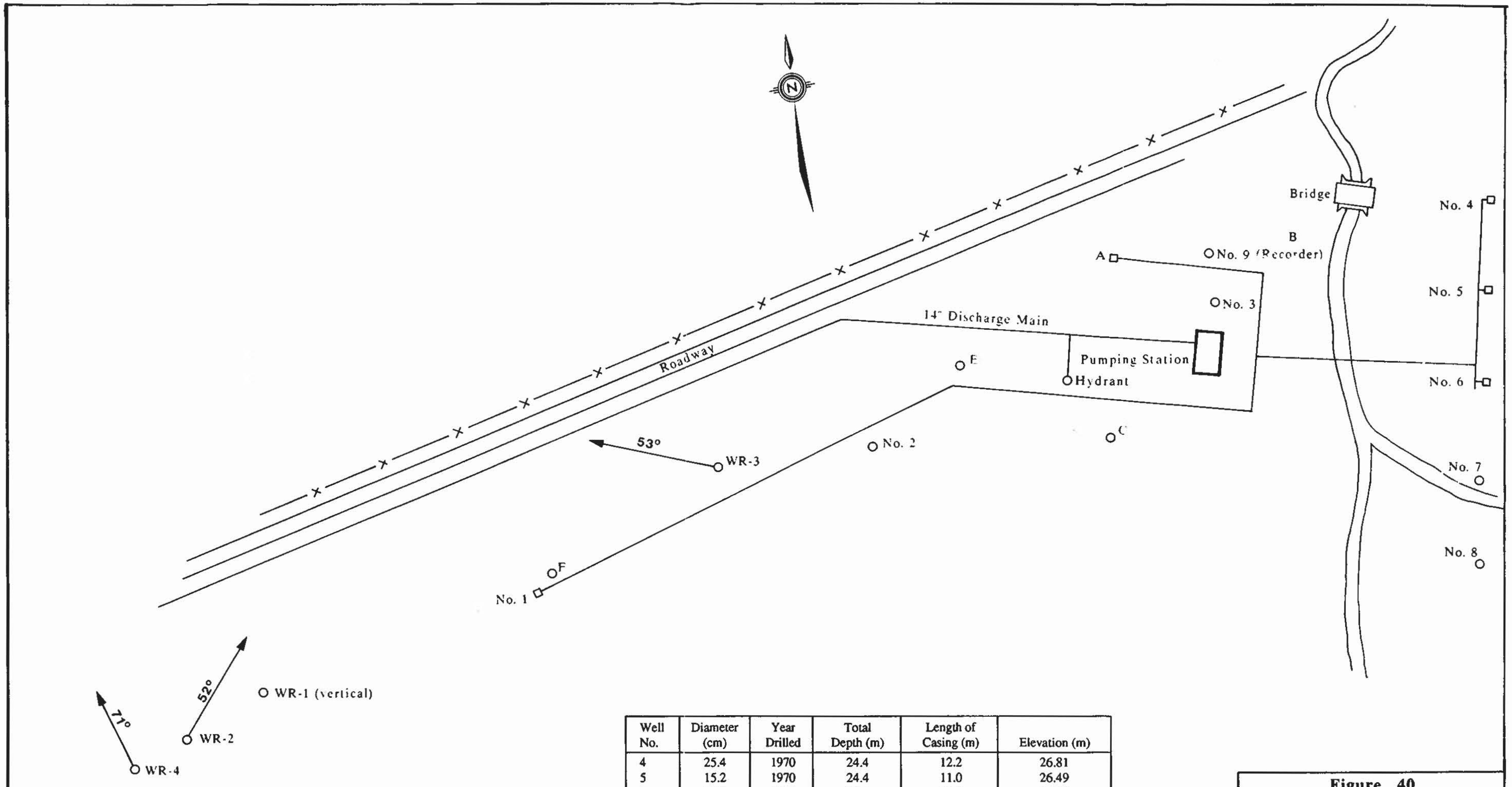


Figure 39

Brackley Pumping Station Well Location Map

Well No.	Diameter (cm)	Year Drilled	Total Depth (m)	Length of Casing (m)	Elevation (m)
1	25.4	1967	155.5	16.5	30.39
2	10.2	1967	194.0	9.8	
3	10.2	1967	154.5	9.8	
4	25.4	1967	11.6	9.4	
5	15.2	1967	12.5	9.4	
6	15.2	1967	12.2	9.4	
7	15.2	1967	11.9	9.4	31.73
8	15.2	1970	30.3	<6.0	30.51
9	35.6	1972	154.5	21.0	31.14
10	15.2	1972	<15.0	<6.0	
11	15.2	1972	<15.0	<6.0	
12	35.6	1976	154.2	11.3	31.32
13	10.2	1976	154.2	11.3	
5-B	5.1	1982	5.8	2.7	30.81
B-34	12.7	1983	150.0	15.1	30.0



Well No.	Diameter (cm)	Year Drilled	Total Depth (m)	Length of Casing (m)	Elevation (m)
4	25.4	1970	24.4	12.2	26.81
5	15.2	1970	24.4	11.0	26.49
6	15.2	1970	24.4	13.1	25.68
7	15.2	1970	24.4	11.3	26.07
8	15.2	1970	24.4	12.2	26.07
9	15.2	1977	24.4	12.2	27.32
A	25.4	1977	24.4	12.2	27.68
B	10.2	1977	24.4	12.2	26.05
C	10.2	1977	24.4	12.2	27.05
E	10.2	1977	24.4	12.2	27.5
F	10.2	1977	24.4	12.2	27.14
1	25.4	1970	132.6	31.4	27.08
2	15.2	1970	131.7	30.5	27.42
3	25.4	1970	132.3	23.8	26.92
WR-1		1981	76.2*	6*	26.54
WR-2		1981	76.2*	6*	26.39
WR-3		1981	76.2*	6*	27.21
WR-4		1983	76.2*	6*	26.49

*Length along Borehole

Figure 40

Union Pumping Station Well Location Map

□	Pumping Well
○	Observation Well
—x—x—	Property Line
○↘	Arrow shows direction and inclination of corehole in degrees from horizontal.

SCALE

0 50 100 150 200 m

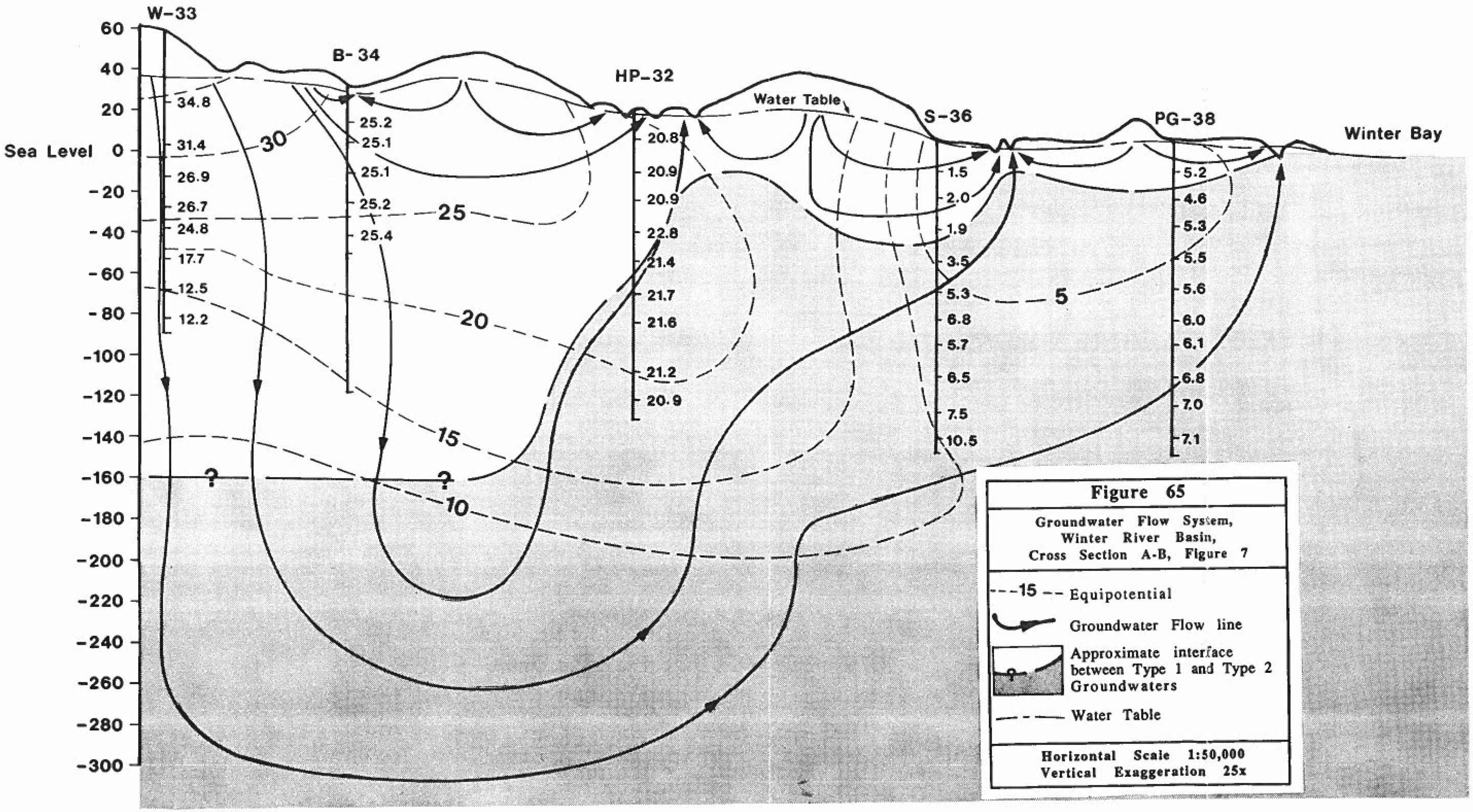


Figure 65

Groundwater Flow System, Winter River Basin, Cross Section A-B, Figure 7