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**LA THÈSE A ÉTÉ
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AN INVESTIGATION OF THE GROUNDWATER RIDGING THEORY
FOR LARGE GROUNDWATER CONTRIBUTIONS TO STREAMS
DURING STORM RUNOFF EVENTS

A Thesis
Submitted to the Faculty of Graduate Studies Through the
Department of Geology and Geological Engineering
in Partial Fulfilment of the Requirements for the Degree of
Master of Applied Science at the
University of Windsor



by

Bruce A. Wilson

Windsor, Ontario
1981

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CHAPTER 1

INTRODUCTION

1.1.0 The problem

Most of the current theories for storm runoff generation in streams relegate groundwater to a minor role in the production of storm runoff. They contend that as a result of its inherent low subsurface velocities, groundwater is unable to increase in discharge rapidly enough to participate greatly in the rapid response of stream levels to precipitation.

However, recent studies by Sklash et al (1976), Sklash and Farvolden (1979), O'Brien (1980) and others contend that in many cases groundwater is the dominant storm runoff component.

The problem, then, is the inability of present runoff generation theories to account for the large amounts of groundwater that have been shown to exist in storm runoff.

There is, therefore, a need to re-examine the existing theories of runoff generation in streams, and the nature of the response of watersheds to storm events in order to arrive at a model that will explain the apparent groundwater domination of storm runoff.

1.2.0 Significance of the Problem

The significance of the groundwater domination of storm runoff lies not in the quantitative aspects of storm runoff, which existing models can simulate but in the qualitative

aspects of storm runoff. For example Lynch and Ryan (1980) found that present dilution models failed to account for the

2

chemical behaviour observed during storm runoff in a watershed in Vermont. They subscribe to the general belief that the overall quality of stream flow should improve during storm runoff as dissolved species in the stream water are diluted by rainfall.

Several studies have demonstrated that the dilution of stream water chemistry during storm runoff events is much less than anticipated, suggesting that the baseflow contribution to storm runoff is greater than it was previously thought to be (Pinder and Jones, 1969; Nakamura, 1971). A recent study by Sklash et al (1978) showed that nitrate concentrations in streams can increase during stormflow as a result of an increase in the discharge of nitrate enriched groundwater.

The groundwater ridging theory (Sklash and Farvolden, 1979) is a new theory which may be able to explain these observations. If the groundwater ridging theory is valid, then the quality of groundwater in near-stream areas will have to be assessed in order to predict potential effects on the quality of streamflow.

1.3.0 Objective of this study

The objective of this study is to monitor the response of the near-stream groundwater table to rain events in an attempt to determine the validity of the groundwater ridging theory proposed by Sklash and Farvolden (1979). This theory is an

attempt to reconcile the large groundwater component observed during runoff events with the physical response of a watershed to storm events. Hydrometric techniques were used to collect data on the physical response of the groundwater table in relation to its proximity to a discharge area. Details on the method of study can be found in Chapter 3.

CHAPTER 2

A REVIEW OF PRESENT THEORIES FOR STORM RUNOFF GENERATION

2.1.0 Introduction

The three basic theories of storm runoff generation according to Freeze (1974) are:

1. partial area overland flow
2. variable source area subsurface storm flow, and
3. variable source area overland flow.

These theories meet the two major requirements for generating storm runoff: rapid conversion of rain to runoff in the stream and a low yield of runoff from rainfall. In addition to the above theories are the Hortonian overland flow, channel interception, groundwater flow and groundwater ridging theories of storm runoff generation. All of these theories will be reviewed briefly in the following sections.

2.2.0 Partial area overland flow

Linsley et al (1958) define overland flow as water which travels over the ground surface to a channel. The partial area overland flow theory suggests that overland flow does not commonly occur throughout a watershed, but instead occurs only in small, fixed, isolated areas of the watershed where the soil has become saturated from above by rainfall (Figure 2.1). The partial areas regularly contribute overland flow to the stream, whereas other areas seldom or never do (Freeze, 1974).

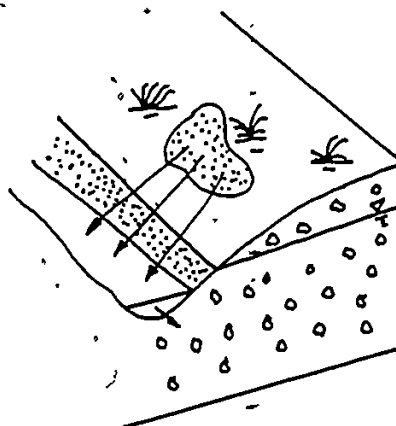


Figure 2.1 Block diagram showing the partial area overland flow concept.

The partial areas can be located anywhere in a watershed but are usually associated with soils that have a shallow A horizon.

The partial area overland flow theory was first suggested by Betson (1964). Studies by Ragan (1968), Betson et al (1968), Betson and Marius (1969) and Weyman (1970) support the partial area overland flow theory. These studies have concluded that Hortonian overland flow is a rare occurrence in humid, vegetated basins and that storm runoff originates from small but consistent portions of the watershed that usually make up 1-3% of the basin area (Freeze, 1974).

2.3.0 Variable source area subsurface storm flow

According to Hewlett and Nutter (1970), the variable source area subsurface storm flow theory suggests a process by which an expanding channel network reaches out to tap subsurface flow systems that have exceeded their capacity to transmit subsurface flow (Figure 2.2). The expanding channel allows relatively slowly moving subsurface flow to reach the channel in time to contribute to, and to sustain the storm runoff. The subsurface flow occurs either as Darcian flow through the soil matrix or as turbulent flow through soil cracks, root channels and animal burrows (Gaiser, 1952). The expanding channel concept of Hewlett and Nutter (1970) is shown in Figure 2.3.

Studies by Hewlett (1961), Hewlett and Hibbert (1963,

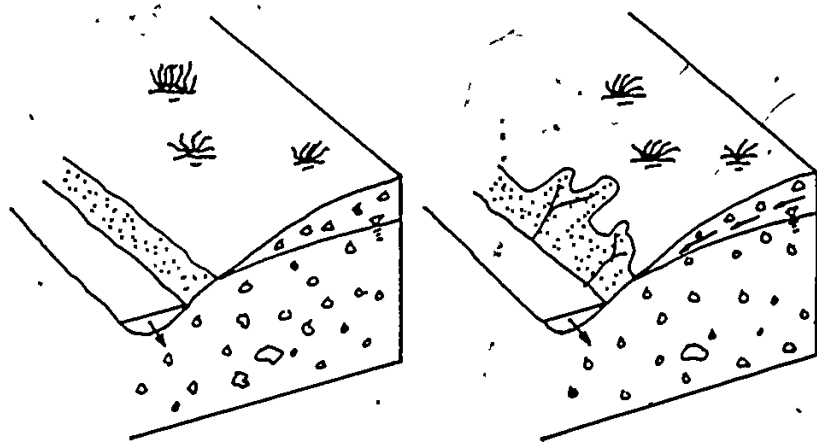


Figure 2.2 Block diagram showing the variable source area subsurface flow concept.

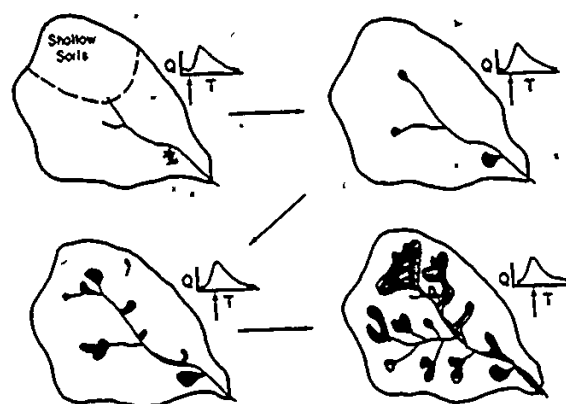


Figure 2.3 Variable source area concept expanding channel system (after Hewlett and Nutter, 1970)

1967) and Hewlett and Nutter (1970) have concluded that the majority of storm runoff in humid, vegetated areas is the result of variable source area subsurface storm flow. However, there is still considerable doubt as to the ability of this mechanism to generate sufficient amounts of runoff quickly enough to produce observed storm hydrographs. Dunne and Black (1970a,b) stated that subsurface storm flow contributions were too small, too late and too insensitive to fluctuations of rainfall intensity to add significant amounts of water to storm flow in the channel. This argument has been supported by Freeze (1972a,b), Engman and Rogowski (1974) and Dunne et al (1975).

2.4.0 Variable source area overland flow

Most of the recent studies on storm runoff generation, such as Dunne and Black (1970a,b), Freeze (1972a,b), Freeze (1974) and Dunne et al (1975), have concluded that variable source area overland flow is the major source of storm runoff. According to the variable source area overland flow theory, runoff is produced from areas that have become saturated from below by a rising water table (Figure 2.4). These areas, located adjacent to the stream, expand and contract in response to climatic conditions. Rain falling on these saturated areas flows overland to the stream along with return flow that is discharged at these areas. Return flow is subsurface flow that has returned to the surface before

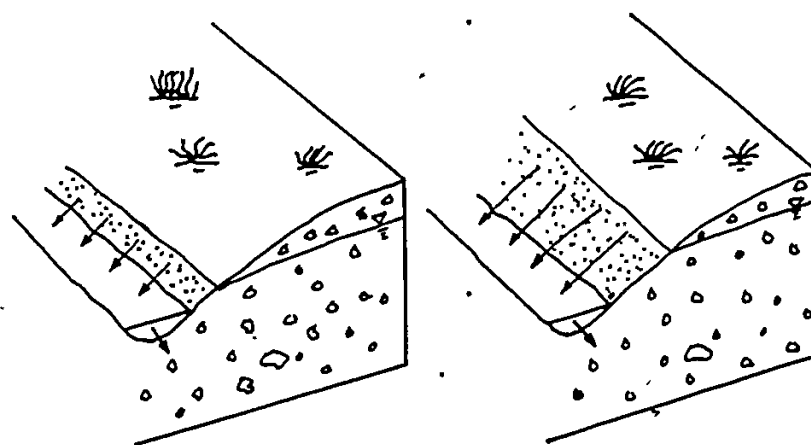


Figure 2.4 Block diagram showing the variable source area overland flow concept.

reaching the stream channel (Whipkey and Kirkby, 1978). The proportions of rainfall and return flow in the overland flow have not yet been firmly established.

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2.5.0 Hortonian overland flow

The Hortonian overland flow concept is based on the theory that the infiltration rate at the ground surface will decrease with time and eventually reach a steady state during rain. If the amount of precipitation exceeds this steady state of infiltration, overland flow will occur as the soil becomes saturated from above (Horton, 1933) (Figure 2.5). According to this theory, most storms produce overland flow and it is assumed to be a widespread occurrence within the drainage basin. Recent field studies have confirmed that Hortonian overland flow is a rare occurrence in humid, vegetated basins (Ragan, 1968; Betson et al, 1968; Weyman, 1970; Freeze, 1974).

Freeze (1974) provides a detailed argument to show that Hortonian overland flow should be a rare occurrence.

True Hortonian overland flow may occur in areas where vegetation is sparse such as arid areas, or where frost or permafrost create areas with low infiltration capacities. Paved areas in urban centres provide the most commonly seen examples of Hortonian overland flow.

2.6.0 Channel interception

Channel interception is generally considered to be a

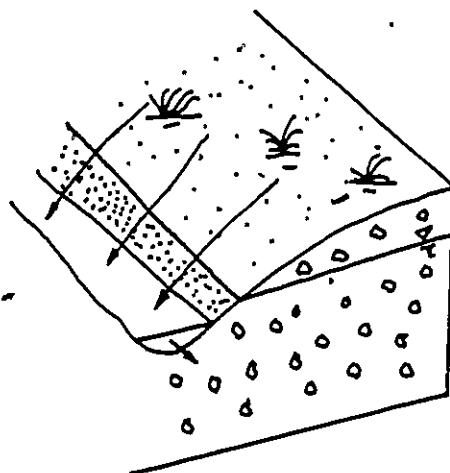


Figure 2.5 Block diagram showing Hortonian overland flow.

minor contributor to storm runoff during most storm events (Figure 2.6). It may be important during brief storms following periods of drought when other runoff generation mechanisms are least likely to respond significantly (Sklash, 1978).

2.7.0 Groundwater flow

According to Freeze (1974), groundwater flow is the portion of a stream's inflow that comes from water that enters the permanent groundwater flow system and discharges into the stream channel. Groundwater can discharge directly into the stream channel, through near-stream springs or through seepage faces along the stream bank (Figure 2.7). A seepage face is that portion of the stream bank which is above the water level of the stream and below the point where the water table intersects the stream bank.

Groundwater flow has been thought to mainly sustain base flow during periods between storms and contribute little to storm runoff. The baseflow response of a watershed was discussed by Freeze (1971) who found that baseflow contributions increased only after infiltration of the rain had produced a widespread rise in the water table. Figure 2.8 shows Freeze's theoretical baseflow hydrograph. Freeze (1972a,b) discussed the role of groundwater flow in generating baseflow and storm runoff.

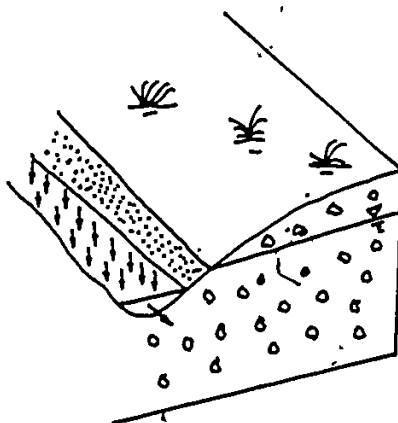


Figure 2.6 Block diagram showing channel interception.

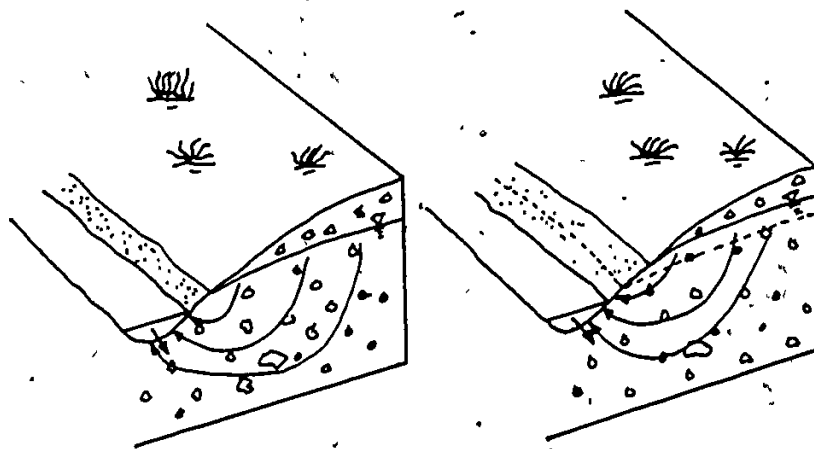


Figure 2.7 Block diagram showing traditional groundwater flow concept.

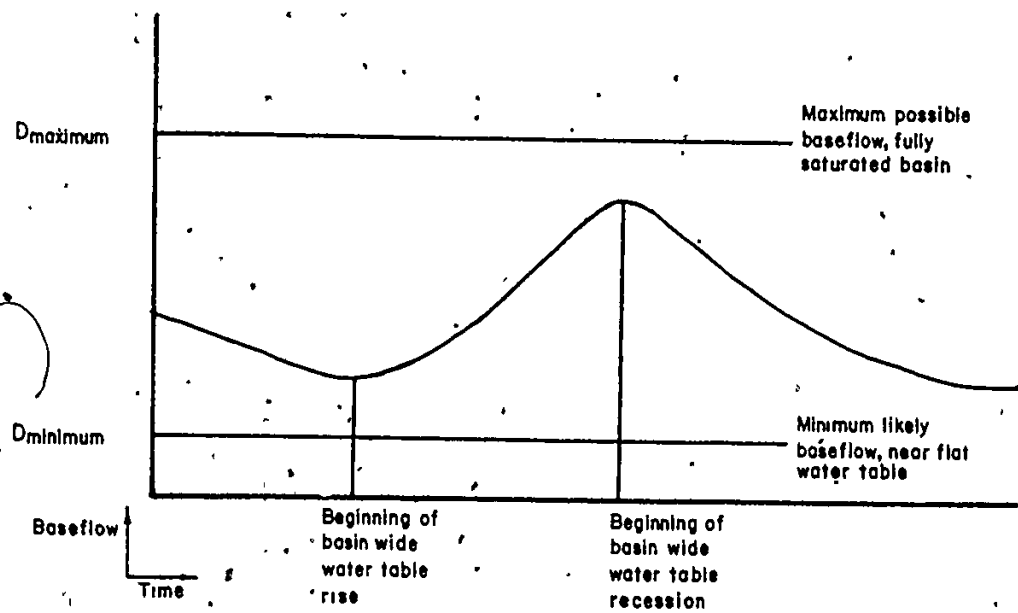


Figure 2.8 Baseflow hydrograph (after Freeze, 1971)

2.8.0 Groundwater ridging theory

2.8.1 Evidence of groundwater response to storm events

~~Evidence that groundwater discharge may be an important~~
contributor to streamflow has been reported by Dincer et al (1970), Martinec et al (1974), Martinec (1975), Fritz et al (1976), Sklash et al (1976), Sklash and Farvolden (1979) and others. Using oxygen isotopes, other isotopes and chemical techniques, these authors found that groundwater often dominated both storm runoff and snowmelt hydrographs. Sklash and Farvolden (1979) also observed rapid increases in groundwater levels and hydraulic gradients near the stream during most of the storm events they monitored.

The chemical techniques used most often in runoff studies are the analysis of total dissolved solids (TDS) and of electrical conductivity. Pinder and Jones (1969) used analyses of total chemistry in the stream to determine the groundwater component of runoff in three small watersheds in Nova Scotia. Analyses of runoff using these methods showed that TDS, conductivity and certain chemical species in the stream were not diluted as much as would be expected if rain water flowing overland to the stream was the major source of the storm runoff. The smaller than expected dilution values suggest that groundwater may be an important contributor to storm runoff.

Isotopic evidence of the large groundwater component in storm runoff has been based most commonly on the results of oxygen-18 (O^{18}) analyses. Analyses of deuterium (D) and

tritium (T) have also been used with similar results. Isotopic evidence is more reliable than the chemical parameters because the concentration of the isotopes is generally very uniform in shallow groundwater whereas the concentrations of the chemical parameters can be quite variable spatially (Freeze and Cherry, 1979). Also environmental isotopes such as O^{18} , D and T are conservative tracers because they do not undergo concentration changes unless mixed with another mass that is isotopically different (Fritz et al, 1976). Chemical tracers tend to change concentration when in contact with soil surfaces (Nakamura, 1971).

Separation of storm runoff hydrographs into groundwater and rain components can be made by determining the isotopic values of the precipitation, the groundwater (or baseflow) and the total runoff in the stream during storm events (Sklash et al, 1976). An example of this type of analysis is given in Figure 2.9 which shows a storm runoff hydrograph and δO^{18} values from a stream in Québec. Prestorm baseflow values of δO^{18} were approximately -12.00/00. The δO^{18} value of the rain was -8.30/00 and the δO^{18} value of the stream at peak discharge was -10.80/00. Using the mass balance equations for the water flux and isotopic content, these values indicate that groundwater contributed more than 65% of the peak discharge in the stream (Sklash and Farvolden, 1979).

Many authors have noted that the groundwater table in discharge areas often responds rapidly to rainfall and that

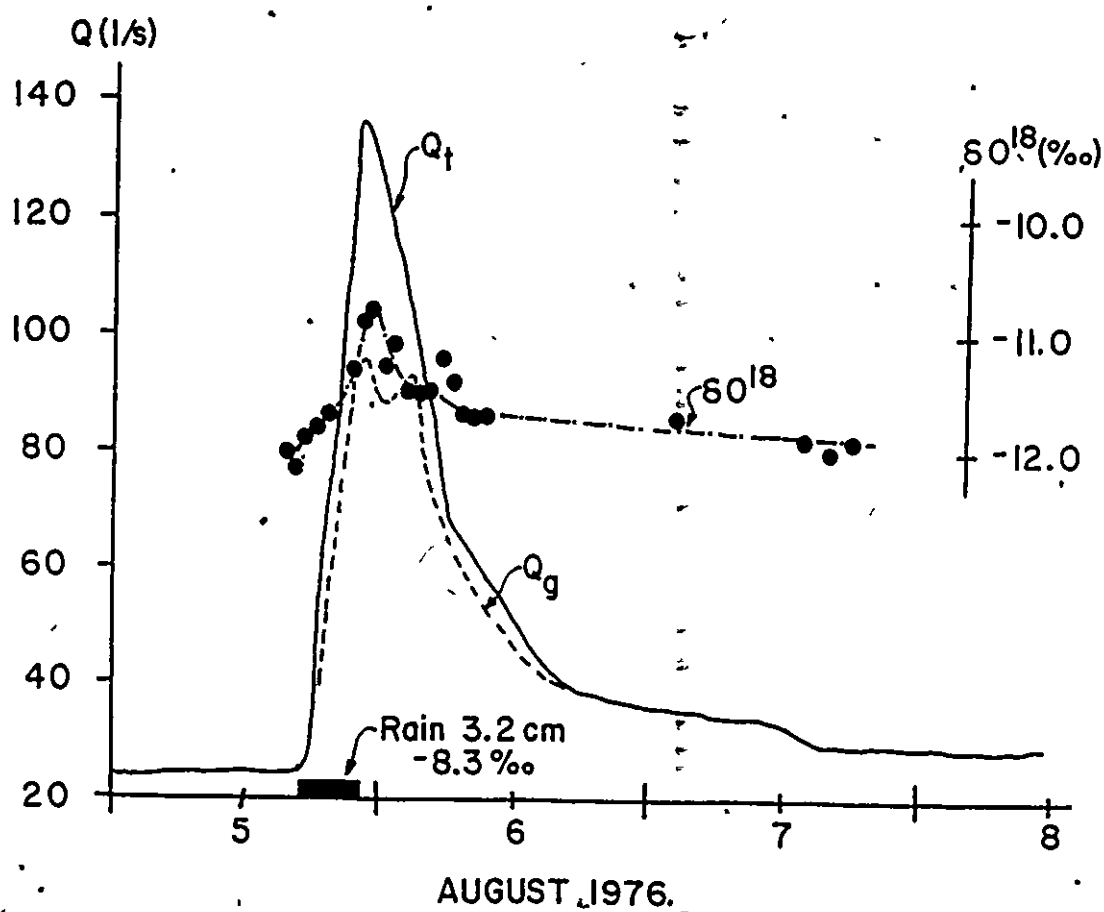


Figure 2.9 Storm runoff hydrograph and stream δO^{18} ,
Ruisseau des Eaux Volées, Quebec
(after Sklash and Farvolden, 1979)

the increase in storm runoff can be often related to a water table rise. Ragan (1968), in his studies of partial area contributions of a watershed in Vermont noticed "...a rapid

response of the groundwater at some points along the channel ...and... the formation of a ridge in the groundwater table along the length of the channel..."(after Ragan, 1968). Moser and Stichler (1975) thought that the rapid response of a river discharge in Ecuador to precipitation was the result of rainwater infiltrating and creating a "pressure wave" which acted upon the groundwater to increase groundwater discharge into the stream. O'Brien (1980) studied the role of groundwater in stream discharge and found that there was a rapid rise in the groundwater table, following precipitation, that was closely followed by a rise in stream levels.

2.8.2 The groundwater ridging theory

In an attempt to explain the apparent discrepancy between the existing theories of runoff generation which suggest that groundwater flow is an insignificant contributor to storm runoff in conflict with the observed large amounts of groundwater in storm runoff documented in tracer studies, Sklásh and Farvolden (1979) presented the groundwater ridging theory. The theory was stated by them as follows:

" Along the perimeter of transient and perennial discharge areas, the water table and its associated capillary fringe lie very close to the surface. Soon

after a rain or snowmelt event begins, infiltrating water readily converts the near-surface tension-saturated capillary fringe into a pressure-saturated zone or groundwater ridge (Ragan, 1968). This groundwater ridge not only provides the early increased impetus for the displacement of groundwater already in a discharge position, but it also results in an increase in the size of the groundwater discharge area which is essential in producing large groundwater contributions to the stream. The response of the upland area groundwater may become important at later times in the runoff but has little influence in the early part of the runoff event.

The groundwater may discharge directly into the stream through the stream bed or it may issue from the growing near-stream and/or remote seep areas and flow as overland flow to the stream (as in the variable source area overland flow theory). Following periods of drought during which the water table has fallen far below the ground surface, intense storms may result in surface saturation from above and rain-like overland flow (partial area overland flow) —before the water table can emerge."

Figure 2.10 is a block diagram showing the groundwater ridging concept.

Mathematical simulations of the response of four

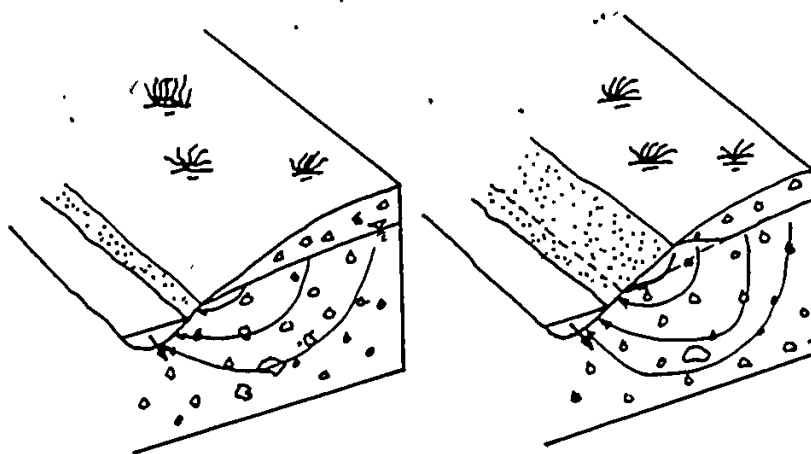


Figure 2.10 Block diagram showing the groundwater ridging concept.

hypothetical watersheds to precipitation were used by Sklash and Farvolden (1979) to support their theory. The four watersheds modelled had different near-stream relief and basin

width combinations. Figures 2.11 and 2.12 represent the discharge and water table responses of one of the watersheds to a rain event. The formation of a groundwater ridge near the stream can be seen. The groundwater ridge eventually disappears as the remainder of the basin responds to the rain event.

The groundwater ridging theory may be considered to be a refinement of the variable source area concept. The rise in the water table levels noted in the variable source area concept can be explained by the formation of the groundwater ridge. When the ridge reaches surface overland flow consisting mainly of groundwater occurs. However, unlike the variable source area concept, the groundwater ridging theory does not necessarily require that the water table emerge at the ground surface to produce overland flow during each storm event. The formation of the groundwater ridge increases the discharge area of the groundwater table, a response similar to the expanding channel concept, thereby allowing an increased groundwater discharge to the stream.

The groundwater ridging concept meets both of the constraints placed on storm runoff theories. It rapidly discharges water into the stream after the onset of rain, although it is not a conversion of rain to runoff, and its

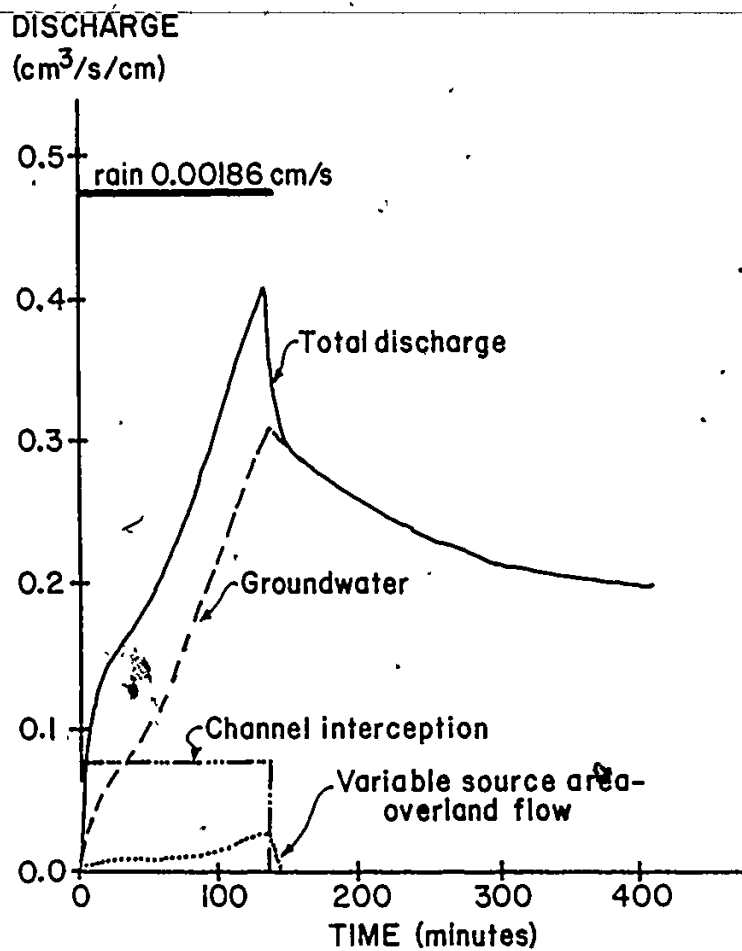


Figure 2.11 Computer simulation discharge hydrograph (after Sklash and Farvolden, 1979)

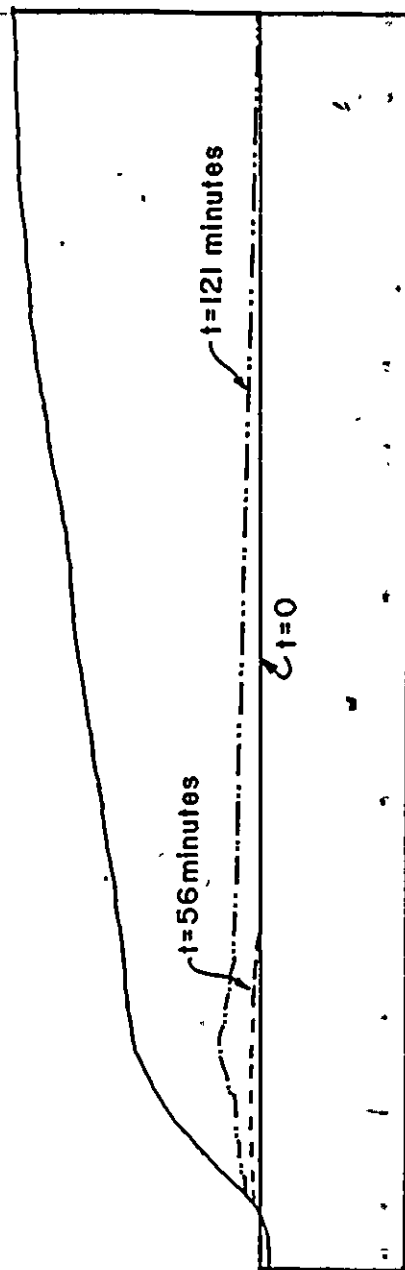


Figure 2.12 Formation of near-stream groundwater ridge in response to rain event (after Sklash and Farvolden, 1979).

yield of runoff is low since only a small portion of the watershed is involved in the process.

In summation the groundwater ridging theory offers an explanation of how groundwater can dominate storm runoff through the mechanism of increased discharge areas and increased hydraulic gradients near the stream.

CHAPTER 3

METHOD OF STUDY

3.1.0 Introduction

There are three major mechanisms that are thought to be able to create a rapid rise in the level of the groundwater table. Two of the mechanisms, the Lisse effect and the reverse Wieringermeer effect were first noticed and presented by Hooghoudt (1947) and were later discussed by Meyboom (1967). The third mechanism is the groundwater ridging theory.

The Lisse effect explains the rapid rise of the groundwater table noticed in some areas as the result of air entrapment during infiltration due to rain. Infiltrating rain creates a zone of inverse saturation in the soil which effectively seals off the soil from atmospheric pressure. As this wetting front moves down into the soil, pressure on the water table is increased to above atmospheric levels. This pressure increase results in the compression of the capillary fringe which releases water to the water table. The addition of water to the water table raises the level of the water table (Figure 3.1). The water levels gradually decline as entrapped air escapes laterally through the soil. Optimum conditions for the Lisse effect exist in light soils where the water table is less than 1.2 metres below ground.

The reversed Wieringermeer effect occurs in areas where the water table is so close to surface that the capillary

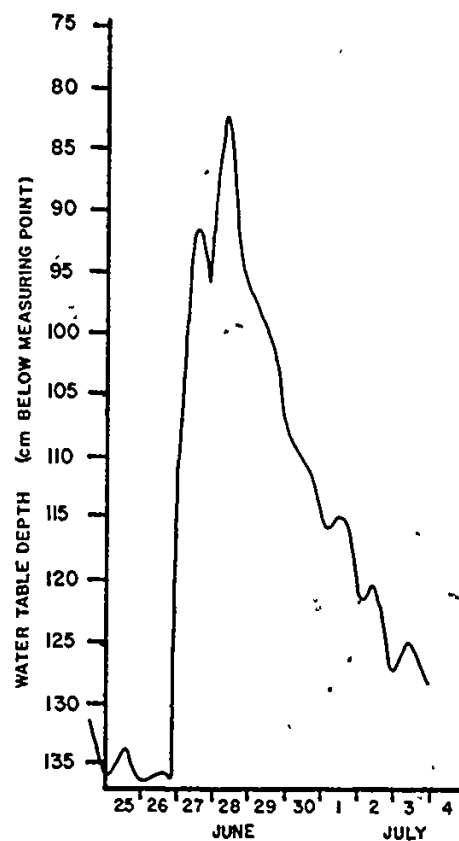


Figure 3.1 Water table response to Lisse effect (after Meyboom, 1967).

fringe reaches surface. Rain produces an almost instantaneous rise of the water table similar to the Lisse effect. The rapid rise, however is followed by an equally fast decline (Meyboom, 1967). Figure 3.2 shows an example of the reverse Wieringermeer effect.

The groundwater ridging theory explains the rapid rise of the water table as the instantaneous conversion of the tension saturated zone to a pressure saturated zone. The rapid rise of the water table is similar to that caused by the reverse Wieringermeer effect but it is not followed by the rapid decline of water levels. This conversion can be explained by the position of the tension saturated zone on the pressure-moisture content relation of soils (Figure 3.3). The capillary fringe is saturated under tension or negative water pressure. The addition of small amounts of water to this tension saturated zone will result in positive water pressure and the water table will rise to the top of the former capillary fringe as the capillary water is released. The groundwater ridging effect should be most noticeable in fine soils where the capillary fringe can easily reach 30 cm or more. The time delay from the start of the rain event to the groundwater ridging is related to the distance from the ground surface to the top of the capillary fringe.

3.2.0. Evidence of rapid water level increases

Field evidence of rapid water level increases following

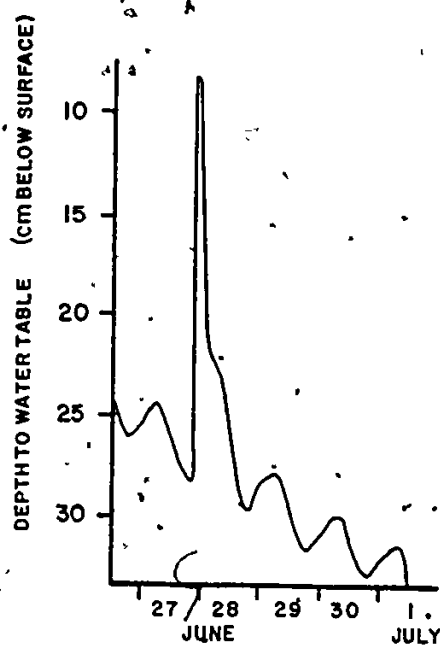


Figure 3.2 Water table response to reverse Wieringermeer effect (after Meyboom, 1967).

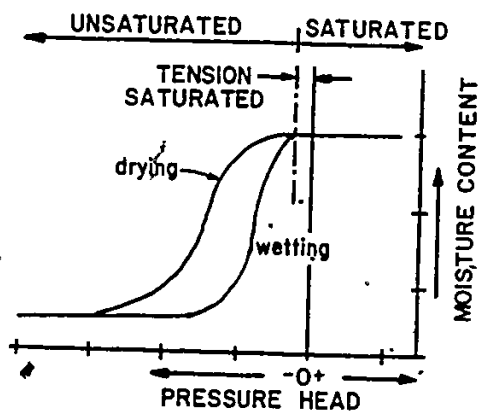


Figure 3.3 Typical pressure head-moisture content curve for a sandy soil.

storm events has been shown by Ragan (1968), Sklash (1978), O'Brien (1980) and others. Computer simulations of watershed response to rain events by Sklash (1978), Sklash and Farvolden

(1979) and Babu (1980) also demonstrate the rapid rise of the groundwater table in near stream areas during rain events.

An actual observation of the rapid rise in the groundwater table was made by the author during a hydrogeological field camp run by the University of Waterloo, Waterloo, Ontario at Canadian Forces Base Borden, Ontario in April 1980. A small diameter well was placed in the centre of an approximately one metre square depression in sandy soil where the water table was approximately 0.8 metre below surface. The addition of about four litres of water to the depressed area produced a rise of the water table of about 20 cm in one minute. The change from tension to pressure saturation was shown by tensiometers attached to pressure transducers.

3.3.0 Experimental approach

To determine if a groundwater ridge actually forms in the near stream area, it was decided to monitor the water table and capillary fringe of a near stream area. To detect changes in the water table level, small diameter wells equipped with automatic level recorders were used. Tensiometers, placed at depths varying from below the water table to just below ground surface, were installed to detect the change from a tension saturated zone into a pressure saturated zone.

The Ruisseau des Eaux Volées experimental basin in Québec (Chapter 4), was selected for study since the basin is well instrumented, the general response of this basin to rain

events has been documented, and it rains often. Sklash and Farvolden (1979) concluded that groundwater dominated the storm runoff events in the watershed. In addition, the site at which the instrumentation was installed for this study, resembled the conditions used by Sklash and Farvolden (1979) in one of their computer models.

3.4.0 Instrumentation

The water table wells were made from 25.4 mm OD/32 mm ID black steel pipe. Wells of this size were selected to optimize response time to fluctuations in the groundwater table. The wells were driven into the ground using a sledge hammer. Table 3.1 lists well data. Figure 3.4 is a section through the instrumentation site showing the locations of the wells. One well was placed in Ruisseau des Eaux Volées to act as a stream stage recorder (Photo 1).

The design of the water level recorders (Photo 2) is based on a design by Anderson and Burt (1978). The level recorders convert water level fluctuations into electrical signals using a float attached to a potentiometer. The float was attached to monofilament fishing line and was counterbalanced using clamp-on lead fishing sinkers. The line was looped around an aluminium wheel which was attached to a

	TOP	GROUND		DISTANCE
WELL	ELEV (mASL)	ELEV (mASL)	LENGTH (m)	FROM STREAM
1	731.14	729.26	2.13	in stream
2	730.20	729.85	1.52	1.83
3	730.63	730.06	1.52	3.66
4	730.62	730.33	1.52	6.611
5	730.83	730.42	1.52	8.53
6	731.07	730.60	1.83	11.07
7	731.50	730.74	1.83	14.33
8	731.26	731.03	1.83	16.76
9	731.50	730.89	1.83	20.03
10	732.01	731.50	1.96	23.29
11	732.63	732.09	2.13	26.69

Table 3.1 Well data

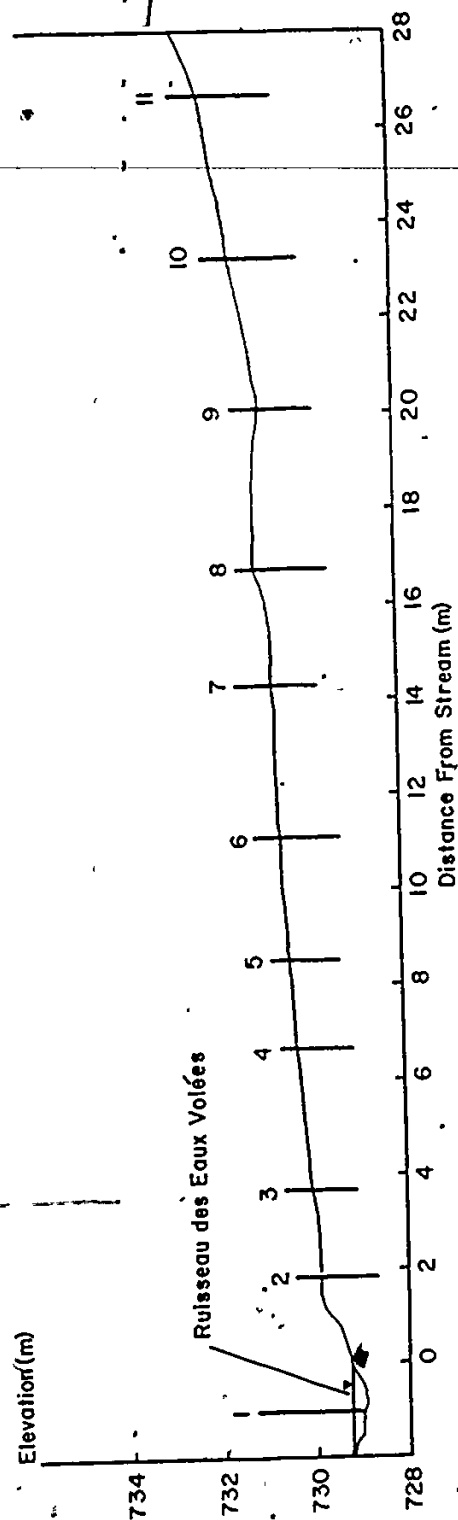


Figure 3.4 Section through instrumentation site showing location of wells.

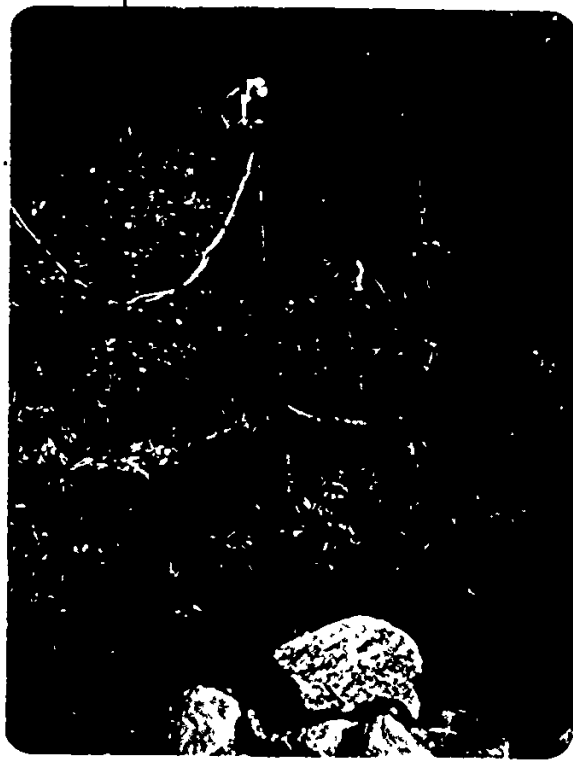


Photo 1 Stream stage recorder

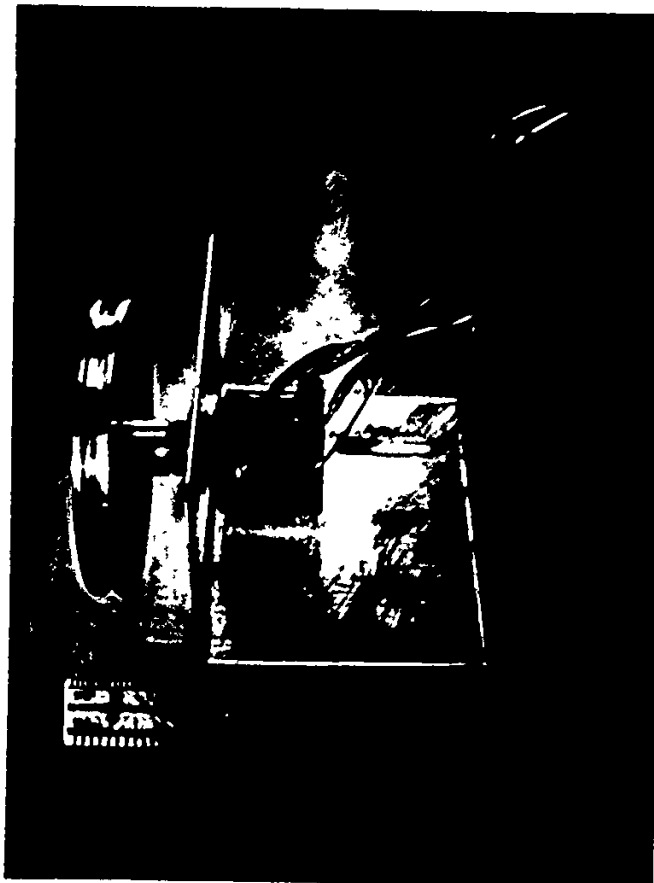


Photo 2 Water level recorder

low-torque, 10-turn, 1K-ohm potentiometer. As the float rises the resistance of the potentiometer is changed. The change in resistance changes the output voltage from the level recorder.

The output of the water level recorders was measured and recorded on a time-sharing, two channel chart recorder. The electrical circuit of the level recorders is shown in Figure 3.5.

The floats and water level recorders were constructed at an average cost of \$20 per unit. This is a considerable saving over the commercially available water level recorders that can cost more than forty times as much. The floats were 19 mm in diameter to fit inside the small diameter wells used. Floats of this size were not commercially available and had to be specially designed. An installed water level recorder is shown in Photo 3.

The tensiometers were made from 16.7 mm OD PVC pipe. Porous ceramic cups (Soil Test Model 655X1-B1M1) were cemented to the tubes after they had been cut to the desired length. The tensiometers were connected in sequence to a Druck model PDCR 26 pressure transducer by a 24 position scanivalve fluid switch (Scanivalve Model W0602/1P-24T). The fluid switch had the capability to be operated manually or automatically by a stepping relay controlled by the electronic timing circuit designed by the author (Figure 3.6). In the automatic mode of operation the relay is actuated at 2 minute intervals. The stepping relay also operated 1P-24T wafer switches that

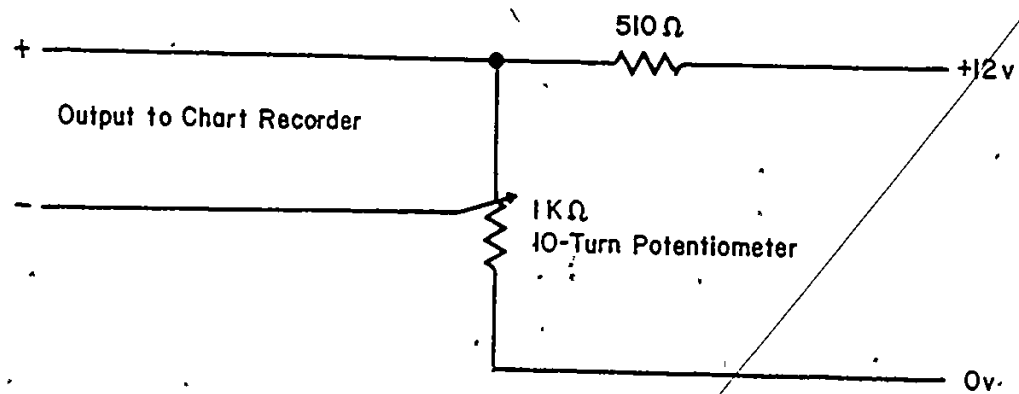


Figure 3.5 Circuit diagram of water level recorders



Photo 3 Installed water level recorder

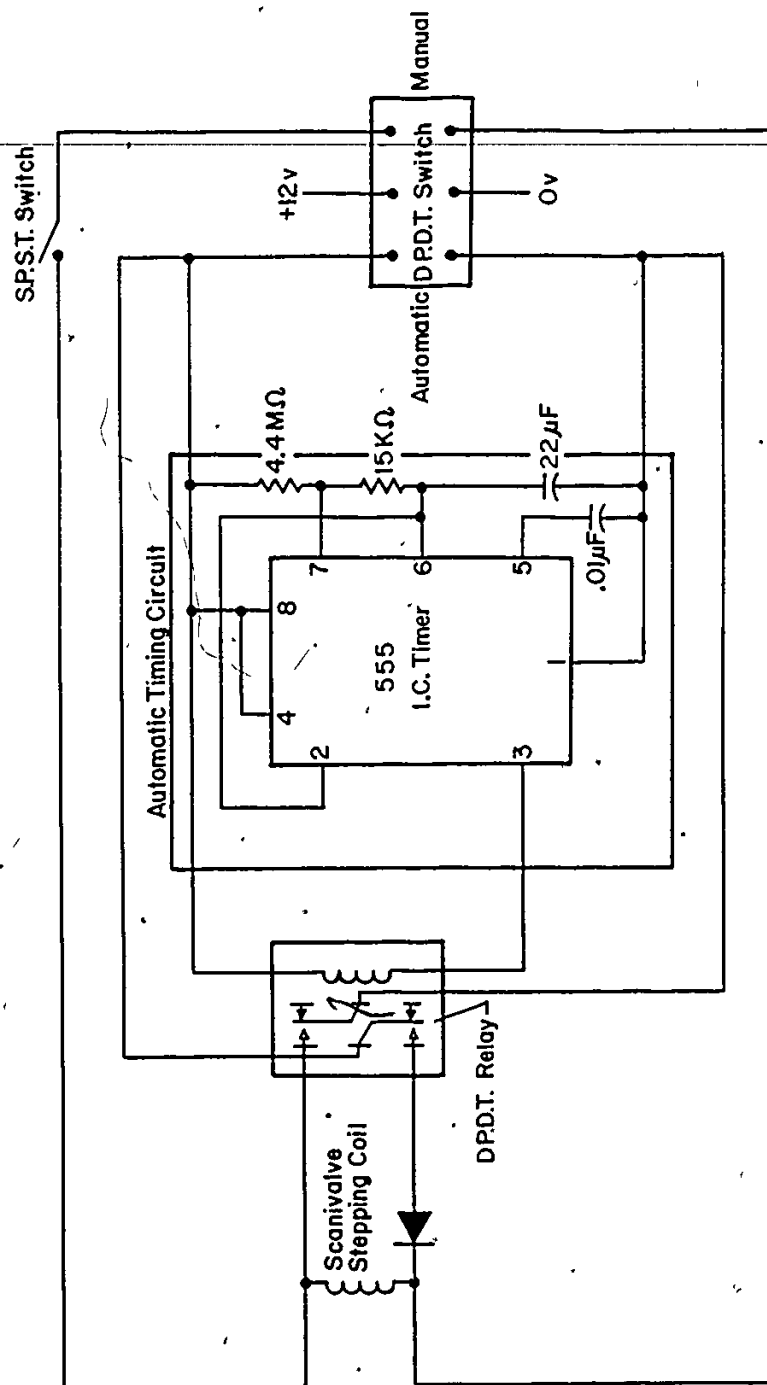


Figure 3.6 Circuit diagram of electronic timing unit

controlled the output from the water level recorders. The general layout of the monitoring system is shown schematically in Figure 3.7. The scanivalve system is shown in closeup in Photos 4a and 4b, and in the field in Photo 5. A bank of tensiometers is shown in Photo 6.

To record the output from the pressure transducer and the water level recorders, a Rustrack Model 388/F137 two channel strip chart recorder was used. This recorder is equipped with a time sharing mechanism that allows four channels to be recorded on pressure sensitive paper. The recorder and other instruments were powered by two 12 volt DC automobile batteries that were recharged every second day. The batteries, chart recorder and scanivalve were protected from rain and snow by the box shown in Photo 7.

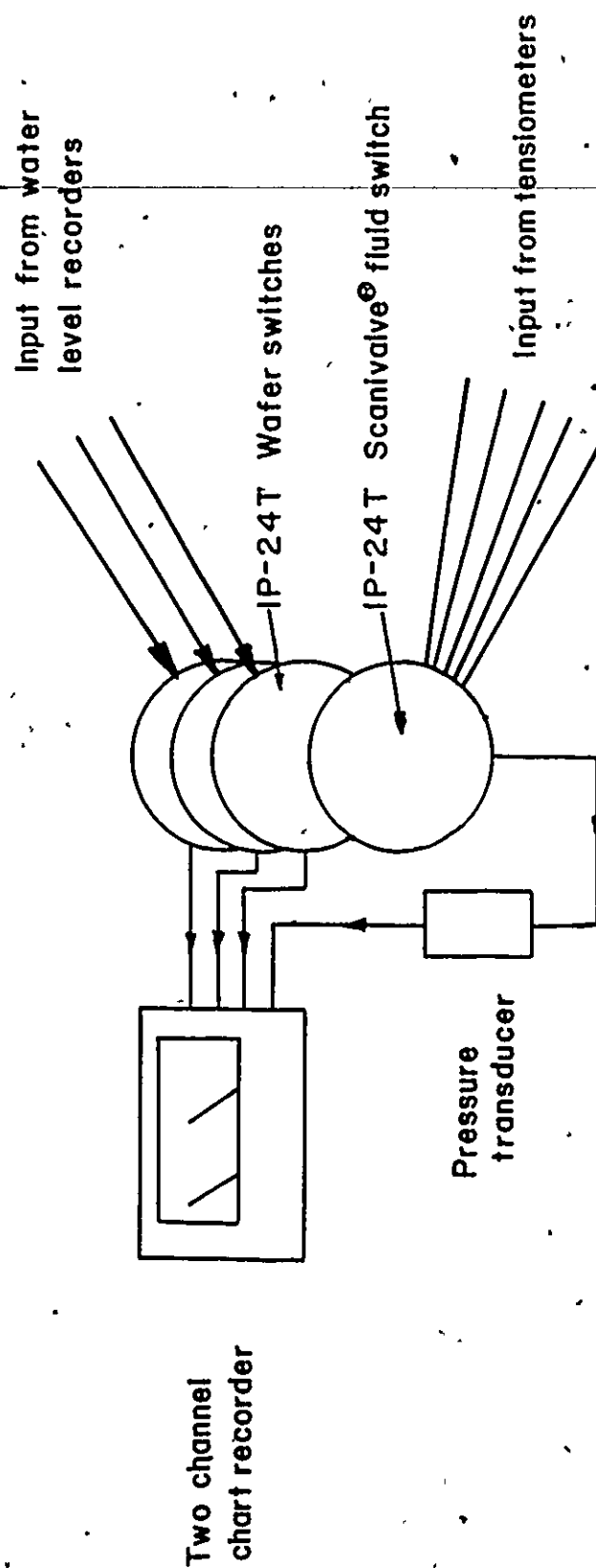


Figure 3.7 Schematic diagram of monitoring system.

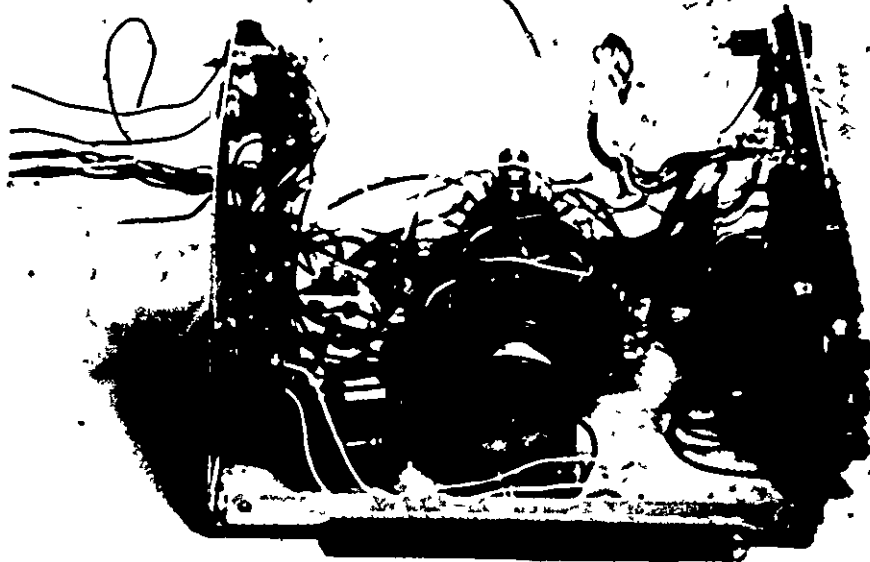
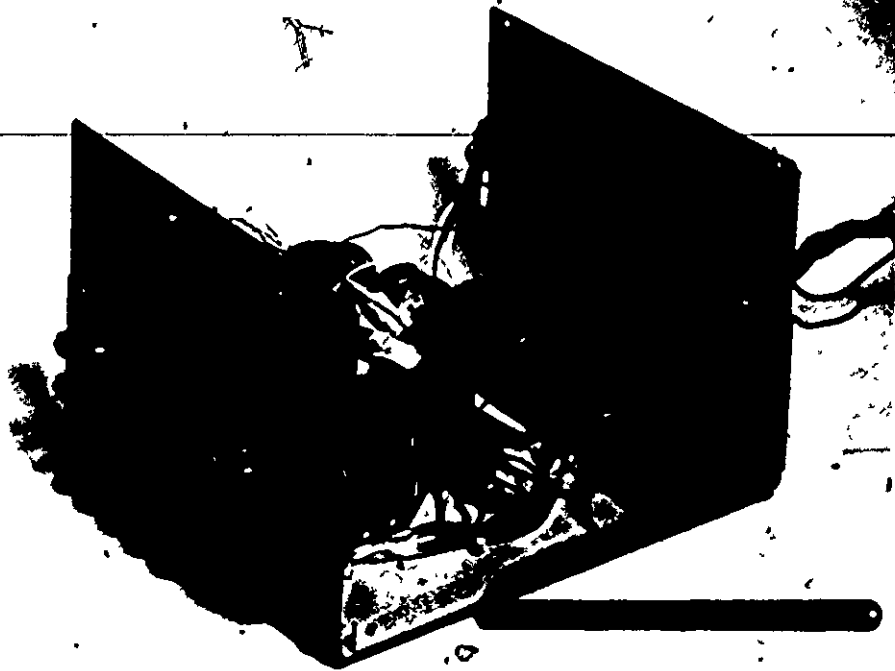


Photo 4a (top) Scanivalve unit

Photo 4b (bottom) Scanivalve unit



Photo 5 Scanivalve unit showing field connections



Photo 6 Tensiometer bank

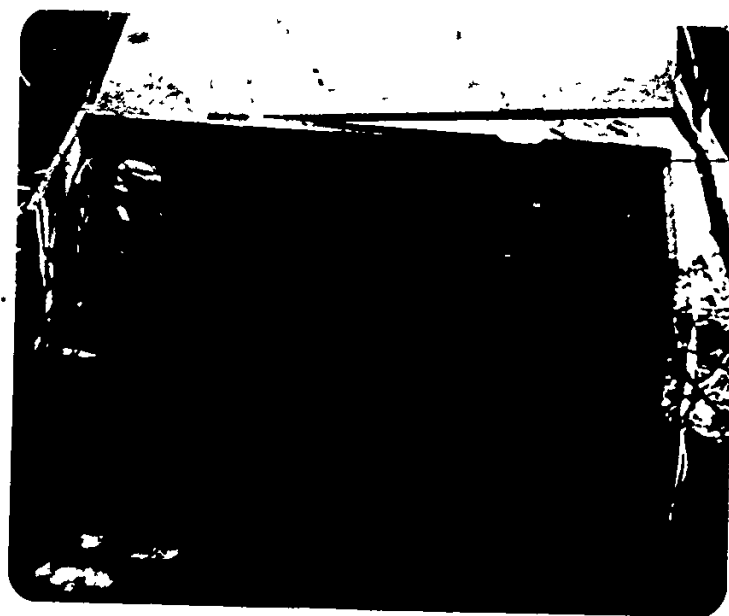


Photo 7 Instrument box

CHAPTER 4

RUISSEAU DES EAUX VOLÉES STUDY AREA

4.1.0 Location, access and history

The Ruisseau des Eaux Volées experimental watershed is located in Forêt Montmorency which lies in Laurentide Provincial Park in Québec (Figure 4.1). The basin is approximately 80 km north of Québec City, Québec and is most easily reached by following Provincial Highway 175 north from Québec City to Route 33 East. An all-weather gravel road, Chemin du Belvedere, which runs approximately north-south through the Ruisseau des Eaux Volées basin, provides access from Route 33.

The Ruisseau des Eaux Volées watershed was established for research in 1965, during the International Hydrologic Decade, as a cooperative project between Laval University and the Québec Ministry of Natural Resources. Studies in meteorology, hydrology, water quality, forest hydrology and hydrogeology have been initiated in the basin. The most comprehensive hydrogeological report on the basin to date is an M.Sc. thesis by Rochette (1971).

4.2.0 Physiography (Rochette, 1971; Plamondon and Naud, 1975)

Forêt Montmorency is typical of the Laurentian Uplands of the Canadian Shield. High hills with steep slopes are separated by U-shaped valleys trending north-south and hanging

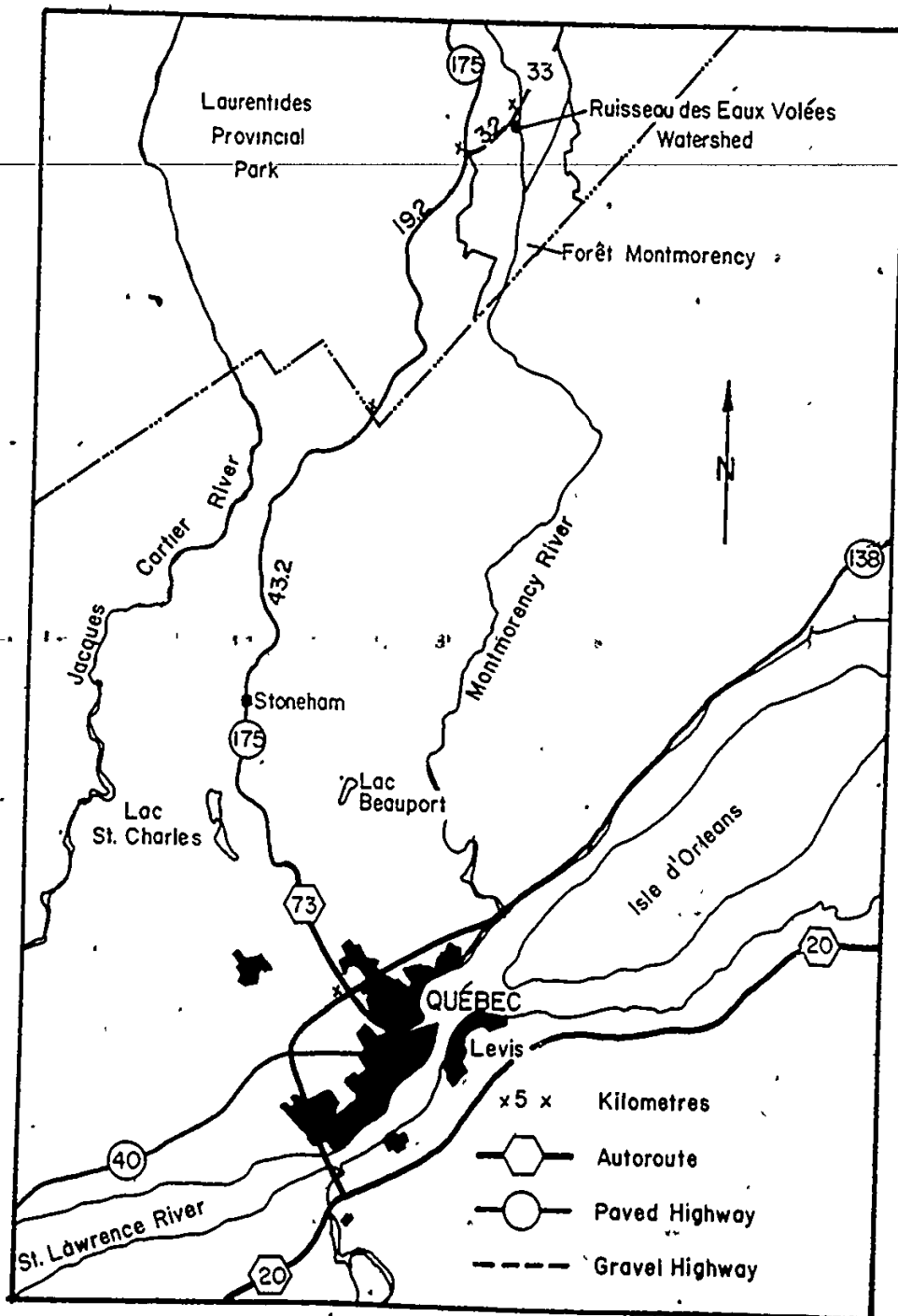


Figure 4.1 Location of Ruisseau des Eaux Volées experimental basin (after Plamondon and Naud, 1975)

valleys trending east-west. The hanging valleys are generally filled with glacial debris.

The Ruisseau des Eaux Volées watershed is a hanging valley tributary of the Montmorency River. The watershed covers an area of 9.2 km^2 and ranges in elevation from 1000 m at its summit to 550 m at its outlet (Figure 4.2). The boundary of the watershed is formed by hills except at the southeastern limit where glacial deposits form the divide and at the western limit where Lac Huppé occupies a shallow depression in a col near the divide. On rare occasions Lac Huppé discharges into Ruisseau de Eaux Volées as the result of beaver activities.

Four sub-basins have been defined within the watershed (Figure 4.2). Sub-basins 7A and 7, which occupy 1.2 km^2 and 2.3 km^2 of forested land respectively, contain Ruisseau des Aulnaies which is a tributary of Ruisseau des Eaux Volées. Sub-basins 5 and 6, which occupy 1.7 km^2 and 3.9 km^2 of forested land respectively, contain Ruisseau des Eaux Volées. The physiographic characteristics of the watershed are summarized in Table 4.1.

4.3.0 Climate (Rochette, 1971; Plamondon and Naud, 1975)

The climate of Forêt Montmorency is the coldest and rainiest south of 50° North latitude in the province of Quebec. It can be classified as cool microthermal with water surplus (Thornwaite classification), or as moist cold

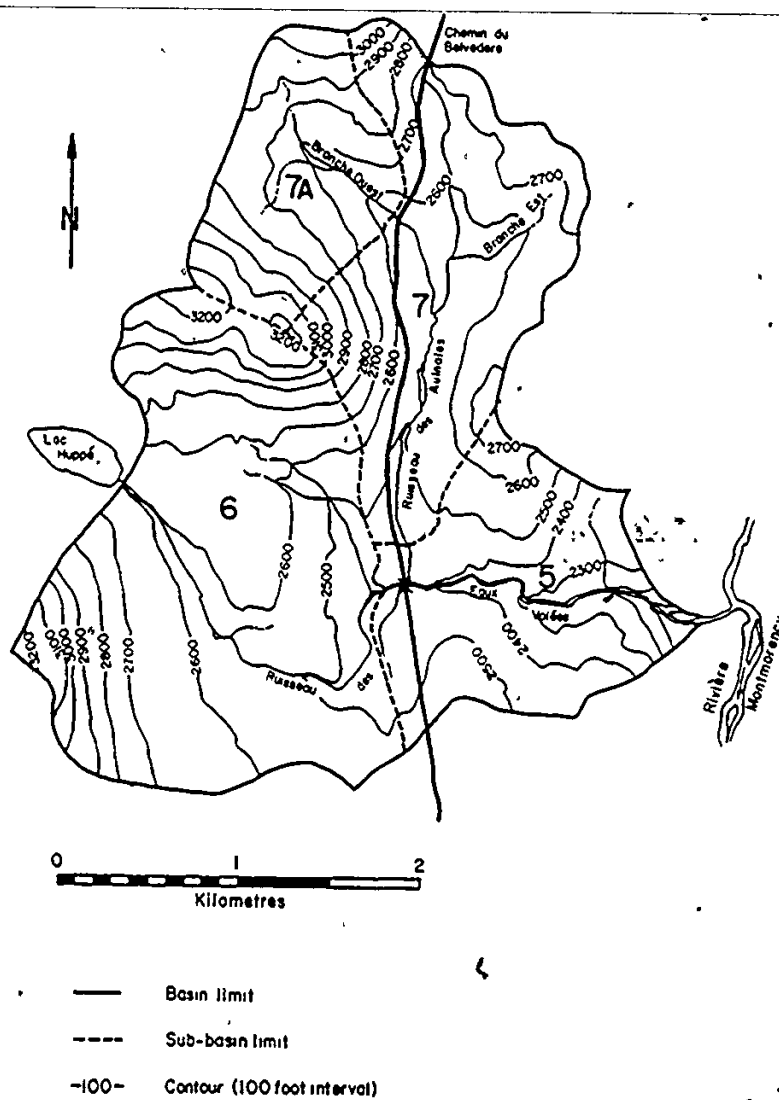


Figure 4.2 Topography of Ruisseau des Eaux Volées basin
(after Rochette, 1975)

SUB-BASIN	AULNAIES	AULNAIES	EAUX, VOLÉES	EAUX, VOLÉES
	(7A)	(7)	(6)	(5)
Station No.	51004	51007	51002	51003
Area (km ²)	1.26	2.33	3.94	1.68
Mean Elev (m)	875	806	823	810
Land Slope (%)	14.4	20.3	7.7	7.6
Drainage Density	2.16	1.85	1.71	2.42
Channel Slope (%)	9.7	3.0	2.3	2.2
Length (m)	1036	2940	2499	5090
Sinuosity	1.05	1.04	1.01	1.18
Area Lake (%)	0	0.15	0.03	0.04
Area Swamp (%)	0	1.9	0	0.46
Area Forest (%)	100	98.0	99.97	99.5

Table 4.1 Physiographic characteristics of sub-basins
(Plamondon and Naud, 1975)

temperate, without dry season and with short, cool summer (Köppen classification). The mean annual temperature is 0.2°C with the mean temperature of the coldest month (January) -14.9°C and the mean of the warmest month (July) 14.7°C .

The main meteorological station at Forêt Montmorency has been in operation since 1966. Observations from 1966 through to December 1974 serve as the basis for the following climatic characteristics. The maximum and minimum values given may have changed since 1974. Annual precipitation in the area averages 1453 mm, ranging from 1157 mm in 1968 to 1661 mm in 1974. The annual snowfall, which makes up approximately one-third of the total precipitation, averages 600 cm. The largest snowfall recorded prior to 1975 was 759 cm in 1973-74. On the average snowfall is observed during 111 days of the year. The mean number of days with precipitation is 213, ranging from 194 in 1967 to 232 in 1973 and 1974. The monthly averages for precipitation and temperature are shown in Figure 4.3. During the 1980 field season, snow was recorded on June 8 and 9.

4.4.0 Vegetation (Plamondon and Naud, 1975)

Commercial forest covers 95% of the area and non-commercial the remaining 5%. Approximately 70% of the basin is covered by second-growth forest under 50 years of age. Balsam fir, white birch and white spruce compose 80, 10 and 10% of the forest respectively. Some of the forest in sub-basin 6 has been logged on an experimental basis.

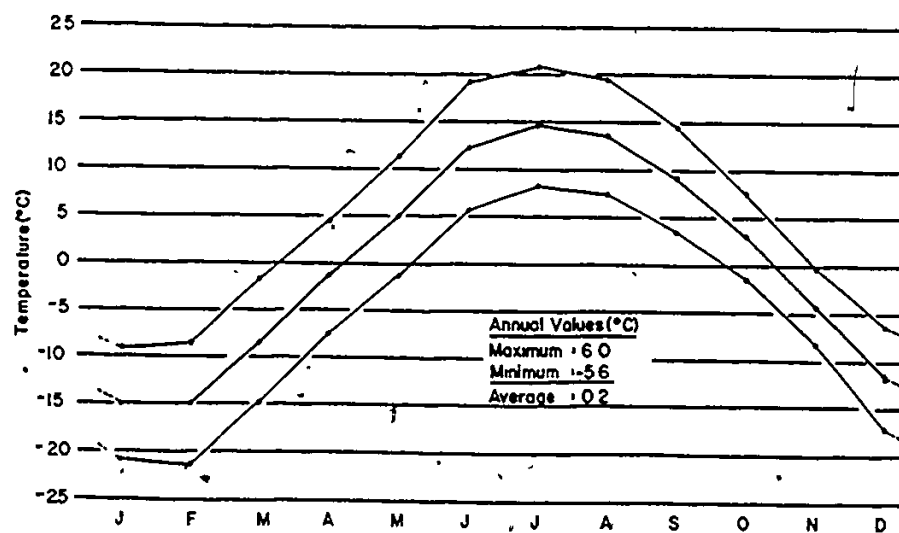
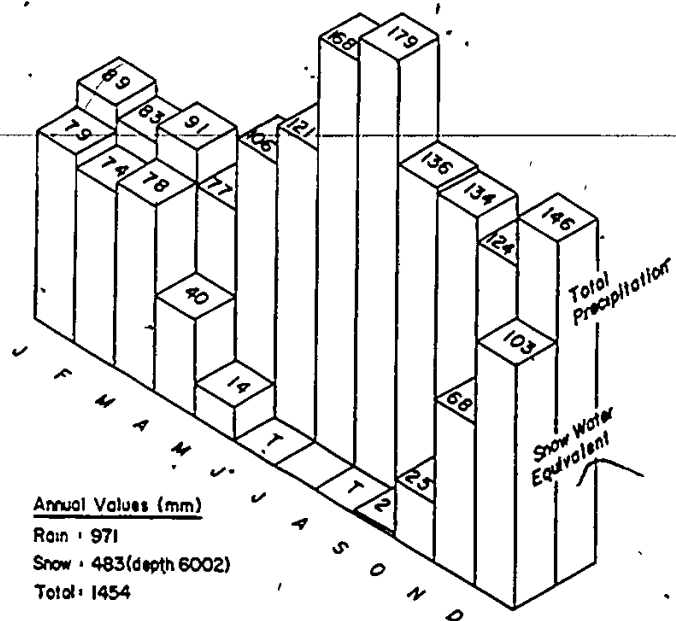


Figure 4.3 Monthly averages for precipitation and temperature
 Ruisseau des Eaux Volées basin (after Rochette,
 1971)

4.5.0 Geology (Rochette, 1971)

The Ruisseau des Eaux Volées basin is underlain by crystalline Precambrian rocks. Outcrops, which make up approximately 20% of the basin area, occur mainly in the higher areas of the basin. The bedrock of the basin is charnockitic gneiss. Vertical joints that are up to 7 cm wide at surface and generally filled with unconsolidated material, trend north-south and east-west. Core recovered during well-drilling indicates that fractured rock is found at depths up to 45 m in some areas of the basin. The weathered zone of the rock is generally a few centimeters thick.

The surficial geology of the basin is shown in Figure 4.4. The surficial deposits in the basin are of mainly glacial origin. These deposits cover approximately 80 % of the basin, with depths ranging from 1 to 20 m. Figure 4.5 is an isopach map of the surface deposits in the basin.

4.5.1 Glacial deposits

The glacial deposits in the basin are composed of ground moraine, washed till, contact drift and shallow drift over bedrock. The ground moraine, ranging from 1 to 10 m in thickness, is the basal unit throughout most of the basin. It is predominantly sand and gravel with some boulders, mostly of granitic origin, with a compacted layer on top.

The washed till, ranging from 1 to 7 m in thickness, is

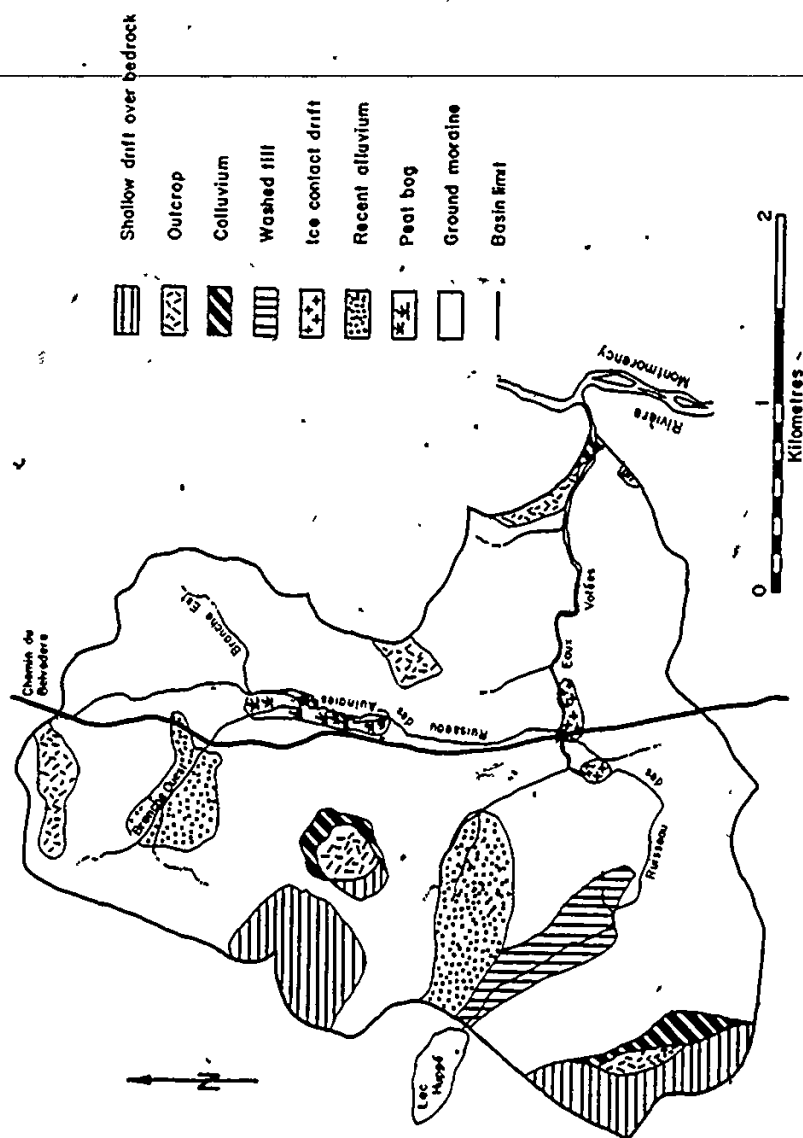


Figure 4.4 Surficial geology of Ruiseau des Eaux Volées basin (after Rochette, 1971)

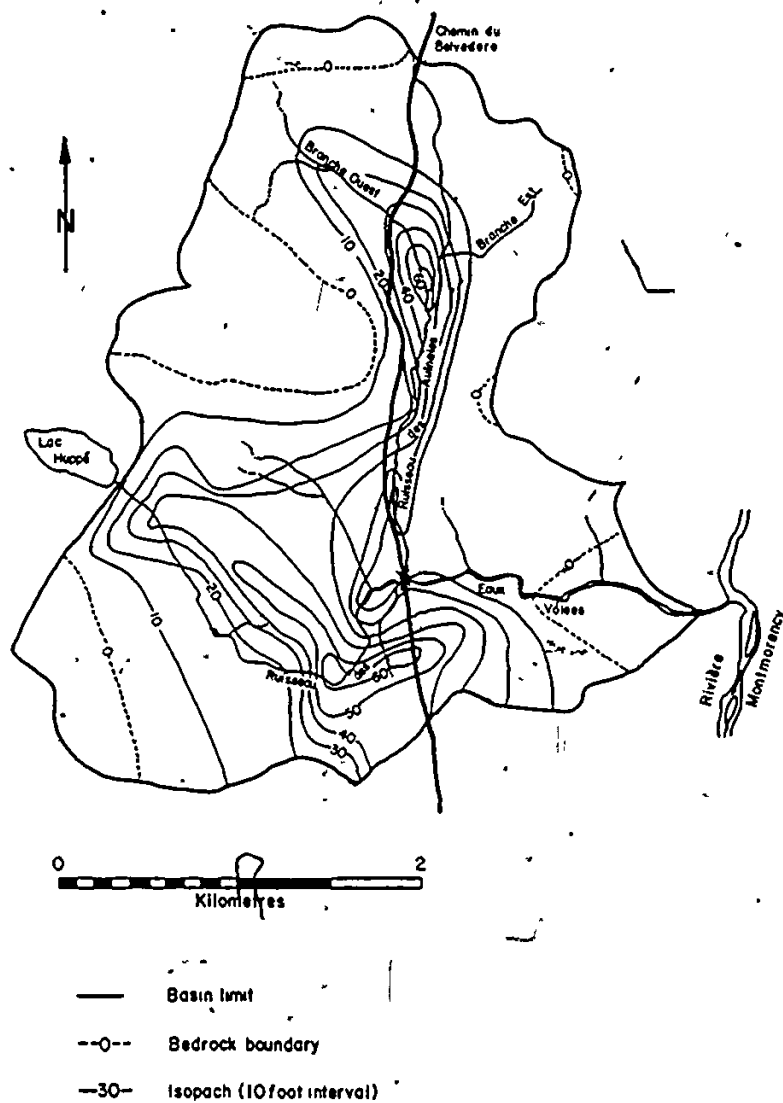


Figure 4.5 Isopach map of surface deposits, Ruisseau des Eaux Volées basin (after Rochette, 1971)

found in bedrock depressions where it is either above or below the ground moraine. It consists mainly of sand and gravel with most of the fines removed by fluvial action.

The contact drift is a glacio-fluvial drift consisting of sand and gravel, sand with silt and silt with sand, all coarsely stratified. The contact drift is found in a thin layer near the outlet of sub-basin 6 and in sub-basin 6 near the confluence of Ruisseau des Aulnaies and Ruisseau des Eaux Volées, where thicknesses up to 5 m have been observed.

The shallow drift unit consists of a sandy till with boulders and is found close to outcrops on the tops of hills. Except for the lack of the compacted top layer, it is similar in composition to the ground moraine. The thickness of this unit is generally less than 1 m.

4.5.2 Post-glacial deposits

Post-glacial deposits consist of colluvium, recent alluvium and peat bogs. The colluvium is composed of loose gravel and sand with angular boulders and is usually found at the base of slopes or cliffs and at the basin outlet. The recent alluvium, found in sub-basins 6, 7 and 7A, is composed of sandy and silty material with some well sorted gravel lenses. Thickness ranges from 1 to 8 m. In sub-basin 7, up to 6 m of peat bog overlies the recent alluvium.

4.6.0 Hydrology (Plamondon and Naud, 1975)

Streamflow in the drainage basin is measured at four gauging stations located at the outlets of each of the four

sub-basins. Three of the gauging stations (5, 6, and 7A) are equipped with sharp-crested V-notch weirs. The fourth gauging station (7) has a control structure constructed from concrete bags. All of the gauging stations are equipped with gas bubbling water level recorders.

Streamflow normally peaks in May due to snowmelt and in June and August due to rainfall. Lowest flows for the year occur at the end of the winter in March or April. Figure 4.6 is a typical stream hydrograph for the basin.

4.7.0 Hydrogeology (Rochette, 1971)

The surficial deposits and the bedrock of the drainage basin have been divided into four hydrostratigraphic units on the basis of similar water-bearing properties. Unit 1 is usually composed of recent alluvium and contact drift, materials having a large amount of sand and silt particles. This material is fairly uniform and has an average composition of 69% sand, 20% silt and 11% gravel. Unit 2 is predominantly ground moraine. This unit is composed mostly of sand and gravel, the average composition being 59% sand, 29% gravel and 12% silt. These first two hydrostratigraphic units are the dominant surface materials. Unit 3 is composed mainly of washed till and colluvium. This material is poorly sorted and

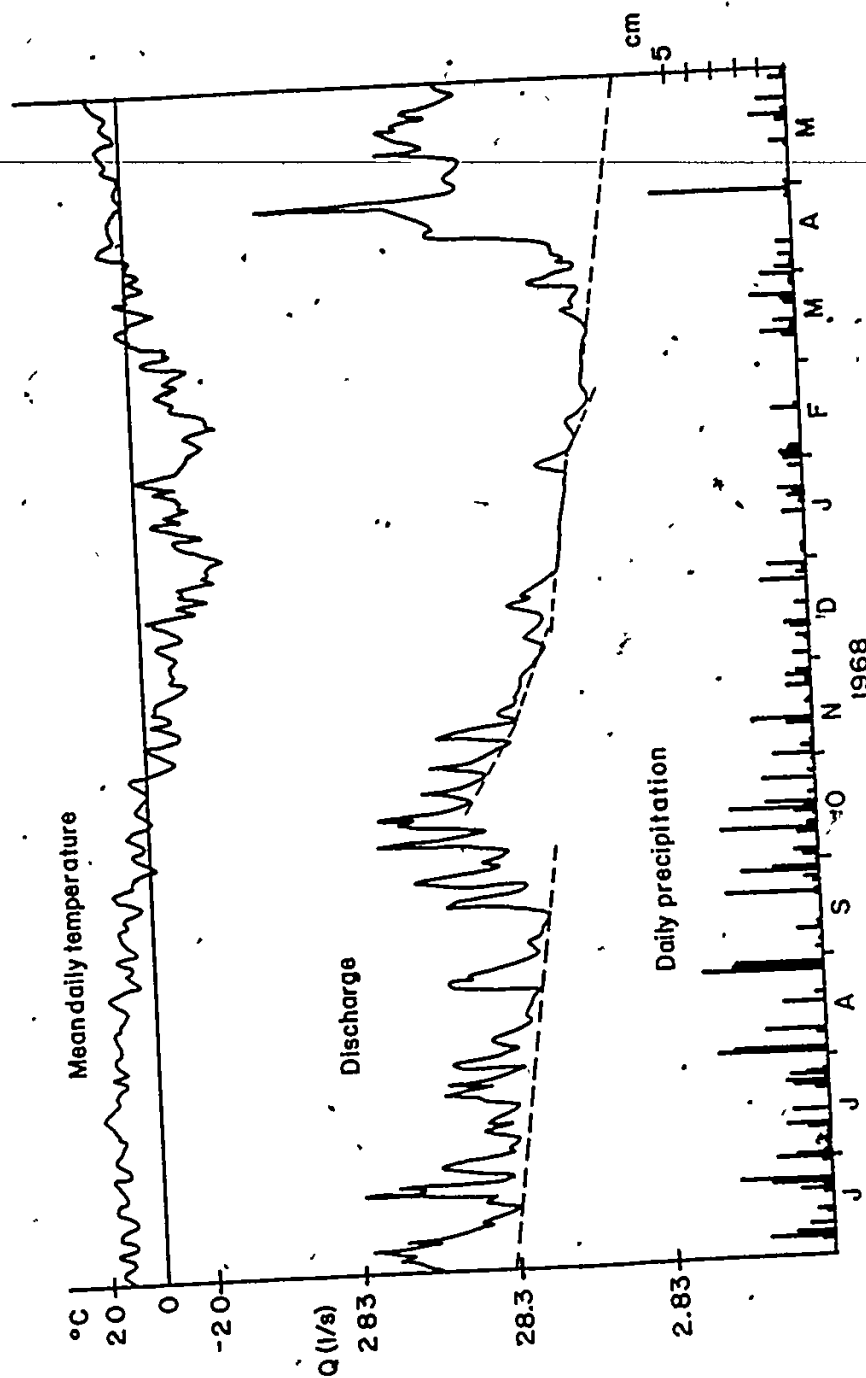


Figure 4.6 Typical stream hydrograph, Ruisseau des Eaux Volées basin (after Rochette, 1971)

has an average composition of 57% gravel, 36% sand and 7% silt. Unit four is the well jointed bedrock. The surface cover of soil, roots, branches, moss, etc., forms a layer that has a high infiltration and retention capacity, but it is too thin (generally less than 1 m) to be considered as a hydrostratigraphic unit.

Analysis of well and piezometer records indicate that the groundwater system is unconfined and that the bedrock is hydraulically connected to the surficial deposits. The water table is close to the surface even in areas of higher elevations. The shallow groundwater table is indicated by the presence of springs along streams and paths and also by saturated and swampy surfaces. Rochette's concept of the groundwater flow system is shown in Figure 4.7.

The average hydraulic conductivities for the basin range from 1×10^{-3} to 1×10^{-7} cm/sec. These values were determined by Rochette, using a steady state, finite difference, groundwater flow model.

The TDS for the basin is approximately 24 ppm and the electrical conductivity is $20.5 \mu\text{S}$. These low values can be expected with the type of geologic materials present.

4.8.0 Field instrumentation for this study

The system to monitor possible groundwater ridging consists of a network of small diameter wells, equipped with automatic water level recorders, and recording

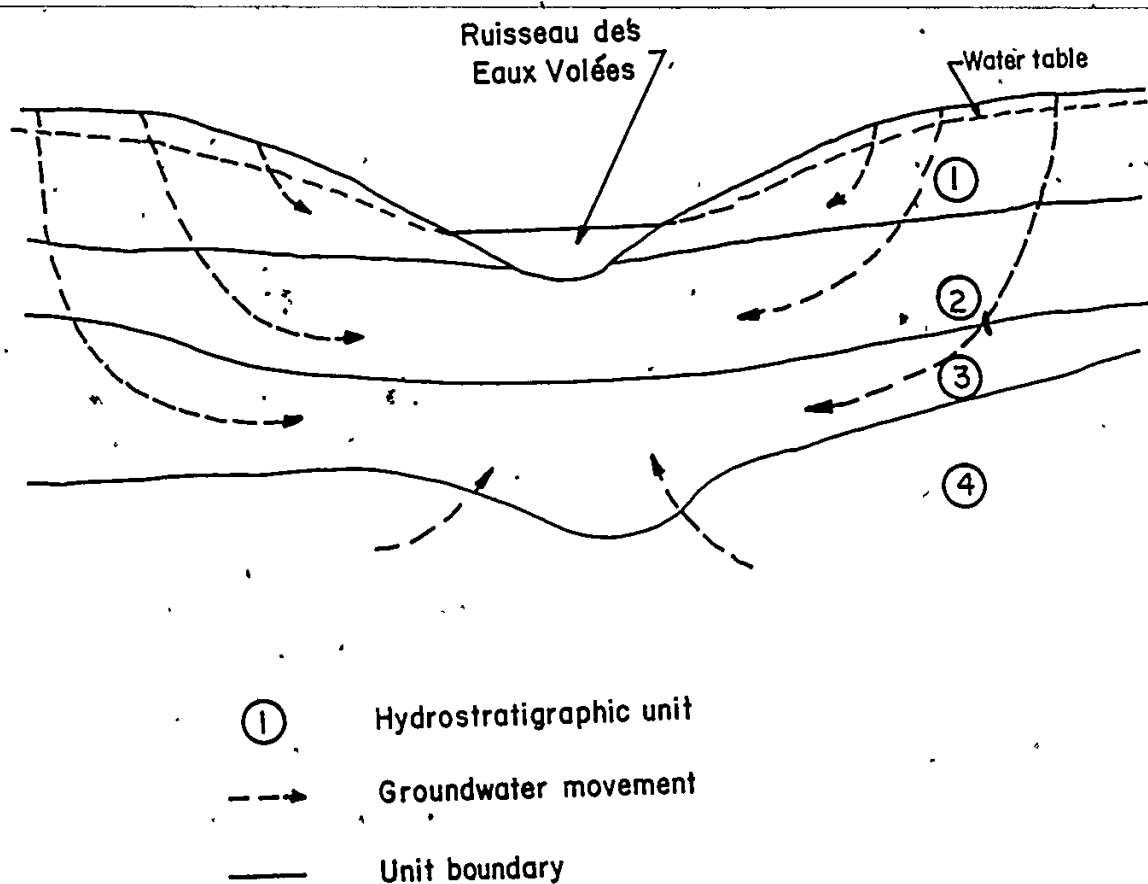


Figure 4.7 Groundwater flow system, Ruisseau des Eaux Volées basin (after Rochette, 1971)

tensiometers. The monitoring system is located on the south bank of Ruisseau des Eaux Volées a few metres upstream from its confluence with Ruisseau des Aulnaies (Figure 4.8).

~~Standard rain gauges were placed at the instrumentation site~~ and at gauging stations G6 and G7A. In addition to the instrumentation installed for this study, stream discharge records for the basin and daily precipitation records from a recording rain gauge at station G6 were made available by the personnel at Foret Montmorency and the Quebec Ministry of the Environment.

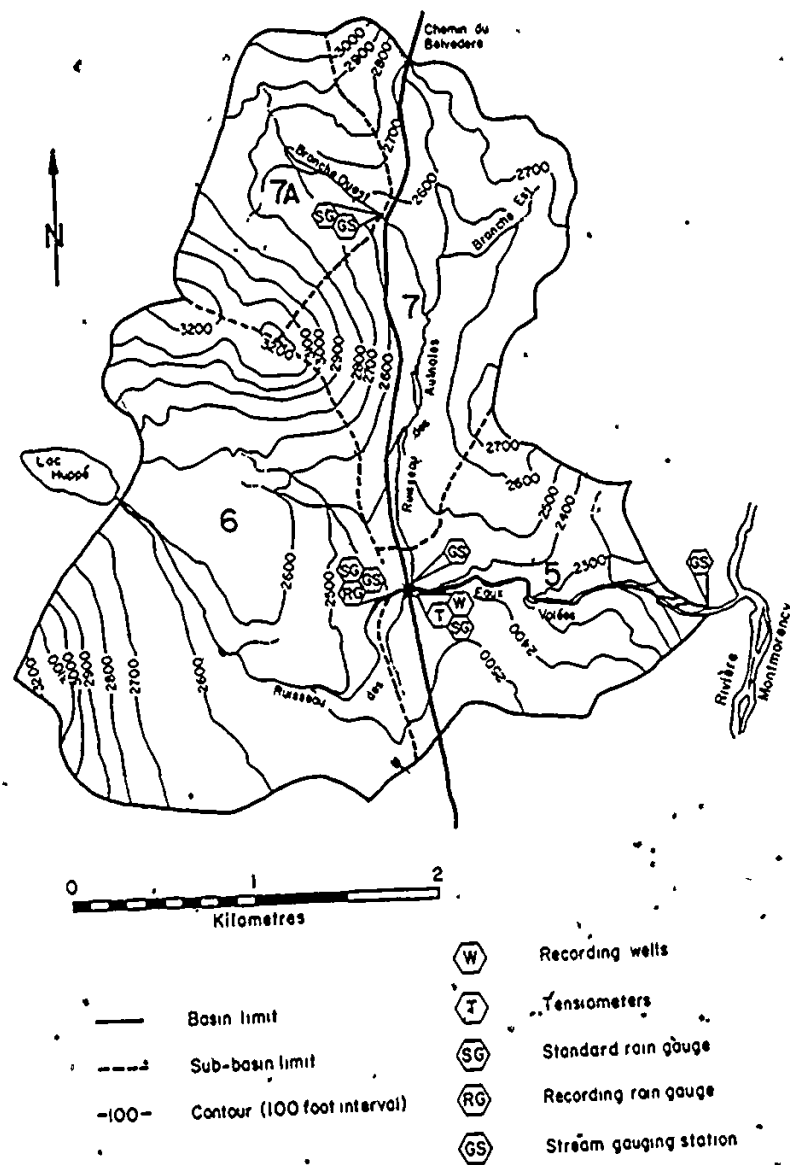


Figure 4.8 Location of instrumentation for this study

CHAPTER 5

RESULTS AND DISCUSSION OF RESULTS

5.1.0 Introduction

The water table level data which was recorded on the strip charts at the instrumentation site was reduced to a workable format by hand, using a HP-25 hand-held calculator. This reduced data was tabulated to obtain time-water level values for each of the wells which were then plotted to show the time relationship between precipitation and water level changes.

The data that was to be collected from the tensiometer system was unavailable as the result of the failure of an amplifying unit that was supposed to amplify the output from the pressure transducer.

Discharge data for Ruisseau des Eaux Volées measured at gauging station G6 was unavailable for the period of study as the result of the failure of the monitoring equipment operated by the Quebec Ministry of the Environment.

Stream levels were measured at gauging station G6 when possible and were used to compute discharges for some of the storms. The well that was placed in the stream at the instrumentation site yielded poor results as a result of its small diameter float being pinned against the side of the well by the current of the stream.

For this study storms of high intensity and brief

duration were desirable for they would yield simple water table hydrographs. During the 1980 field season storms of this type occurred on May 31, June 8, June 15, June 26, July 5, July 11, and July 19. The May 31 storm occurred before all of the monitoring equipment had been installed and therefore no data was available for this storm. Data from the June 8 and July 19 storms was lost as the result of the malfunction of the strip chart recorder. Of the remaining storms the June 15, July 5 and July 11 storms were selected for study.

5.2.0 June 15, 1980 storm event

The storm on June 15, 1980 occurred after a period of four days without precipitation. The storm event was preceded by a small amount of rain (1mm) between 13:15 and 15:00 hours with the main storm beginning at approximately 16:15 hours. The storm occurred in two parts, the first part occurring from 16:15 to 18:00 hours and the second part occurring between 18:15 and 21:00 hours. Between 16:15 and 18:00 hours a total of 11.3 mm of rain fell with the peak rainfall intensity occurring between 16:30 and 16:45 hours when 3.3 mm of rain fell. Between 18:15 and 21:00 hours a total of 8.8 mm of rain fell with the peak rainfall intensity occurring between 18:45 and 19:00 hours when 2.5 mm of rain fell. Total precipitation for the storm event was 20.1 mm. The distribution of the rainfall is shown in Figure 5.1.

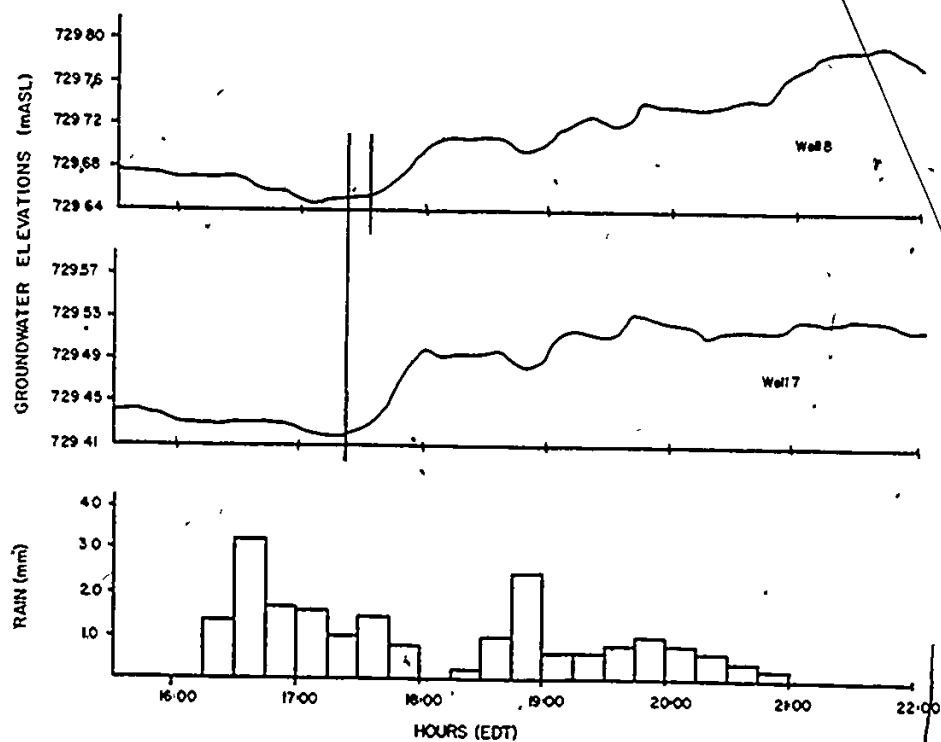


Figure 5.1 Groundwater levels during June 15, 1980 storm event

5.2.1 Stream response

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The response of the streams to the storm event given here are based upon measurements taken at gauging station G6 during the storm event. The discharge was computed by measuring the water levels with a staff gauge located at the weir and using these levels to determine the discharge.

Prior to the storm event of June 15, 1980 the streams in the study area were at baseflow conditions. After the precipitation began the water levels in the streams began to rise quickly. At gauging station G6 the water level rose by 4.5 cm in a one hour period and 23 cm in a five hours and twenty five minute period. The increase in the discharge of the stream at G6 was approximately 0.11 cubic metres per second from a flow rate of approximately 0.01 cubic metres per second at 14:40 hours to approximately 0.12 cubic metres per second at 20:15 hours. Based on past records for the stream, the peak flow probably occurred between 21:00 and 22:00 hours. Stream levels had dropped by 11.5 cm at 08:38 on June 16, 1980.

During the storm event very little overland flow was observed actually discharging into the stream. Overland flow did discharge into the stream at points where the road was adjacent to the stream and at bridge abutments. Most of the observed overland flow was along the roads and appeared to be the result of precipitation falling on the roads and from springs and seeps along the roads discharging onto the roads.

This overland flow, once it had left the road surface, infiltrated quickly into the ground.

5.2.2 Water table response

Groundwater levels prior to the storm event ranged from 50 cm below the ground near the stream to 80 cm below the ground in the wells located furthest from the stream. The response of the water table to the storm event is shown in Figure 5.1. The response of the wells plotted are typical of the changes observed in the wells during the storm event. The data from wells #2 to #6 showed electrical interference and therefore were not plotted.

From the plots of the response of the water table to the storm event it can be seen that well #7 which is nearer to the stream responded before well #8 which is further away from the stream. Figure 5.1 also shows that the main response of the water table to the storm event occurred approximately 30 minutes after the first peak of the storm. This delay is probably the result of the low water table prior to the storm event. With low groundwater levels the precipitation would have to infiltrate a considerable thickness of dry soil to cause the groundwater rising effect. Following the initial rapid rise of the water table, the groundwater levels continued to rise at a steady rate until they peaked and then began to fall slowly as normal groundwater flow and consumption resumed.

The water levels rose by 20 to 30 cm overall during the storm which involved only 20 mm of rain.

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5.3.0 July 5, 1980 storm event

The July 5, 1980 storm event occurred after a period of three days without precipitation. The storm event began at approximately 18:30 hours and occurred into two parts. The first part occurred between 18:30 and 21:30 hours and the second part occurred between 21:45 and 00:15 hours on July 6, 1980. Between 18:30 and 21:30 hours a total of 12.1 mm of rain fell with the peak intensity occurring between 19:30 and 19:45 hours when 2.7 mm of rain fell. Between 21:45 and 00:15 hours a total of 6.9 mm of rain fell with the peak intensity occurring between 21:15 and 21:30 hours when 1.8 mm of rain fell. Total precipitation for the storm event was 19.0 mm. The distribution of the rainfall is shown in Figure 5.2.

5.3.1 Stream response

Prior to the storm event the streams in the study area were close to baseflow conditions. Stream level measurements taken before and after the storm event showed a rise in the stream level of 9.6 cm. Since the second measurement was taken 10 hours after the storm event had ended peak stream levels were likely higher than this measurement. Peak streamflow probably occurred between 22:00 and 00:00 hours.

Since the storm occurred at night measurements of the

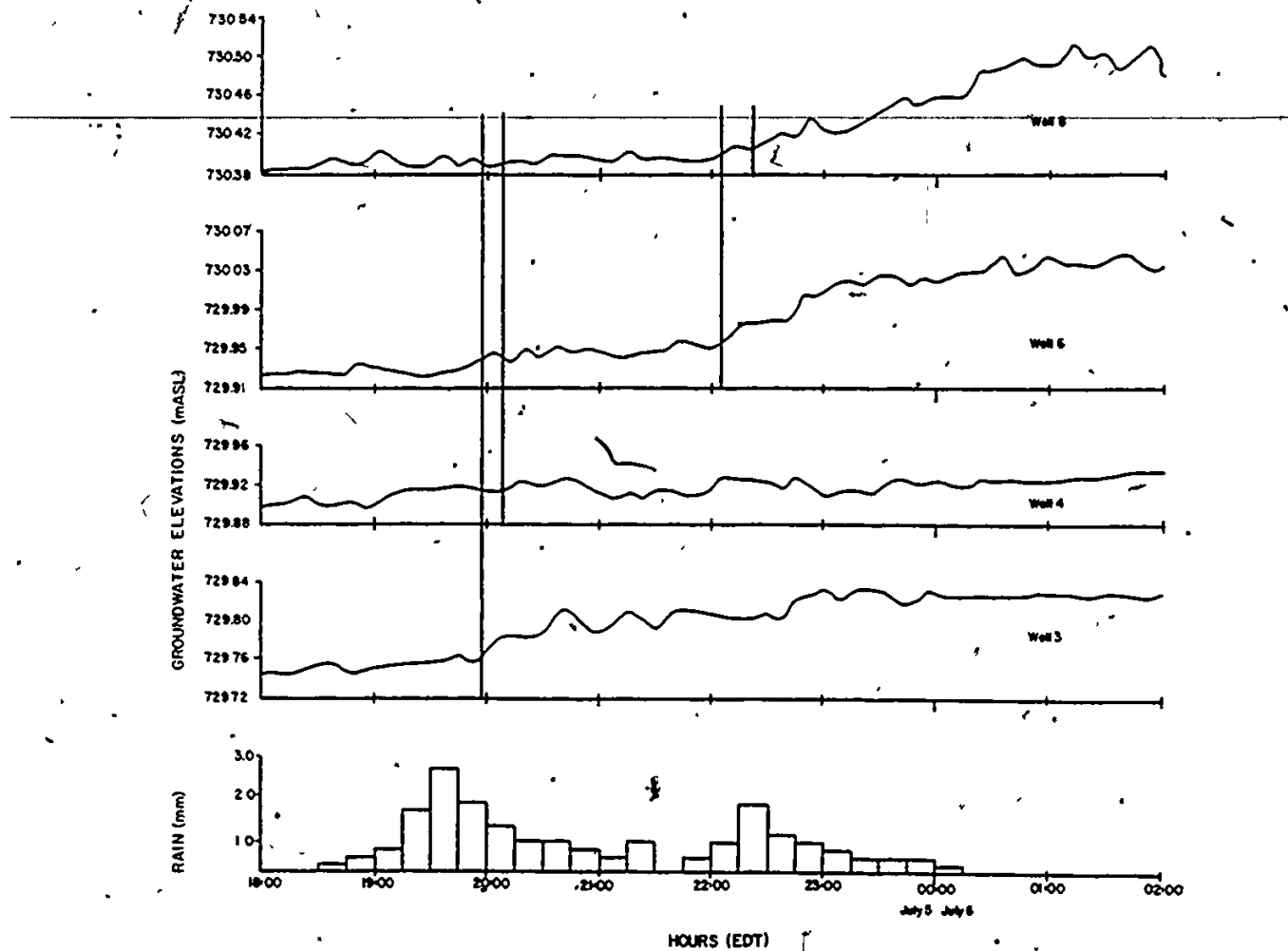


Figure 5.2 Groundwater levels during July 5, 1980 storm event.

water levels at gauging station G6 were not taken and therefore the discharge of the stream during the storm event could not be computed.

5.3.2 Water table response

Prior to the storm event groundwater levels ranged from 40 cm below ground near the stream to 60 cm below the ground in the wells 30 m from the stream. The response of the water table to the storm event is shown in Figure 5.2. The response of the water table in the plotted wells are typical for the storm event.

From the plots of the response of the groundwater table to the storm events it can be seen that the near stream wells responded before wells located further away from the stream. The near stream wells began to respond approximately 30 minutes after the first peak in rainfall and also showed a response to the second peak of the storm. The wells further away from the stream responded mainly to the second peak in rainfall. This is also shown in Figure 5.3 which shows the percentage of total rise in the wells at several times during the rain event. The wells nearer to the stream reached their maximum levels before the wells further away from the stream. The delay in response time is again the result of the low groundwater levels prior to the storm event. The response of the near stream wells to the second peak of the storm event suggests that the capillary fringe was near or at surface at

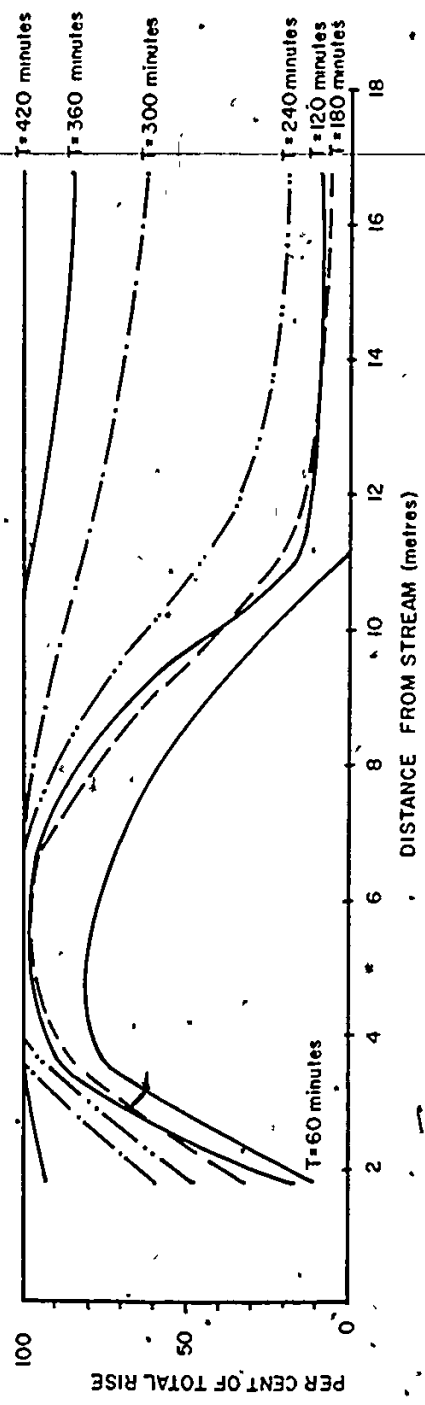


Figure 5.3 Per cent rise of water table at various times during July 5, 1980 storm event.

this time. The second part of the rain event resulted in the release of more water from the capillary fringe to the water table resulting in a second rise of the water table.

Groundwater levels rose by 12 to 20 cm during the storm event which consisted of 19 mm of rain.

5.4.0 July 11, 1980 storm event

The July 11, 1980 storm event occurred after five days during which little precipitation fell. There was no rainfall recorded for July 6, 7 and 8 and only 2.8 mm and 3.0 mm of rain fell on July 9 and 10 respectively. The storm event began at approximately 14:30 hours and occurred in two parts. The first part occurred between 14:30 and 15:15 hours and the second part occurred between 15:15 and 16:30 hours. Between 14:30 and 15:15 hours 7.7 mm of rain fell with the peak intensity in the rainfall occurring between 14:30 and 14:45 hours when 5.7 mm of rain fell. Between 15:15 and 16:30 hours 11 mm of rain fell with the peak intensity in rainfall occurring between 15:45 and 16:00 hours when 5.5 mm of rain fell. Total precipitation for the storm event was 18.7 mm. The distribution of the rainfall is shown in Figure 5.4.

5.4.1 Stream response

The streams in the study area were at baseflow prior to the storm event. Water level measurements taken before and after the storm event at gauging station G6 showed a rise of

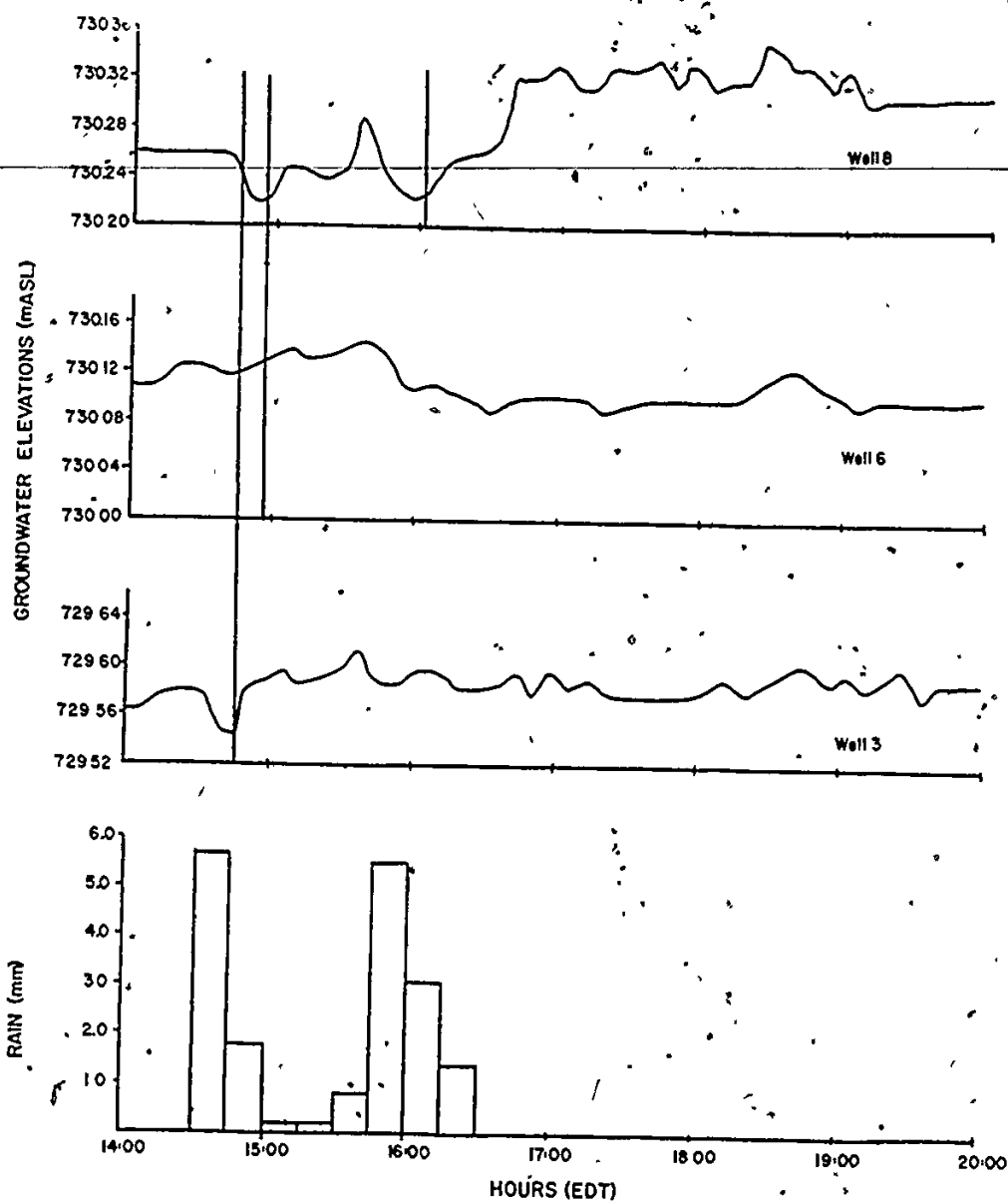


Figure 5.4 Groundwater levels during July 11, 1980 storm event.

8.8 cm. Since the second measurement was made 16 hours after the end of the storm event peak water levels would have been higher. Peak streamflow probably occurred between 16:00 and 18:00 hours.

Since no water level measurements were taken at gauging station G6 during the storm event the discharge of the stream during the storm event was not computed.

5.4.2 Water table response

Groundwater levels prior to the storm ranged from 30 cm below ground near the stream to 60 cm below the ground in wells located furthest from the stream. The response of the water table to the storm event is shown in Figure 5.4. The response of the plotted wells is typical of the response for all of the wells.

Figure 5.4 shows that the near-stream wells responded first to the storm event. There is a slight delay in the response of the water table to the first part of the rain event. The delay in response was probably caused by the low groundwater levels prior to the storm. The response to the second peak of the storm is most easily seen in well #8 where the water table was approximately 50 cm below the ground before the rain event. The second peak response in the other wells is minimal as the result of the water table having reached almost maximum levels before the second peak in rainfall occurred.

5.5.0 1981 Storm events

A second trip to the Ruisseau des Eaux Volees watershed was made between July 27 and August 31, 1981. Before this trip

several modifications were made to the monitoring equipment to improve the data collection. The maximum output of the water level recorders was increased from 8 volts to 12 volts by removing the 510 ohm resistor. This change made it easier to measure small changes in the water level. The second major change was the rewiring of the wafer switches controlling the output from the water level recorders to increase the length of time that a well was connected to the chart recorder. In addition to these electrical changes, changes in the field measurement procedures were made. Groundwater levels were measured at the instrumentation site in the morning and evening with an electrical well probe to obtain readings that could be used to correct for chart drift. Commercial water level recorders were installed at the instrumentation site and at a point upstream from gauging station G6 to record the stream stage in case of failure of the government equipment.

Three storms suitable for study occurred during the 1981 field season. These storms occurred on August 6, 11 and 16. The results for the August 6 storms were lost as a result of the chart recorder malfunctioning. The precipitation records for the August 11 storm were not available and therefore this storm was not studied. The results from the August 16 storm

are presented here.

5.6.0 August 16, 1981 storm event

The August 16, 1981 storm event was a very intense storm of brief duration. The storm lasted from 13:45 to 15:15 and precipitation totaled 16.7 mm of which 11.8 mm fell in the first 15 minutes of the storm. There had been 11.45 mm of precipitation on August 15 and early August 16 and no precipitation before that since August 11. The distribution of the precipitation is shown in Figure 5.5.

5.6.1 Stream response

The response of the stream to the storm event is shown in Figure 5.6. The two small peaks prior to the main peak are the result of the precipitation on August 15 and early August 16. The major peak is the result of the August 16 storm event. The stream level rose by 11.5 cm in approximately 1.5 hours beginning at approximately 14:00 hours. The stream levels peaked at approximately 15:30 hours and then fell until another rain event occurred on August 17.

5.6.2 Water table response

The response of the water table to the storm event is shown in Figure 5.5. Groundwater levels before and after the storm are given in Table 5.1.

Figure 5.5 shows the the near-stream well responded to

	PRE-STORM	POST-STORM		GROUND
WELL	LEVEL (m)	LEVEL (m)	CHANGE (cm)	ELEV (masl)
2	729.505	729.610	10.5	729.85
3	729.665	729.790	12.5	730.06
4	729.795	729.945	15.0	730.33
5	729.930	730.095	16.5	730.42
6	730.105	730.285	18.0	730.60
LYSB	730.335	730.540	20.5	730.72
7	730.305	730.490	18.5	730.74
8	730.355	730.510	15.5	731.03
10	730.700	730.835	13.5	731.50
11	730.535	730.710	17.5	732.09
P5.1	729.970	730.140	17.0	-----

Table 5.1 Groundwater levels August 16, 1981
Ruisseau des Eaux Volées, Quebec

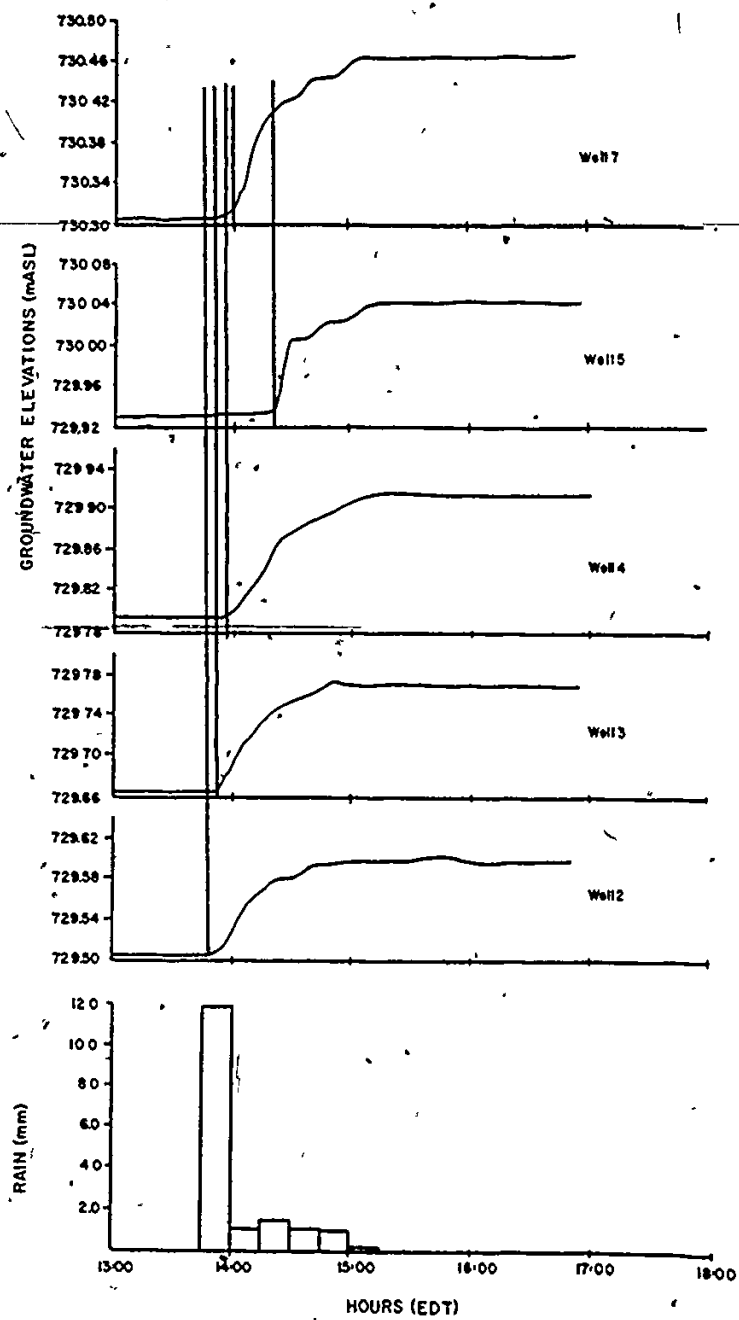


Figure 5.5 Groundwater levels during August 16, 1981 storm event.

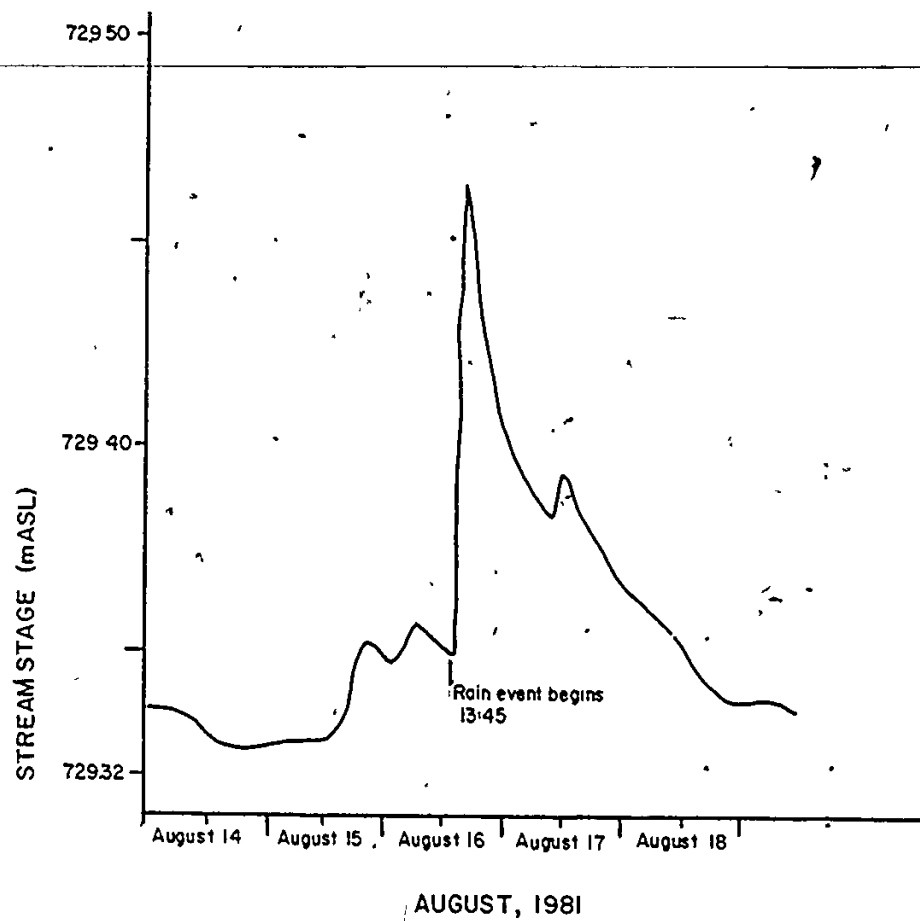


Figure 5.6 Stream response to August 16, 1981 storm event.

the storm event before the wells located further away from the stream began to respond. Well #2 began to respond at about 13:48, well #3 at 13:50, well #4 at 13:55, well #5 at 14:20 and well #7 at 14:00. The apparent delay in the response of well #5 is probably the result of the small diameter float not moving up until a rise of several centimetres in the water level had occurred. Well #5 most likely began to respond at approximately 14:10 hours. Well #7 began to respond to the rain before well #5 as a result of the water table being closer to the surface at this point. Responses from wells #10 and #11 did not show up on the chart recorder although the water levels in these wells rose by 13.5 cm and 17.5 cm respectively. The lack of response at well #10 was the result of the float not being replaced in the well after measuring the water level in the morning. The small response of well #11 seen on the chart is most likely the result of the small diameter float not moving until a change in water level of several centimetres had taken place.

The formation of the groundwater ridge at the instrumentation site can be seen in Figure 5.7 which shows groundwater profiles at several different times during the storm event. The groundwater levels at time T=30 minutes shows that there is also a rapid response of the groundwater table to the rain event approximately 12 metres from the stream. This response can be explained by the water table being closer to surface at this point. The capillary fringe is closer to

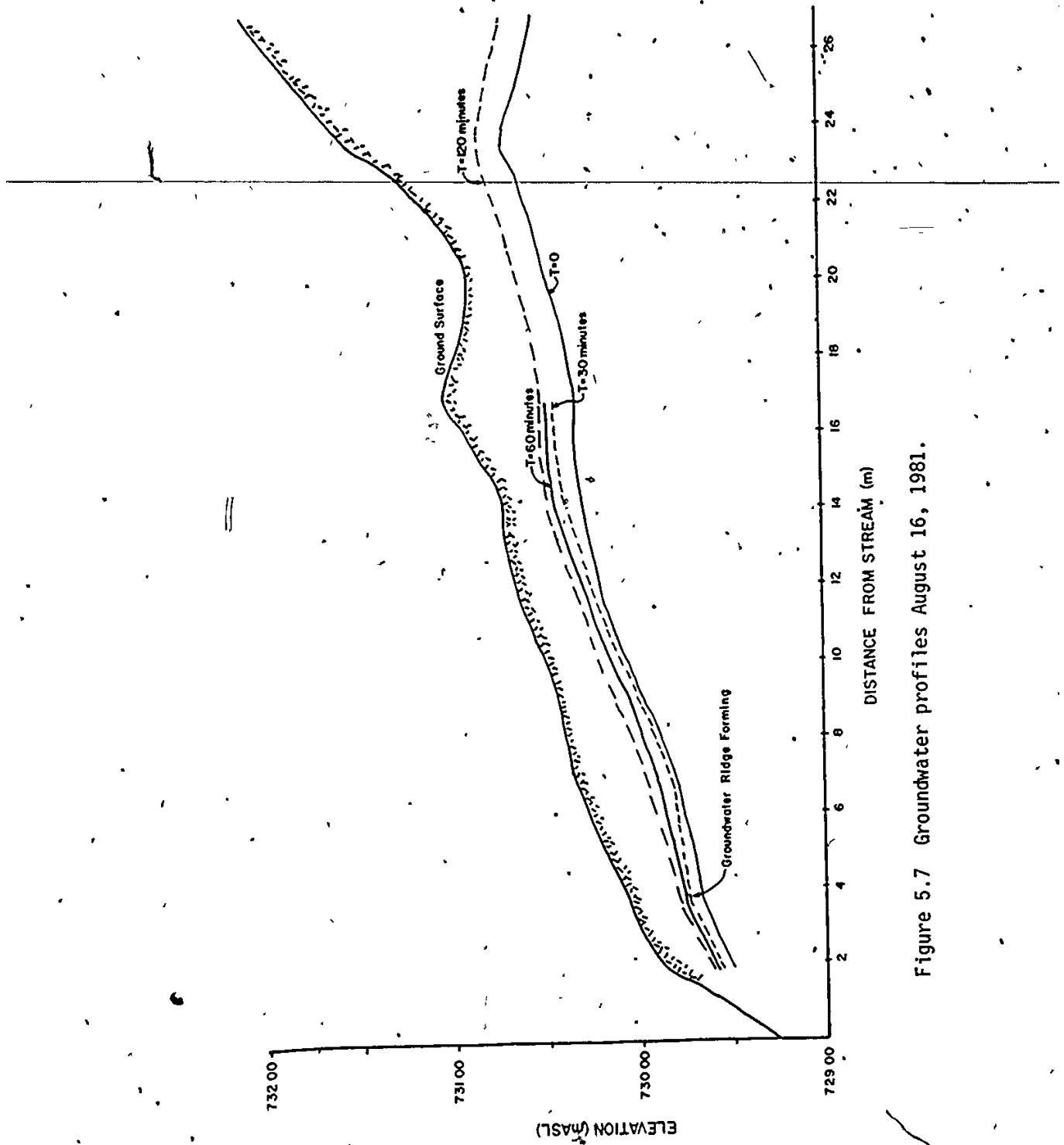


Figure 5.7 Groundwater profiles August 16, 1981.

surface causing the quick response to the rain event. This response is also shown in Figure 5.8 which shows the percent of the total rise of the water table at several times during the storm event. The near stream wells reached their maximum levels before the wells located further from the stream. The response of well #2 lags behind well #3 because the water level in well #2 closely follows the stream level.

5.7.0 Summary of results

The results seen in the study of the four storm events are summarized below:

1. The groundwater table near the stream appeared first to the precipitation followed later by wells located further away from the stream.
2. The areas where the groundwater table was close to surface responded before other areas.
3. The rapid rise of the groundwater levels was followed by a more gradual rise of the water table as the rain continued or was followed by peak groundwater levels.
4. Groundwater levels began to decline after peak groundwater levels were reached as normal usage of the groundwater, i.e. phreatophyte consumption and discharge to streams continued.
5. Stream levels rose quickly beginning shortly after the well nearest to the stream began to respond to the rain event.

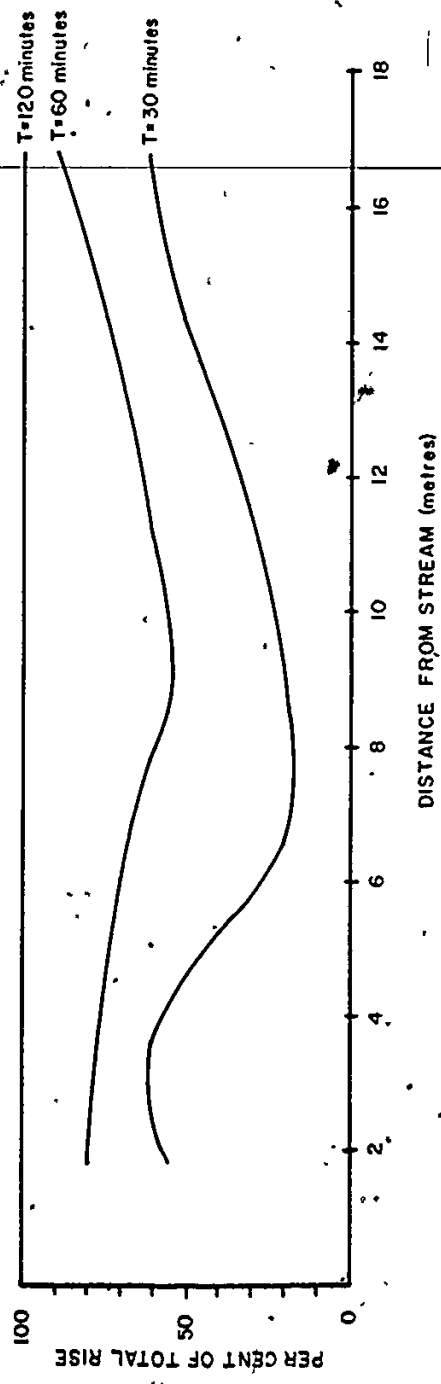


Figure 5.8 Per cent rise of water table at various times during August 16, 1981 storm event.

5.8.0 Discussion of results

The results obtained from the study of the groundwater response to storm events support the groundwater ridging theory proposed by Sklash and Farvolden (1979) in the following ways:

1. The groundwater table responded to precipitation first in near-stream areas followed later by areas located farther away from the stream.
2. The groundwater showed a rapid increase in levels in response to precipitation.
3. The groundwater response was controlled by the depth to the water table.
4. The water levels in the stream began to rise shortly after the groundwater table near the stream began to rise.

These are four of the five main points of the groundwater ridging theory. The fifth point which could not be substantiated by this study was the rapid conversion of the tension-saturated portion of the capillary fringe into a zone of pressure saturation. However, some evidence that this change does occur was noted at a hydrogeological field camp run by the University of Waterloo (see Chapter 3 Section 3.2.6). The groundwater ridging theory appears to be an acceptable mechanism through which the large groundwater component of storm runoff in streams can be explained.

5.9.0 Significance of the results

The significance of the groundwater ridging mechanism of storm runoff generation in streams affects mostly the qualitative aspects of storm runoff and not the quantitative aspects.

5.9.1 Qualitative aspects

The qualitative aspect that will be affected most by the groundwater ridging theory will be the idea that water chemistry in the stream should be greatly diluted during storm runoff. The groundwater ridging mechanism when considered with the results from several other recent studies, (see Chapter 2, Section 2.8.1) means that the quality of the runoff in the stream may become less desirable during storm runoff events if the groundwater discharging into the stream during the storm event is polluted. Sklash et al (1978) presented a case where nitrate concentrations in a stream in southern Ontario increased during storm runoff as nitrate enriched groundwater discharges into the stream. This fact means that all areas of a watershed should be examined before the application of fertilizer to the soil to determine the groundwater flow patterns and to prevent the pollution of surface water bodies during runoff events. Computer models for dilution of stream chemistry during storm runoff should be re-examined in light of the groundwater ridging concept.

5.9.2 Quantitative aspects

In most cases the quantity storm runoff can still be predicted using the current prediction methods. Most of these methods are based on long term observations of watershed response. These models should be examined to determine if the groundwater ridging mechanism will alter them significantly.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

6.1.0 Conclusions

The groundwater ridging theory appears to be an acceptable theory for the generation of storm runoff in first order streams located in humid, vegetated watersheds. This theory explains the domination of storm runoff by groundwater through the mechanism of the formation of a groundwater ridge near the stream.

6.2.0 Recommendations for future study

Future studies of groundwater ridging should concentrate on the following items:

1. The study of the tension saturated portion of the capillary fringe.
2. The development of computer models to determine the qualitative effects of groundwater ridging on storm runoff.
3. Instrumentation of a watershed for the purpose of long term studies of the groundwater ridging effect.

The study of the tension-saturated portion of the capillary fringe should use an extensive network of tensiometers, both manually read and connected to pressure transducers, and neutron access tubes to determine the moisture content-soil pressure relationship in the capillary

fringe during groundwater ridging. This could be combined with the instrumentation of a watershed for the purpose of long term studies.

Further study on the design of small diameter floats is also required. The floats used in this study usually moved in a step-like fashion when the water levels rose but seemed to function satisfactorily when the water levels fell. The problem seems to be to obtain a float which is heavy enough to move the water level recorders while still being light enough to float. Problems with surface tension of the water pulling the floats to the sides of the well may be remedied by designing a float that will have a neutral bouyancy and maintain a constant position in relation to the water level several centimetres below the water surface.

Studies on the relationship between the Lisse effect, which produces rapid water table rises similar to the groundwater ridging theory, and the groundwater ridging theory should also be carried out. A column that could be sealed to prevent the release of pressure to the atmosphere or that could be opened to the atmosphere could be used for such a study. This column would be filled with sandy soil. Wells and tensiometers placed in the column would monitor the changes in the capillary fringe of the soil in the column as water was added at the top of the column. If a rapid rise in the water table occurs when the column is vented to atmosphere then the groundwater ridging concept would be the cause of the rise.

LIST OF REFERENCES

- Anderson, M.G. and Burt, T. P., 1978. Time-synchronised stage recorders for the monitoring of incremental discharge inputs in small streams. *J. Hydrol.*, 37, pp. 101-109.
- Babu, D. K., 1980. The role of a capillary zone in the rapid changes of water table elevations. Abstract, AGU Chapman Conference on Subsurface Water Contributions to Stream-flow., Durham, New Hampshire.
- Betson, R. P., 1964. What is watershed runoff? *J. Geophys. Res.*, 69(8), pp. 1541-1551.
- Betson, R. P. and Marius, J. B., 1969. Source areas of storm runoff. *Water Resour. Res.*, 5(3), pp. 574-582.
- Betson, R. P., Marius, J. B. and Joyce, R. T., 1968. Detection of saturated interflow in soils with piezometers. *Soil Sci. Soc. Am. Proc.*, 32(4), pp. 602-603.
- Dincer, T., Payne, B. R., Flowkowski, T., Martinec, J. and Tongiorgi, E., 1970. Snowmelt runoff from measurements of tritium and oxygen-18. *Water Resour. Res.*, 6, pp. 110-124.
- Dunne, T. and Black, R. D., 1970a. An experimental investigation of runoff production in permeable soils. *Water Resour. Res.*, 6, pp. 478-490.
- , 1970b. Partial area contributions to storm runoff in a small New England watershed. *Water Resour. Res.*, 6, pp. 1296-1311.
- Dunne, T., Moore, J. R. and Taylor, C. H., 1975. Recognition and prediction of runoff producing zones in humid regions. *Bull. Int. Ass. Sci. Hydrol.*, 20(3), pp. 305-327.
- Engman, T. E. and Rogowski, A. S., 1974. A partial area model for storm flow synthesis. *Water Resour. Res.*, 10, pp. 464-472.
- Freeze, R. A., 1971. Three-dimensional, transient, saturated-unsaturated flow in a groundwater basin. *Water Resour. Res.*, 7, pp. 347-366.
- , 1972a. Role of subsurface flow in generating surface runoff 1. Baseflow contributions to channel flow. *Water Resour. Res.*, 8, pp. 609-623.

-----, 1972b. Role of subsurface flow in generating surface runoff 2. Upstream source areas. Water Resour. Res., 8, pp. 1272-1283.

-----, 1974. Streamflow generation. Rev. Geophys. Space Phys. 12, pp. 627-647.

Freeze, R. A. and Cherry, J. A., 1979. Groundwater. Prentice-Hall Inc., Englewood Cliffs, New Jersey. 604p.

Fritz, P., Cherry, J. A., Weyer, K. U. and Sklash, M. G., 1976. Runoff analyses using environmental isotope and major ions. In: Interpretation of environmental isotope and hydrochemical data in groundwater hydrology. I.A.E.A., Vienna, pp. 111-130.

Gaiser, R. N., 1952. Root channels and roots in forest soils. Soil Sci. Soc. Proc., 16, pp. 62-65.

Hewlett, J. D., 1961. Soil moisture as a source of base flow from steep mountain watersheds. G. S. Forest Serv. Southeast Forest Exp. Sta., Res. Pap. SE 132. 11p.

Hewlett, J. D. and Hibbert, A. R., 1963. Moisture and energy considerations within a sloping mass during drainage. J. Geophys. Res., 64, pp. 1081-1087.

-----, 1967. Factors affecting the response of small watersheds to precipitation in humid areas. In: International Symposium on Forest Hydrology. W. E. Sopper and H. W. Lull (Eds.). Pergamon, New York, pp. 275-290.

Hewlett, J. D. and Nutter, W. L., 1970. The varying source area of streamflow from upland areas. In: Symposium on Interdisciplinary Aspects of Watershed Management., Mont. State Univ., Bozeman, Montana. pp. 65-83.

Hooghoudt, S. B., 1947. Waarnemingen van grondwaterstanden voor de landbouw, Commissie voor Hydrologisch Onderzoek TNO; Verslagen Technische Bijeenkomsten. 1(6) pp. 94-110. The Hague (published 1952).

Horton, R. E., 1933. The role of infiltration in the hydrologic cycle. Trans. AGU, 14, pp. 446-460.

Linsley, R. K., Kohler, M. A. and Paulhus, J. L. H., 1958. Hydrology for engineers. McGraw-Hill, New York. 340p.

Lynch, D. R. and Ryan, D. F., 1980. Streamwater chemical modelling at Sleepers River Watershed. Abstract, AGU Chapman Conference on Subsurface Water Contributions to Streamflow., Durham, New Hampshire.

Martínez, J., 1975. Subsurface flow from snowmelt traced by tritium. Water Resour. Res., 11, pp.496-497.

Martínez, J., Siegenthaler, H., Oeschger, H., and Tongiorgi, E., 1974. New insight into the runoff mechanism by environmental isotopes. In: Proceedings. Symposium on isotope techniques in groundwater hydrology. I.A.E.A., Vienna, 1, pp. 129-143.

Meyboom, P., 1967. Groundwater studies in the Assiniboine River drainage basin Part II: Hydrologic characteristics of phreatophyte vegetation in South-Central Saskatchewan. Geol. Surv. Can. Bull. 139.

Moser, H. and Stichler, W., 1975. Use of environmental isotope methods as a reconnaissance tool in groundwater exploration near San Antonio de Pichincha, Ecuador. Water Resour. Res., 11, pp. 501-505.

Nakamura, R., 1971. Runoff analyses by electrical conductance of water. J. Hydrol., 14, pp. 197-212.

O'Brien, A. L., 1980. The role of groundwater in stream discharges from two small wetland controlled basins in Eastern Massachusetts. Groundwater, 18, pp. 359-365.

Pinder, G. F. and Jones, J. F., 1969. Determination of the groundwater component of peak discharge from the chemistry of total runoff. Water Resour. Res., 5, pp. 438-445.

Plamondon, A. P. and Naud, R. C., 1975. The watershed management program at the Montmorency Experimental Forest. Symposium on Montmorency Experimental Forest. 27p.

Ragan, R. M., 1968. An experimental investigation of partial area contributions. Publ. 76 Int. Ass. Sci. Hydrol. Berne. pp. 241-249.

Rochette, F. J., 1971. Hydrogeological study of "Ruisseau des Eaux Volees" Experimental Basin. Unpubl. M.Sc. thesis, Univ. Western Ontario, London, Ontario.

Sklash, M. G., 1978. The role of groundwater in storm and snowmelt runoff generation. Unpubl. Ph.D. thesis, Univ. Waterloo, Waterloo, Ontario.

Sklash, M. G. and Faryolden, R. N., 1979. The role of ground-water in storm runoff. *J. Hydrol.*, 43, pp. 45-65.

Sklash, M. G., Faryolden, R. N. and Fritz, P., 1976. A conceptual model of watershed response to rainfall developed through the use of oxygen-18 as a natural tracer. *Can. J. Earth Sci.*, 13, pp. 271-283.

Sklash, M. G., Gillham, R. W. and Cherry, J. A., 1978. Studies of the agricultural contribution to nitrate enrichment of groundwater and the subsequent nitrate loading to surface waters. Part III: Mechanisms of runoff generation and nitrate flux to streams during runoff events. Waterloo Research Institute, Univ. Waterloo, Waterloo, Ontario.

Weyman, D. R., 1970. Throughflow on hillslopes and its relation to the stream hydrograph. *Bull. Int. Ass. Sci. Hydrol.* 15(2), pp.25-33.

Whipkey, R. Z. and Kirkby, M. J., 1978. Flow within the soil. In: *Hillslope Hydrology* (M. J. Kirkby ed.) John Wiley and Sons, Toronto. pp. 121-144.

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