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VEGETATION PATTERNS AND MOISTURE AVAILABILITY IN THE BAKER CREEK BASIN, NEAR YELLOWKNIFE, NORTHWEST TERRITORIES

BY

JACK ORIN PARK, JR.

A THESIS

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

DEPARTMENT OF GEOGRAPHY

EDMONTON, ALBERTA
SPRING, 1979

THE UNIVERSITY OF ALBERTA

FACULTY OF GRADUATE STUDIES AND RESEARCH

The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research for acceptance, a thesis entitled "Vegetation Patterns and Moisture Availability in the Baker Creek Basin, near Yellowknife, Northwest Territories" submitted by Jack Orin Park, Jr., in partial fulfillment of the requirements for the degree of Master of Science.

Arleigh H. Laycock
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P. H. Crown

Date March 26 1979

ABSTRACT

One of the major problems in water balance studies is that of closely defining soil moisture storage capacities and utilization for the different parts of the basin being studied. Average moisture storage values for drainage basins are often estimated, increasing the possibility of error. Variations in surficial cover types create real differences in soil moisture retention and use. Depending upon the similarity of physical conditions, a correlation exists between soil moisture storage and surficial cover type. It is proposed that an inventory of surficial cover categories and an assignment of appropriate moisture storage values to each will result in more accurate soil moisture storage calculations for the basin.

The Baker Creek Basin, a small subarctic watershed on the Canadian Shield near Yellowknife, Northwest Territories, has been studied in a number of ways but soil moisture variations have not been previously defined. The major emphasis of this study is the division of the Baker Creek Basin into definable surficial cover categories based upon physical relationships developed in the field and in the literature, assignment of soil moisture storage values to each and the calculation of storage capacities for the basin.

The research methodology includes: a comprehensive literature review; selection of nine representative areas

for intensive study within the basin from aerial photos and from the field; the surveying of two transects in each area to sample the vegetation, soil, permafrost table and surficial geology; interpretation and mapping of surficial cover categories from aerial photos; the assignment of moisture storage values to each surficial cover type and mapping of moisture storage categories from surficial cover relationships; and the computation of soil moisture storage capacities for the Baker Creek Basin. The derived values are then inserted into the Thornthwaite water balance equations for the basin for each of the six years from 1971-1976.

The accuracy of the derived water balance is compared with that of a previous study in the basin for the years 1971-1972, in which the average soil moisture storage had been estimated. Also, the computed moisture surplus from the Thornthwaite equation is compared with recorded discharge values from Baker Creek for the six years of the study.

It is concluded that the methodology performed in this study does produce more accurate soil moisture storage values for the Baker Creek Basin than those obtained in earlier and rougher estimations. In comparison with measured stream discharges from Baker Creek, the surpluses of the Thornthwaite water balance equations calculated in part from the moisture storage values obtained from this study, were close in some years and fairly distant in others. Reasons for this variance are thought to be due to a variety of factors, possibly including inaccuracies in the other four parameters of the Thornthwaite equation, the choice of less than representative areas within the Baker Creek Basin for sampling in this study and the assignment of less than accurate moisture storage values for one or more of the surficial cover types.

It is believed that the basic premise of this study was supported: the Thornthwaite water balance for the Baker Creek Basin is a closer fit using calculated soil moisture storage values based upon a number of categories than using a single estimate. With further study the research can be expanded to include a greater portion of the basin and more closely measured values for the soil moisture categories, but this step in more closely defining regional variations is a useful one in the study program.

ACKNOWLEDGEMENTS

First and foremost I would like to thank Dr. A. H. Laycock for an incredible amount of patience during the time period of this thesis, which lasted a bit longer than originally anticipated. Without his constant encouragement and helpfulness I would not have had the opportunity to write these acknowledgements.

Secondly a thank you is due Dave Luff who, for little pay, assisted me in the field during many hardships, especially on the day that over one-third of the total annual precipitation fell in 24 hours. I am also indebted to Bruce Rains and Peter Crown for much helpful criticism.

Many thanks go to Jack Chesterman and Randi Pakan for the many hours of excellent work they performed in regards to this thesis. Thanks also to Geoff Lester and Associates for closing their eyes to cartographic deadlines on my behalf.

And finally, to Louise, Charlie and Kim in the Log Cabin and to all of those who have resided in Holy Smoke during the last four years, in whatever capacity, I would like to say that this thesis is physical evidence that one can make major accomplishments despite major distractions.

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CHAPTER ONE

INTRODUCTION

PROBLEM

There are many information gaps in our understanding of water balance patterns in subarctic regions of the world. One of the main reasons for this incomplete perception is a paucity of data, especially for the Canadian North. In that portion of the Great Slave Lake drainage basin which lies within the Northwest Territories, for example, the density of climatological stations and the density of streamflow gauging stations are both one station per 33,181 square kilometers (Canada, Dept. of the Environment, 1972; Canada, Dept. of the Environment, 1976). The value of the data which are available is further limited by the relatively short periods or records and the incompleteness of the records which do exist.

In water balance studies the amounts of water which are detained and retained in storage by the soil, vegetation and other surficial cover vary with the types and amounts of each. In subarctic Canada, past studies have tended to include estimates of the amount of various types of surficial cover, and general storage values have been used for the entire study areas (Kakela, 1969; Wight, 1973). There has been a general lack of research concerning water storage values and evapotranspiration rates for various subarctic flora. This is rather unusual considering the emphasis placed on soil moisture storage by Thornthwaite in his water balance equation (Thornthwaite, 1948). Measurements of actual evapotranspiration can be made using lysimeters, mass transfer and energy-budget methods. In northern Canada, however, there are too few lysimeter installations, and instruments needed for using the mass transfer and energy-budget methods have apparently been considered too expensive to be regularly employed (Sanderson,1969, p. 45).

In lieu of obtaining adequate data from measured sources, a method commonly used in computing actual evapotranspiration is that of empirically deriving potential evapotranspiration values using mean temperatures and subtracting any water deficits. This study uses such a process, employing the Thornthwaite water balance procedure. Any calculation of soil moisture storage consisting of an inventory of surficial cover types in a given drainage basin and an averaging of values would be a more valid procedure than a mere estimation of a single figure based on less involvement with the physical system. In this thesis such an approach is employed in an attempt to increase the understanding of water balance components.

The United Nations Educational, Scientific and Cultural Organization (UNESCO) and other international organizations, realizing the need for an extended period of research into water resources on a world-wide scale, endorsed the International Hydrological Decade which began in 1965. Canada was one of the countries which agreed to participate in the IHD program. A series of drainage basins was chosen for detailed research by government agencies, universities and private concerns within Canada. Many of these basins were located in remote areas where meteorological and hydrological data had never before been systematically collected, if at all. The IHD program ended in 1974 and the results are still coming in. But, regardless of what those results are, the important aspect of the IHD is that our basic knowledge of the parameters in a water balance of subarctic regions has been improved.

STUDY AREA

The Baker Creek Basin is one of the 'benchwork basins' chosen for research under the IHD program. It was selected for several reasons: it is representative of much of the Precambrian Shield area of western Canada; it is adjacent to existing meteorological and hydrological stations; and it is relatively accessible by road and air. Yellowknife, N.W.T., is approximately 1450 kilometers by highway or 965 kilometers by air north of Edmonton, Alberta, (Figure 1-1).

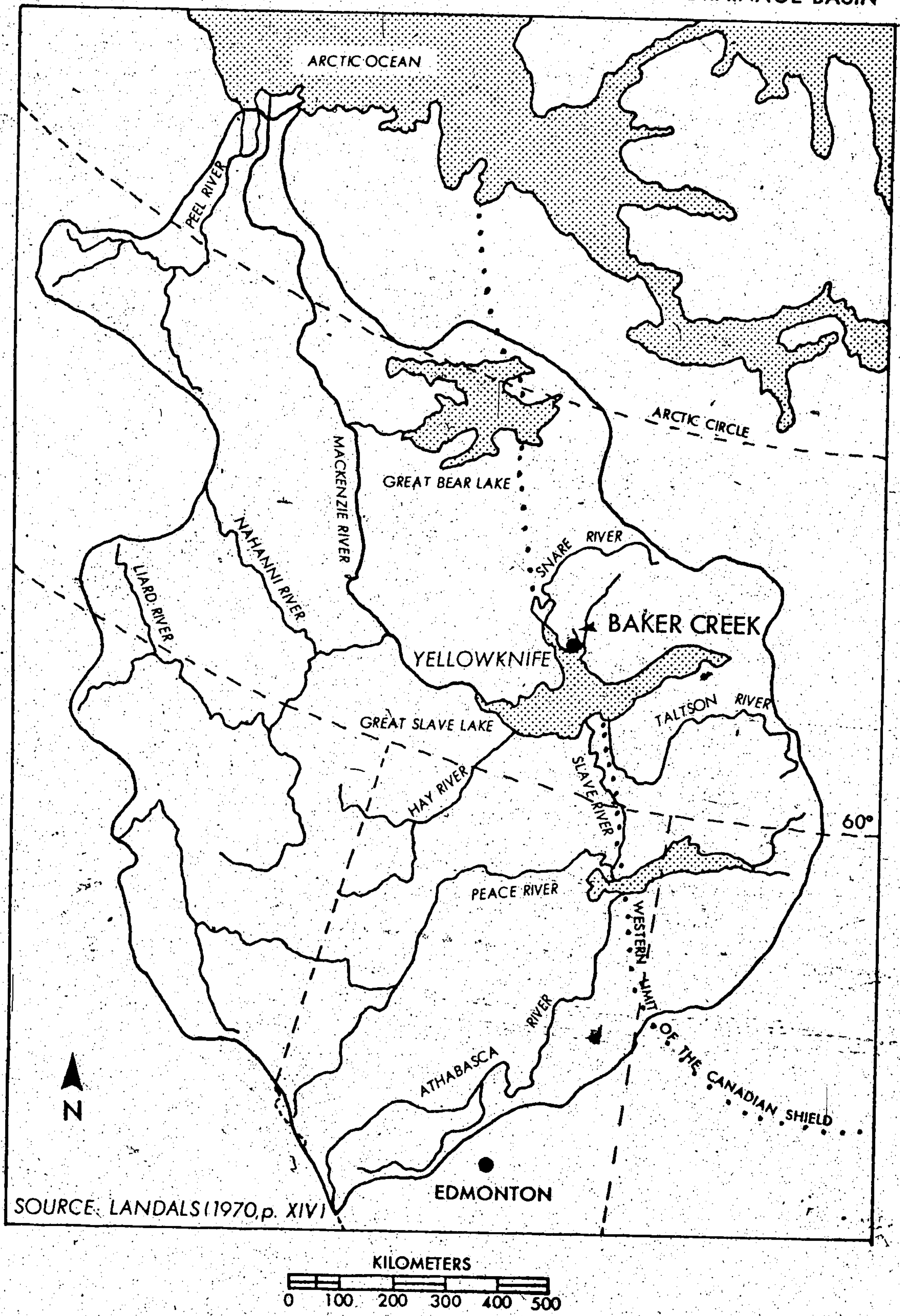
The basin comprises an area of about 180 square kilometers. Baker Creek flows in a southerly direction to enter the North Arm of Great Slave Lake approximately 3.2 kilometers north of Yellowknife. The northernmost portion of the basin is nearly 24 kilometers north of Yellowknife (Figures 1-2, 1-3). The basin lies between 62° 28' and 62° 43' north latitude, and 114° 17' to 114° 32' west longitude. It is located in the zone of discontinuous permafrost, the Subarctic climatic zone and the Boreal Forest or Subarctic Forest-Tundra Transition vegetation zone.

The topography of the Baker Creek Basin is typical of the more ice-scoured portions of the Canadian Shield. The area was heavily glaciated, with the ice advancing from the northeast at approximately S60 - 65° W (Henderson and Brown, 1966, p.3). Preglacial soil and loose rock were largely removed by Pleistocene glaciers and most present rock surfaces remain polished and scoured. The last ice sheet melted from this area approximately 9,700 BP (Prest, 1970, p. 706, Fig. XII-15).

Surficial deposits found in the basin today are a result of direct deposition from glacial ice, glacio-fluvial and glacial-lacustrine processes. They include many erratics, outwash deposits of sand and gravel, till, beach ridges and lacustrine silts and clays. Bateman (1949, p. 10), found that the depth of permafrost was largely a function of the depth of overburden which acts as insulation. Permafrost was not detected beneath outcrops of rock but was discovered to extend to a depth of 79.2 meters under an 18.3 meter-thick

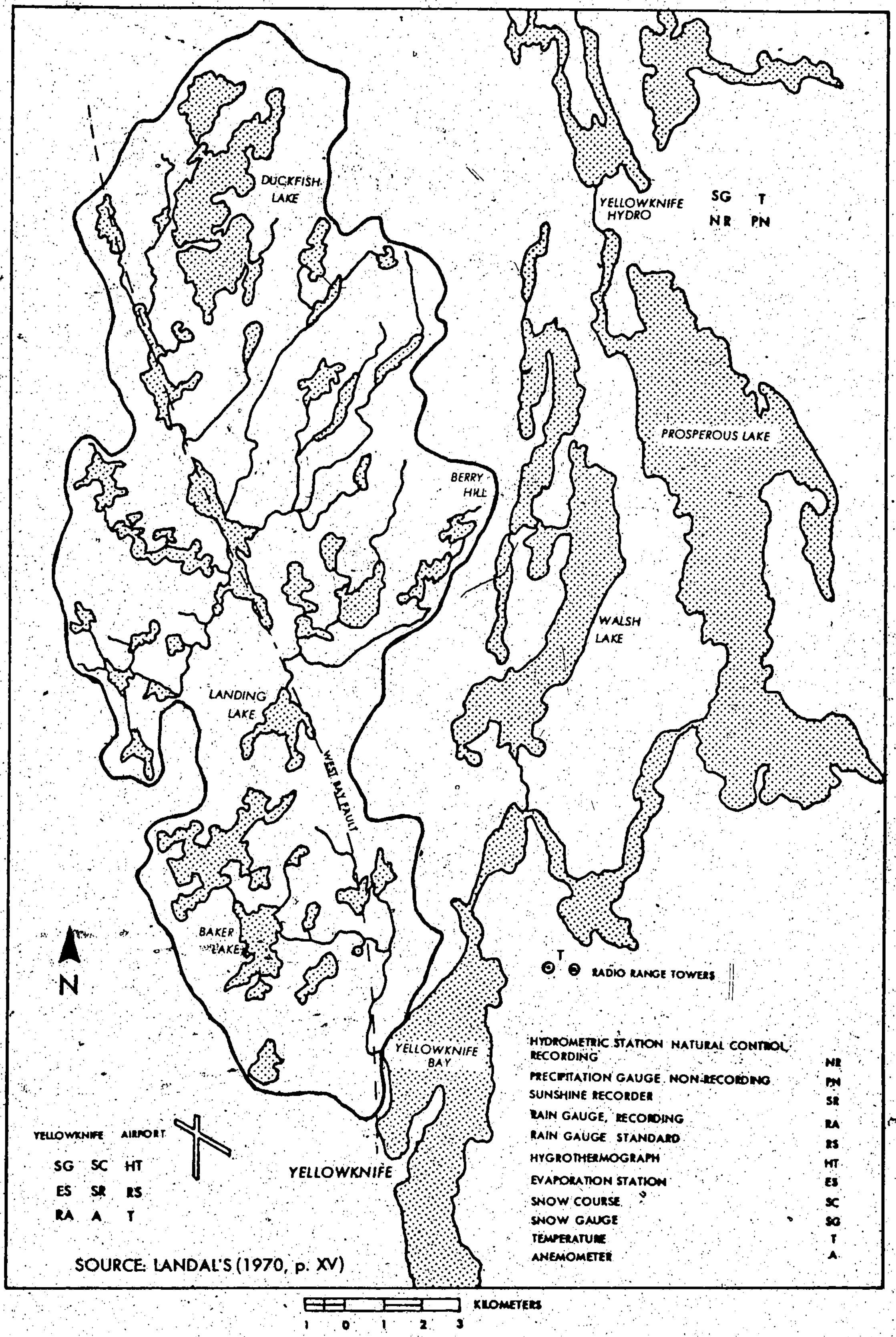
FIGURE 1-1

LOCATION OF BAKER CREEK WITHIN THE MACKENZIE RIVER DRAINAGE BASIN



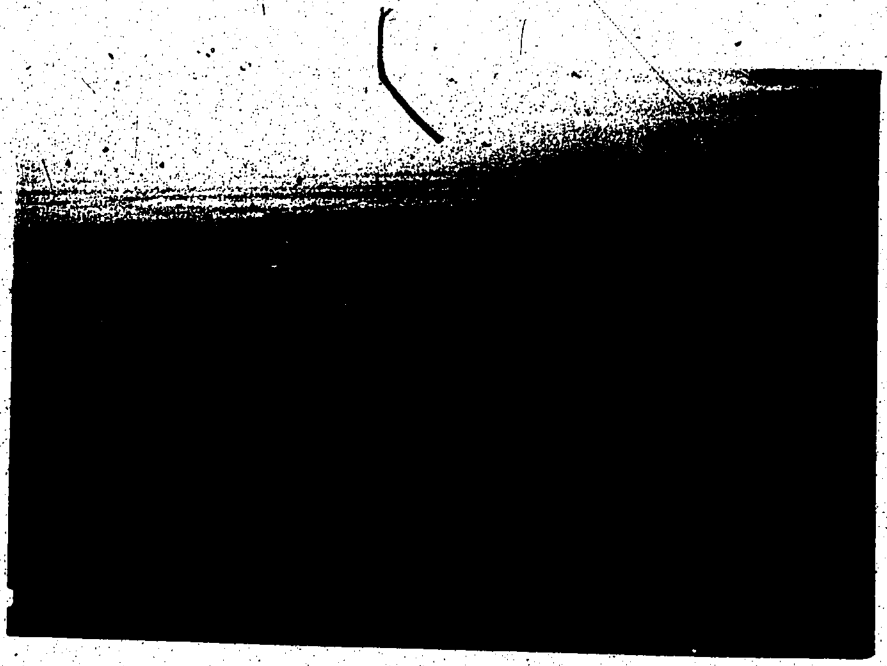
SOURCE: LANDALS (1970, p. XIV)

FIGURE 1-2 MAP OF BAKER CREEK BASIN SHOWING LOCATIONS OF ASSOCIATED METEOROLOGICAL AND HYDROLOGICAL INSTRUMENTS



SOURCE: LANDAL'S (1970, p. XV)

Figure 1-3: Townsite of Yellowknife, N.W.T. from air facing in a southwesterly direction. Southern portion of Baker Creek Basin can be seen in the extreme right centre of the photograph.



overburden of clay, sand or gravel. The presence and thickness of permafrost in a given area is also dependent on other factors, two of which are the drainage characteristics of the land and the type and amount of vegetation cover (Brown, 1964, p. 68). These will be discussed further in Chapter Two.

Outcrop ridges and hills alternate with depressions which are filled by lakes, muskegs or, infrequently, with dense stands of trees. The portion of the Baker Creek Basin which is underlain by plutonic rock exhibits a lower local relief and higher average elevation than that underlain by volcanic types (Jolliffe, 1946) (Figure 2-6). Faults, dykes and shear zones within the bedrock create the alignment of some of the lakes in the basin. The best example is the West Bay Fault which extends from Fault Lake northwest through the entire basin.

The vegetation of subarctic boreal regions is generally poor in genera and species (Hare and Ritchie, 1972, p. 335). The Baker Creek Basin proves no exception. A combination of poor soil, extensive rock outcrops, occasional moisture deficiency and harsh winters provides conditions detrimental to species size and distribution.

The major division of site analysis in the basin is between the upland rock sites with scattered and variable depths of drift cover, characterized by a tree population of jack pine (Pinus banksiana), white birch (Betula papyrifera), and rarely, aspen poplar (Populus tremuloides), and the low-lying muskeg areas in which black spruce (Picea mariana), larch (Larix laricina), willow (Salix spp.), alder (Alnus spp.), and rarely, white spruce (Picea glauca) predominate. However, each species may be found in either site category.

These major components are further subdivided by amount of cover, understory vegetation, depth to permafrost and soil moisture. Site analyses will be developed in Chapter Five.

There are very few mature stands of trees in the Baker Creek Basin. This is partly due to the influence of man. Timber removal for lumber, logs and firewood quickly depleted many of the better stands, especially in the southern portion of the basin in close proximity to Yellowknife. Fires, partly caused by man and partly by lightning strikes, have frequently burned large areas within the basin. But the most severe restriction to the presence of mature stands of trees is limitation in site quality. Large areas of bare rock and poorly-drained organic terrain are not conducive to healthy, mature stands of trees. Although the basin is located on the forested side of the Arctic treeline, the harsh climate tends to promote stunting in most tree species.

It should be noted that arsenic pollution in the area of the Giant Yellowknife Mine has severely crippled or killed the vegetation. It is not known how extensive or severe the arsenic limitation upon growth has been. This is a continuing problem that may severely affect regeneration.

OBJECTIVES

Certainly the reliability of any water balance calculation is enhanced by fewer assumptions and more research concerning the variables. The primary objective of the author in this thesis was to map a portion of the Baker Creek Basin in order to provide accurate data on the type, amount and distribution of vegetation patterns, and to interpret their effect on the evapotranspiration regime of the basin.

Nine smaller areas within the basin were chosen for intensive study (Figure 1-4). In each area two transects were run and information was gathered concerning vegetation composition, soil moisture and depth to permafrost, if present. The data were then used to create a model of the entire basin regarding these patterns.

The multi-stage sampling technique was applied to this study. Information on surface patterns within the Baker Creek Basin was first obtained using large scale photographs with a scale of 1:12,000. This information was then utilized in depicting broader patterns on smaller-scale photography at 1:31,680. Finally satellite imagery from LANDSAT I and II, at a scale of 1:1,000,000 was used in attempt to delimit extremely broad patterns. In this manner the information gathered in the Baker Creek Basin could be applied to other areas of the subarctic.

The collection of evapotranspiration data applied to quantitative analysis of vegetation patterns was not a part of this study. Further studies will be needed to clarify amounts of evapotranspiration for each type of surface. This is an initial attempt to identify, explain and evaluate apparent differences and suggest areas and types of useful studies that might be conducted in the future if a better definition of water balance relationships is to be obtained.

In order to determine the value of this method the following procedure was adopted. The Baker Creek Basin was divided according to a classification system of surficial cover types and the nine smaller areas selected to represent the basin were interpreted as to these cover types on air photos. Each cover type was then assigned a soil moisture storage value and these values mapped for the nine areas. The percentage area of every moisture storage category on the nine maps was determined and averaged. These averages were then applied to the basin as a whole. Once the percentage of the basin occupied by each moisture storage category was known, it could then be converted to a hectare value.

A water balance of the Baker Creek Basin for each year of the study was calculated using all of the moisture storage categories mapped. From this, the amount of water surplus for each category was determined. Multiplication of each of these surplus values (centimeters) by the amount of basin area in each category (hectares), and division by 100 provided moisture surplus values in hectare/meters. The total of these values in the 1.3, 5.0, 10.0, 15.0 and 25.0 cm. storage categories minus those in the two water body categories represented the surplus water in the basin for the given year. This figure was then compared with the recorded discharge for Baker Creek for that time period.

It is believed that this method provides a more realistic moisture storage value for the basin than does estimation of a single figure, resulting in a more accurate input to the water balance equation.

ORGANIZATION

Chapter Two is a description of the physical setting of the Baker Creek Basin. A review of the literature pertinent to the topic is found in Chapter Three. Chapter Four is concerned with the methodology used in this study. Field techniques are explained and photo interpretation procedures are discussed. In addition, the use of multi-stage sampling techniques, LANDSAT imagery and other remote sensing devices are reviewed. In Chapter Five all relevant site criteria are examined and formed into recognizable patterns. Evapotranspiration characteristics are discussed and computations for the study area are presented. Chapter Six is a summation of the results obtained and a discussion of their significance.

FIGURE 1-4

MAP OF BAKER CREEK BASIN SHOWING LOCATION OF NINE STUDY AREAS

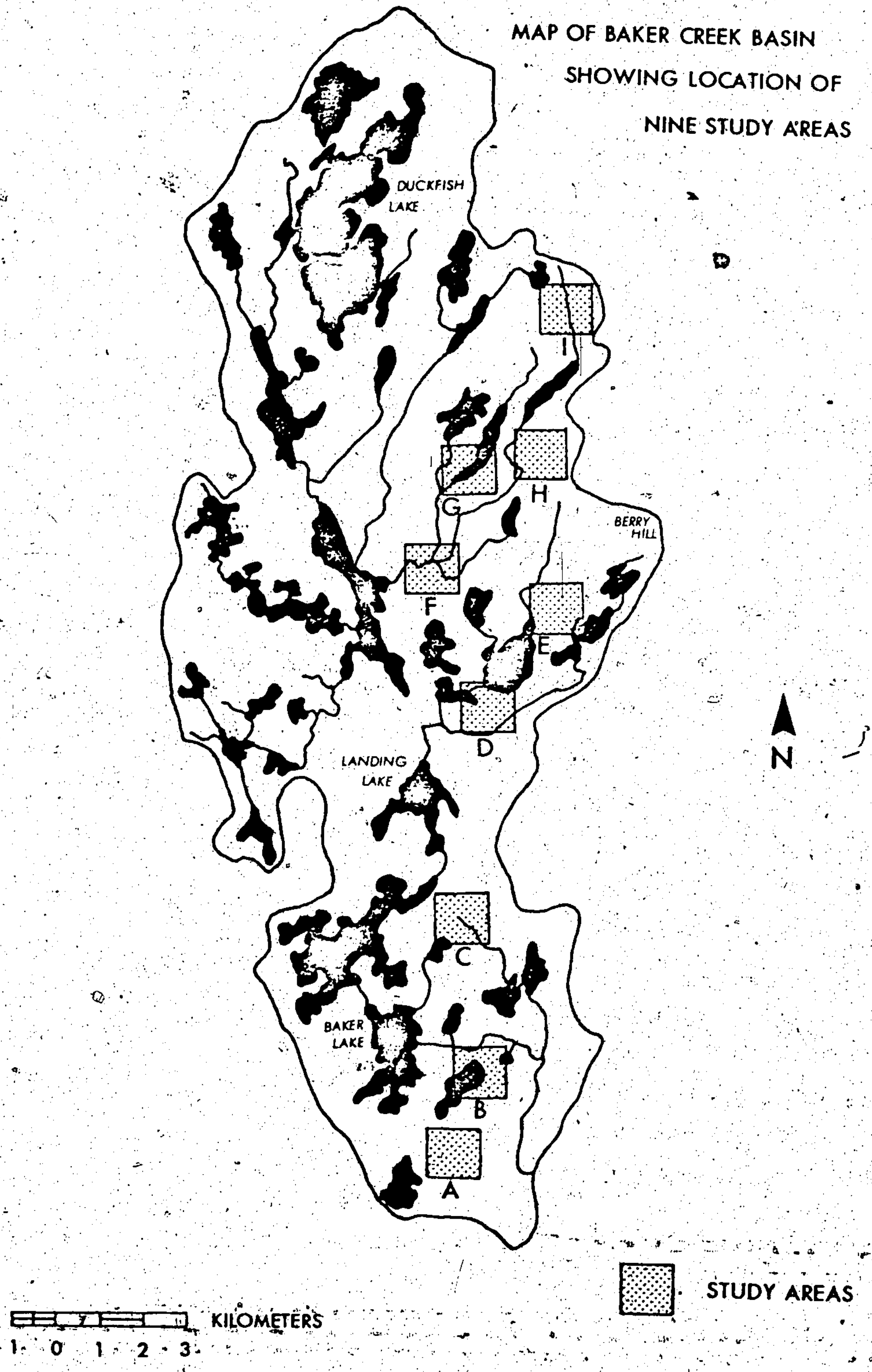
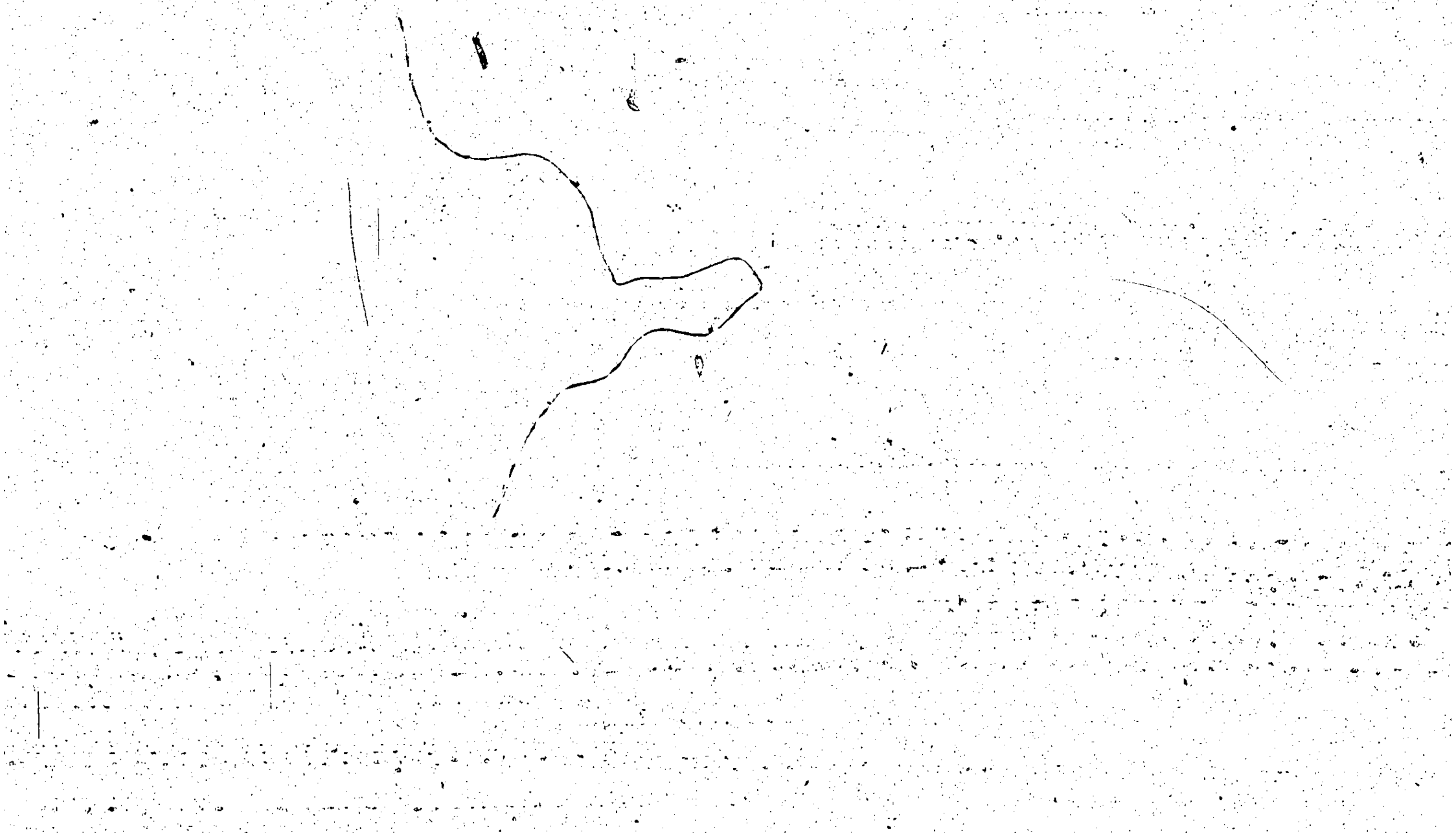


Figure 2-1: Sunset/Sunrise over the Baker Creek Basin on June 21, 1973.



CHAPTER TWO

PHYSICAL SETTING

INTRODUCTION

The physical aspects of an area are of prime importance in the determination of its water balance. Three recent studies of the Baker Creek Basin have included data on its physical setting (Kakela, 1969, Landals, 1970; Wight, 1973). This chapter is a discussion of the physical environment of the study area with particular emphasis on those parameters which pertain to the present study.

CLIMATE

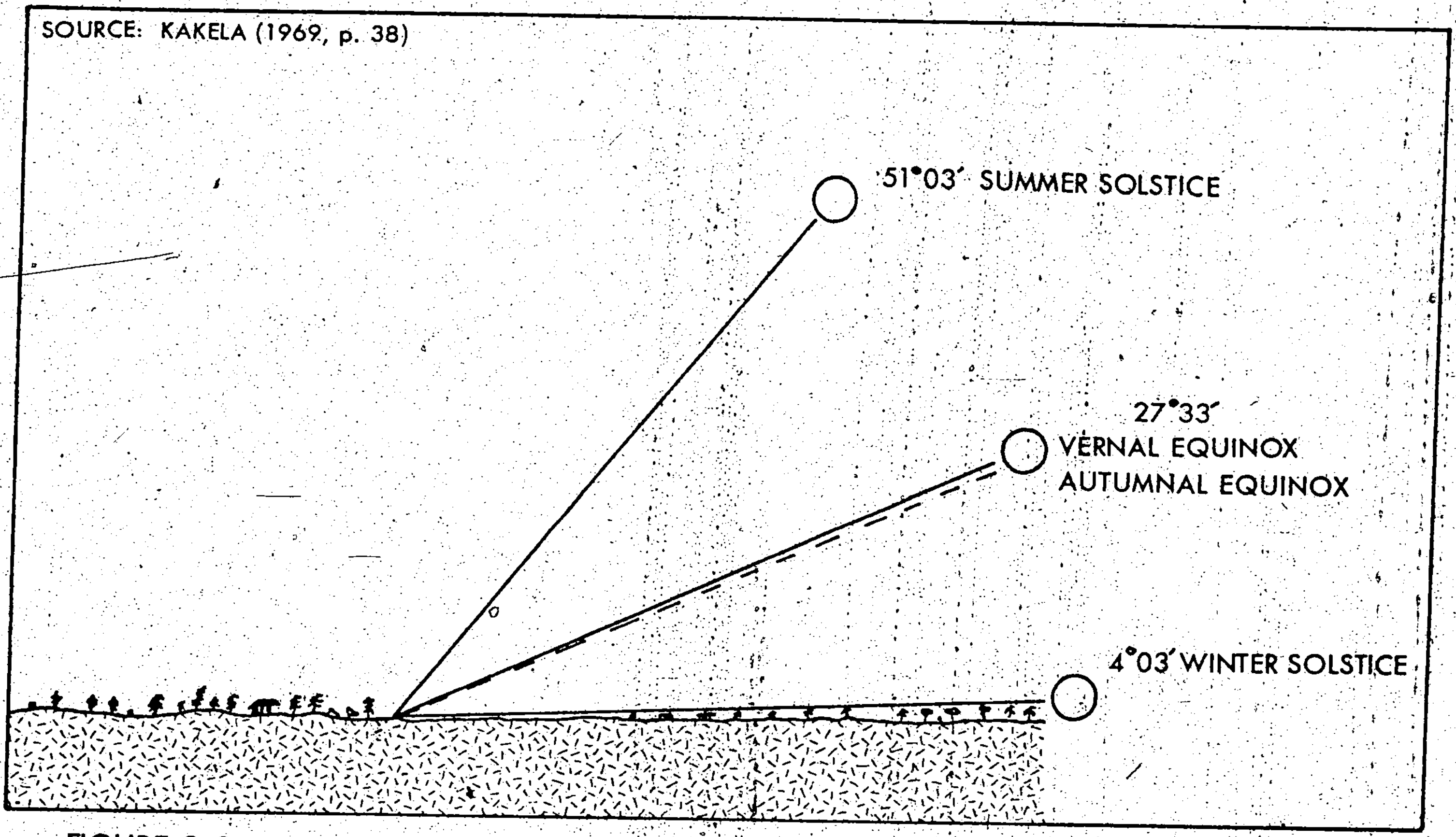
Temperature

The rate of soil formation and the type and structure of vegetation found in the Baker Creek Basin are strongly influenced by its continental climate which is characterized by short warm summers and long cold winters. The Köppen climatic classification for this area is 'Dfc' which is typified by a cold snowy forest climate, moist all year with cool short summers (Strahler, 1975, p. 249). Although located adjacent to an arm of the Great Slave Lake which does, to some extent, modify the climate, the study area is quite distant from any oceanic influences. The Pacific Ocean is approximately 1200 kilometers to the west, Hudson Bay lies 1050 kilometers to the east, and the Arctic Ocean

560 kilometers to the north. In addition, Hudson Bay and the Arctic Ocean are frozen much of the year and thus would not be effective in changing the continental nature of the climate even if they were closer to the basin.

The influence of latitude (approximately 62° 35' 30"N) of the study area is also important in producing the extremes of temperature which the Baker Creek Basin receives. At the winter solstice Yellowknife experiences less than five hours of solar insolation but on the date of the summer solstice it receives almost twenty hours. The sun angle is less than 4° above the horizon at solar noon, December 21, and less than 4° below the horizon at solar midnight on June 21 (Figure 2-2). Although frost may occur in early June and again in early September, it is normally light and of short duration, and the natural vegetation in the area has adapted to withstand it.

The higher sun angle in the summer increases the effectiveness of the insolation by decreasing the absorption and scattering of radiation by the atmosphere. Radiation will be absorbed or scattered by any particle in its path which has a diameter the same or greater than the wavelength of that radiation. Since larger particles such as ice crystals, water droplets and vapor, dust, chemical pollutants, smoke, etc. tend to be found in the lower atmosphere, the lower the sun angle the more radiation is prevented from reaching the ground surface. In high latitudes, such as the study area,



SOURCE: KAKELA (1969, p. 38)

FIGURE 2-2 ANGLE OF MID-DAY SUN ABOVE THE HORIZON AT YELLOWKNIFE winter is thus a time not only of fewer sun hours than the summer, but of less effective solar radiation. The mean annual monthly temperature range, approximately 45°C, is thus considerable (Figure 2-3).

Clouds attenuate solar radiation by reflection and absorption thus reducing the amount of insolation received at the earth's surface. The type and amount of cloud cover over an area has a direct influence on the net radiation it receives. Hay (1970, p. 91), in a study of net radiation over Canada, found that low-level cloud types possess the highest amount of reflectivity and absorptivity and these values decrease as cloud height type increases (Table 2-1).

Cyclonic systems and frontal activity are mainly responsible for the distribution of middle and high cloud over the Baker Creek Basin. The greatest cover of scattered clouds generally occurs in the afternoon when solar radiation is highest. There appears to be a seasonal distribution of cloud types. Winter is a period of low and middle cloud types, accounting for approximately 60% of the total, while convective cumuloform clouds constitute the same percentage of the total in summer (Burns, 1974, p. 181). Figure (2-4) shows a mean monthly distribution of cloud cover at the Yellowknife airport.

The portion of the basin immediately adjacent to the Great Slave Lake does receive a modifying influence from that water body. Due to the different heating and cooling

Table 2-1: Cloud Reflectivity and Absorptivity (Hay, 1970, p. 91)

Cloud Types		Month											
		J	F	M	A	M	J	J	A	S	O	N	D
Ci, Cc, Cs	R	0.23	0.23	0.23	0.22	0.21	0.20	0.20	0.21	0.21	0.22	0.23	0.23
	A	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Ac, As, Acc, Fc	R	0.52	0.52	0.52	0.51	0.51	0.50	0.50	0.51	0.51	0.52	0.52	0.52
	A	0.04	0.04	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.04	0.04	0.04
Sc, St, Fs	R	0.65	0.65	0.65	0.64	0.62	0.60	0.60	0.62	0.64	0.65	0.65	0.65
	A	0.08	0.07	0.06	0.06	0.05	0.05	0.05	0.06	0.06	0.07	0.08	0.08
Ns, Cb, Cu, Cu^+	R	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70
	A	0.10	0.10	0.10	0.10	0.09	0.08	0.08	0.09	0.10	0.10	0.10	0.10
Obscured	R	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70
	A	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10

FIGURE 2-3

MEAN MONTHLY TEMPERATURE AND PRECIPITATION
YELLOWKNIFE AIRPORT (1941 - 1970)

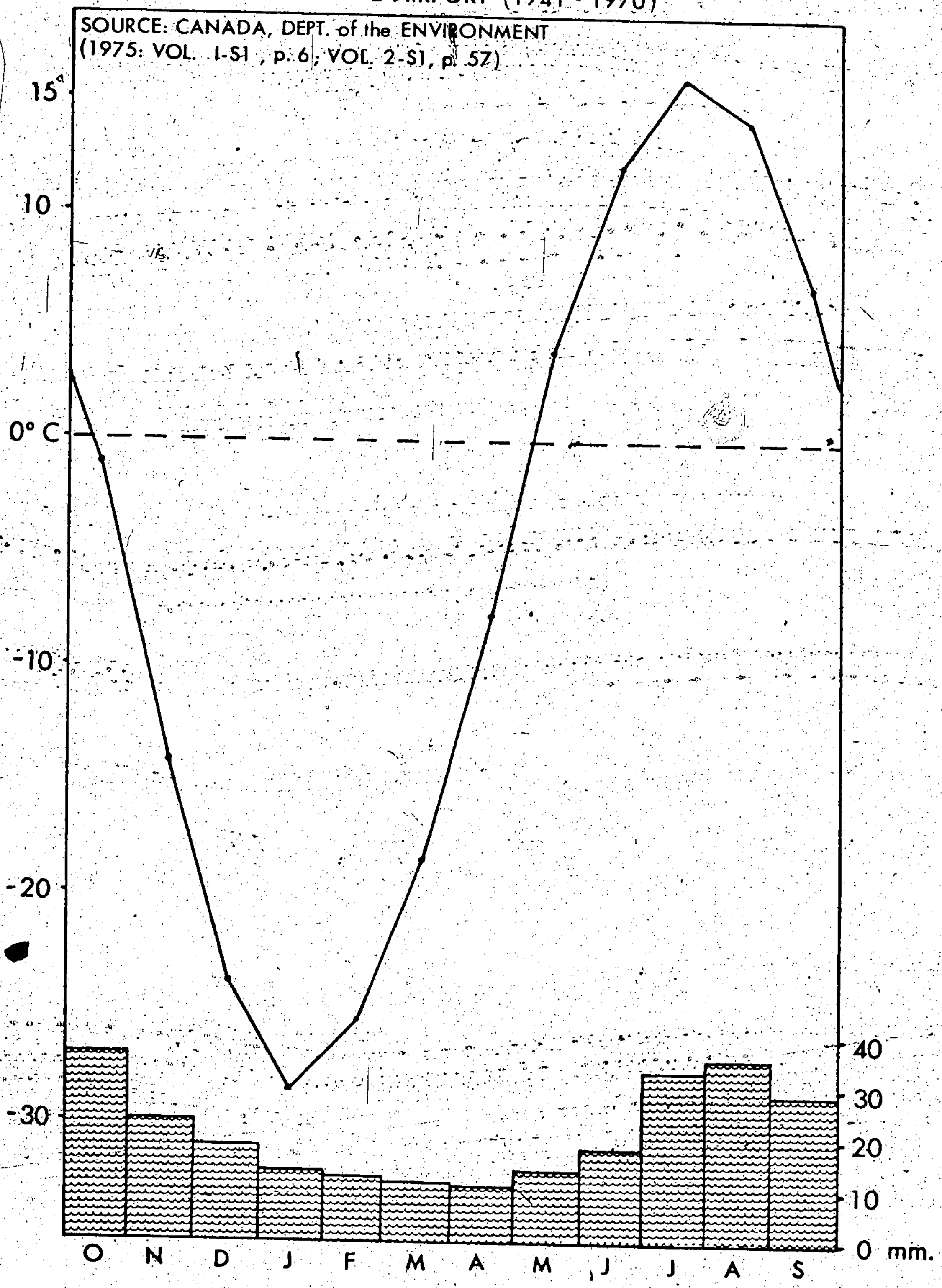
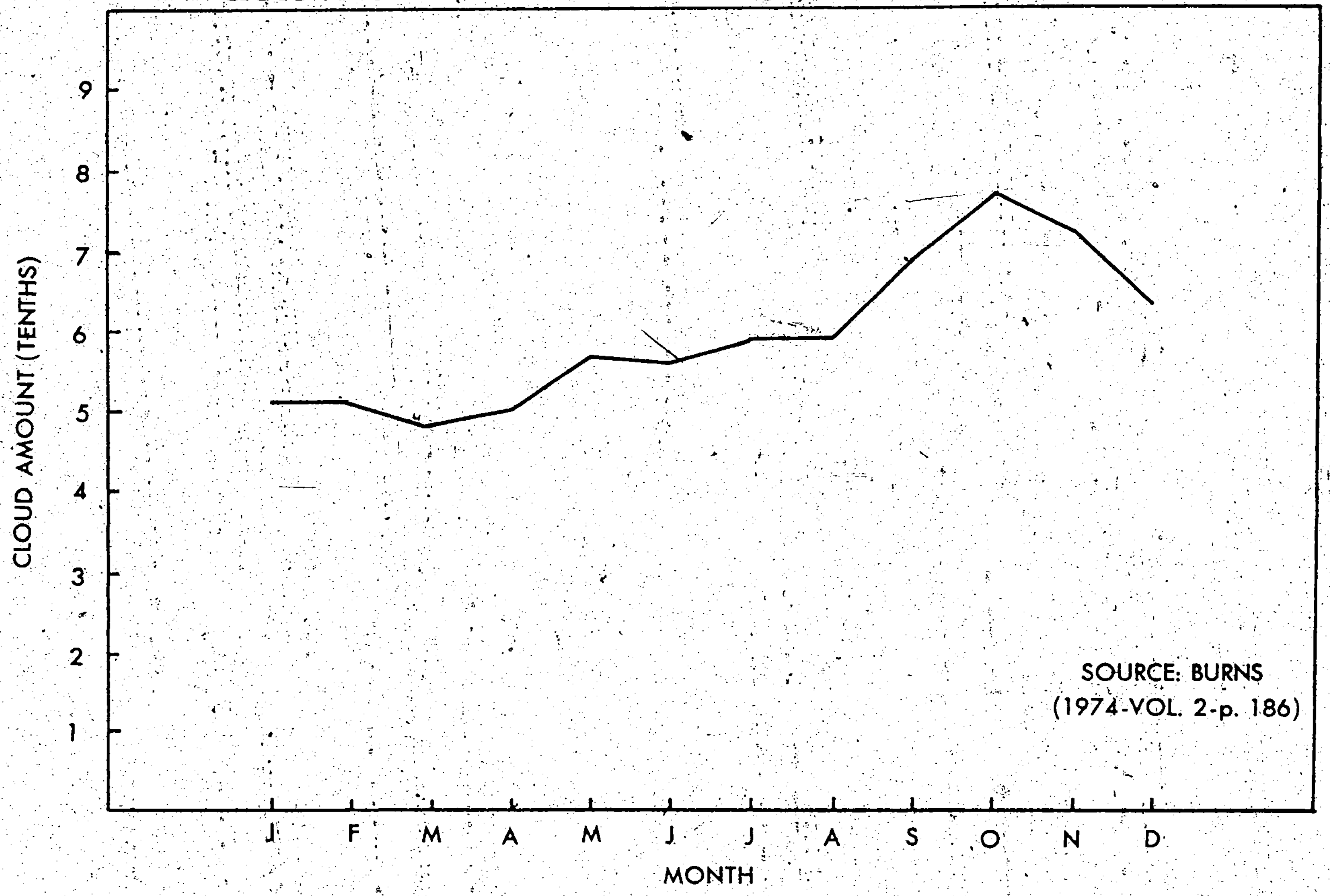

SOURCE: CANADA, DEPT. of the ENVIRONMENT
(1975: VOL. I-S1, p. 6; VOL. 2-S1, p. 57)

FIGURE 2-4

MEAN CLOUD AMOUNT (ALL CLOUD TYPES INCLUDED) YELLOWKNIFE AIRPORT 1953-1970



SOURCE: BURNS
(1974-VOL. 2-p. 186)

regimes of land and water, the cool land temperatures of the early spring may be prolonged by proximity to cold lake waters and, conversely, warm temperatures may persist into the fall due to the warmer water.

A low elevation, from approximately 150 to 275 m.a.s.l., and a low local relief tend to reduce the diurnal temperature range in the study area. Although afternoon and evening convectional storms may be present in the summer period due to intense heating of the ground surface, cyclonic storms, which can cause longer-term temperature fluctuations, are not as common as in more southerly locations.

Precipitation

The Baker Creek Basin experiences a low average annual precipitation. The 29 year mean annual precipitation for Yellowknife airport, between the years 1941-1970, is 250 mm (Table 2-2). There are several reasons for this low precipitation figure. The air mass which normally overlies the area is polar continental and has a limited moisture-holding capacity. If uplifted it will produce relatively little precipitation, but there is limited means for uplift to occur by summer convection or by the infrequent cyclonic storms. The maritime pacific air which does reach the study area has lost much of its moisture in passing over the mountains to the west and must be uplifted to altitudes exceeding those of the mountains for anyprecipitation to occur. The result of these factors is a low annual precipitation (Table 2-3). The precipitation which does occur tends

Table 2-2: Climatic Normals (1941-1970) for Yellowknife Aiport. (Canada, Dept. of the Environment, Climatic Normals Vol.1-51 and 2-51)

	J	F	M	A	M	J	J	A	S	O.	N	D	Y
Mean Daily Temperature (°C)	-28.6	-25.7	-18.6	-7.8	4.0	12.2	16.0	14.1	6.8	-1.2	-14.2	-23.8	-5.6
Mean Monthly Precipitation (mm)	13.7	12.2	11.7	10.2	14.0	17.3	33.3	36.3	28.2	30.7	23.9	18.5	250.0
Mean Rainfall (mm)	T	T	T	1.5	11.7	17.0	33.3	36.3	25.7	12.2	1.0	T	138.7
Mean Snowfall (cm)	14.7	13.2	13.0	8.9	2.5	0.3	0	0	2.5	18.5	25.7	20.1	119.4

to be concentrated in the summer and early fall when convectional uplift and cyclonic storms are most pronounced. The dominant anticyclone over the northwestern part of Canada during the winter months begins to weaken in the spring and as temperatures begin to rise and evaporation increases, the atmosphere becomes less stable and the paths of atmospheric depressions move into the area, increasing precipitation (Hare and Thomas, 1974, p. 133).

Wind

Wind speed, direction, and duration are important in the evaportranspiration regime of the study area. Wind provides a fresh medium into which water molecules may escape. Normally the higher the wind velocity and the longer it occurs the more evaporation is lost from a given surface. Advection of relatively dry air will increase evaporation and, conversely, humid air will lessen it. If the incoming air has passed over a heated surface and gained heat, it can transfer that sensible heat to the ground surface, thus aiding evapotranspiration. If the advected air is colder, however, evapotranspiration will be lower. Evans (1963, p. 71) indicates that warm dry advected air may in fact eventually lower transpiration rates of some plants. If the plant suffers dehydration, or if carbon dioxide concentration at the leaf surface becomes too great, stomatal closure may occur, effectively stopping transpiration. In the majority of cases, water deficit causes stomatal closure (Slavik, 1965, p. 157). Often, however, closure occurs too late to prevent the plant from suffering serious dehydration.

The density and height of the vegetation cover influences the microclimatic effects of wind velocities. In depressional peat bogs trees tend to be stunted and widely spaced permitting higher wind speeds and advection of heat from these areas, creating slightly lower air and ground temperatures (Johnston, et. al., 1963, p. 43).

A closed stand of trees will tend to slow any wind present and thus reduce evapotranspiration, while an area of low herbaceous vegetation would receive the full effect of wind, raising evapotranspiration. It should be noted, however, that the greater depth of rooting of most tree species compared to bushy vegetation would provide a greater amount of water available for evapotranspiration in dry periods and thus reduce the effect of the wind.

In non-vascular species, height can have a positive effect upon evaporation rates. Sphagnum is associated with peat plateaus which tend to be hummocky and raised somewhat above the surrounding organic terrain. These can contribute to turbulence and thus raise the evaporation rate. True mosses and lichens have less microrelief and, other factors being equal, less evaporation.

Monthly average duration and intensity wind roses for Yellowknife are shown in Figure (2-5). The wind direction is indicated by the bearing of the lines. The lengths of

Table 2-3: Mean Daily Temperature and Total Monthly Precipitation at Yellowknife Airport 1971-1976. (Monthly Record)

		J	F	M	A	M	J	J	A	S	O	N	D	Y
1971	Mean Daily Temperature (^oC)	-31.9	-23.8	-17.2	-4.2	7.8	15.1	16.0	14.4	7.7	0.1	-14.4	-27.3	
	Total Precipitation (mm)	19	9.6	13.7	7.6	20	12.4	11.4	61.2	26.6	36.8	22.3	11.4	212
1972	Mean Daily Temperature (^oC)	-31.3	-30.1	-17.2	-10.6	4.7	13.4	16	14.2	2.8	-4.7	-15.3	-27.0	
	Total Precipitation (mm)	5.1	11.9	16.5	15.2	4.3	15.7	37.3	31.2	37.1	35.8	20.8	1.1	204
1973	Mean Daily Temperature (^oC)	-25.3	-26.2	-17.0	-5.5	11.1	15.6	18.4	14.2	8.8	0.8	-15.3	-24.9	
	Total Precipitation (mm)	11	8	21	90	10	14	25	127	16	45	27	16	329
1974	Mean Daily Temperature (^oC)	-30.4	-27.4	-23.2	-6.4	4.3	14.0	16.0	12.3	4.3	-6.2	-11.5	-20.8	
	Total Precipitation (mm)	16	8	13	4	29	35	75	59	48	45	26	46	405
1975	Mean Daily Temperature (^oC)	-33.4	-24.9	-20.4	-2.5	6.7	15.9	18.3	14.2	8.3	-2.4	-17.3	-25.8	
	Total Precipitation (mm)	11	8	7	10	13	2	10	85	24	39	14	18	243
1976	Mean Daily Temperature (^oC)	-28.7	-25.6	-20.6	1.2	8.7	12.7	17.1	15.6	9.5	-0.7	-9.5	-25.8	
	Total Precipitation (mm)	19	17	14	9	17	39	25	38	45	12	13	12	258

the lines are a function of hourly duration and mean wind speed. A distinct southerly component is evident for the summer months. This is probably due, in part, to a developed water/land breeze from the Great Slave Lake. Any limiting effects on evaporation from advected humid air off the lake surface, however, are probably countered by the intense ground surface heating prevalent at that time.

LANDFORMS

The study area is located in the Canadian Shield near its western margin. It is characterized as an ancient plain of low relief with an irregular rolling surface comprised of rocks of Precambrian age. Local relief within the basin seldom exceeds 60 meters. Berry Hill, the highest point in the Baker Creek Basin, has an elevation of 268 m.a.s.l., and is 113 meters above the level of Great Slave Lake. The portion of the basin underlain by granite and granodiorite exhibits less local relief and has a higher average elevation than that part composed of rocks in the Yellowknife Group (Jolliffe, 1945)(Figure 2-6).

Pleistocene glaciation has scoured the region, smoothing and polishing the rock outcrops and creating features such as roches moutonées, striations, chattermarks and crescentic gouges. Glacial ice also created or deepened existing depressions of various sizes in the rock mass, especially along fracture zones. Today these depressions contain water bodies, sedge meadows or peat bogs. The many lakes can be

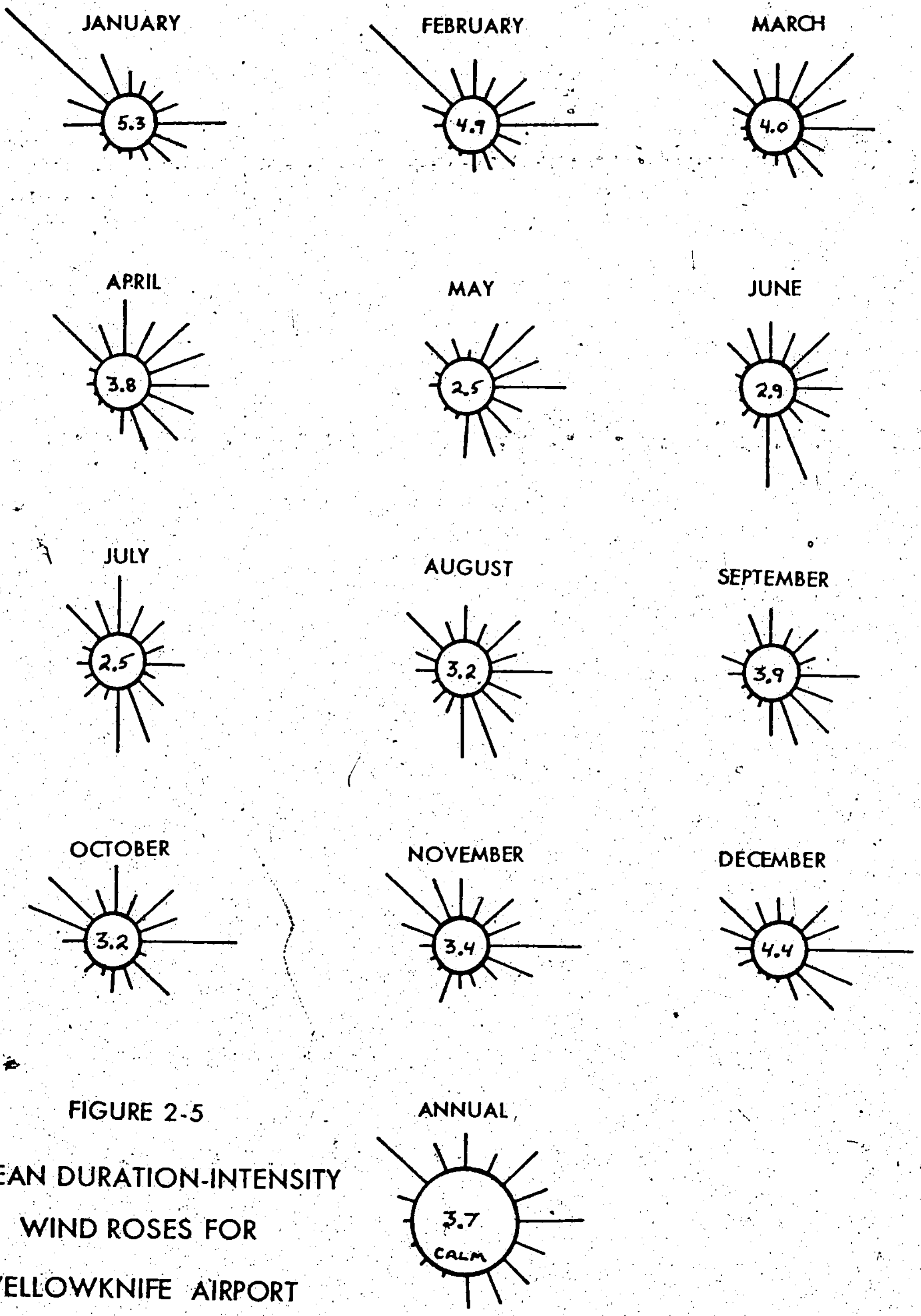
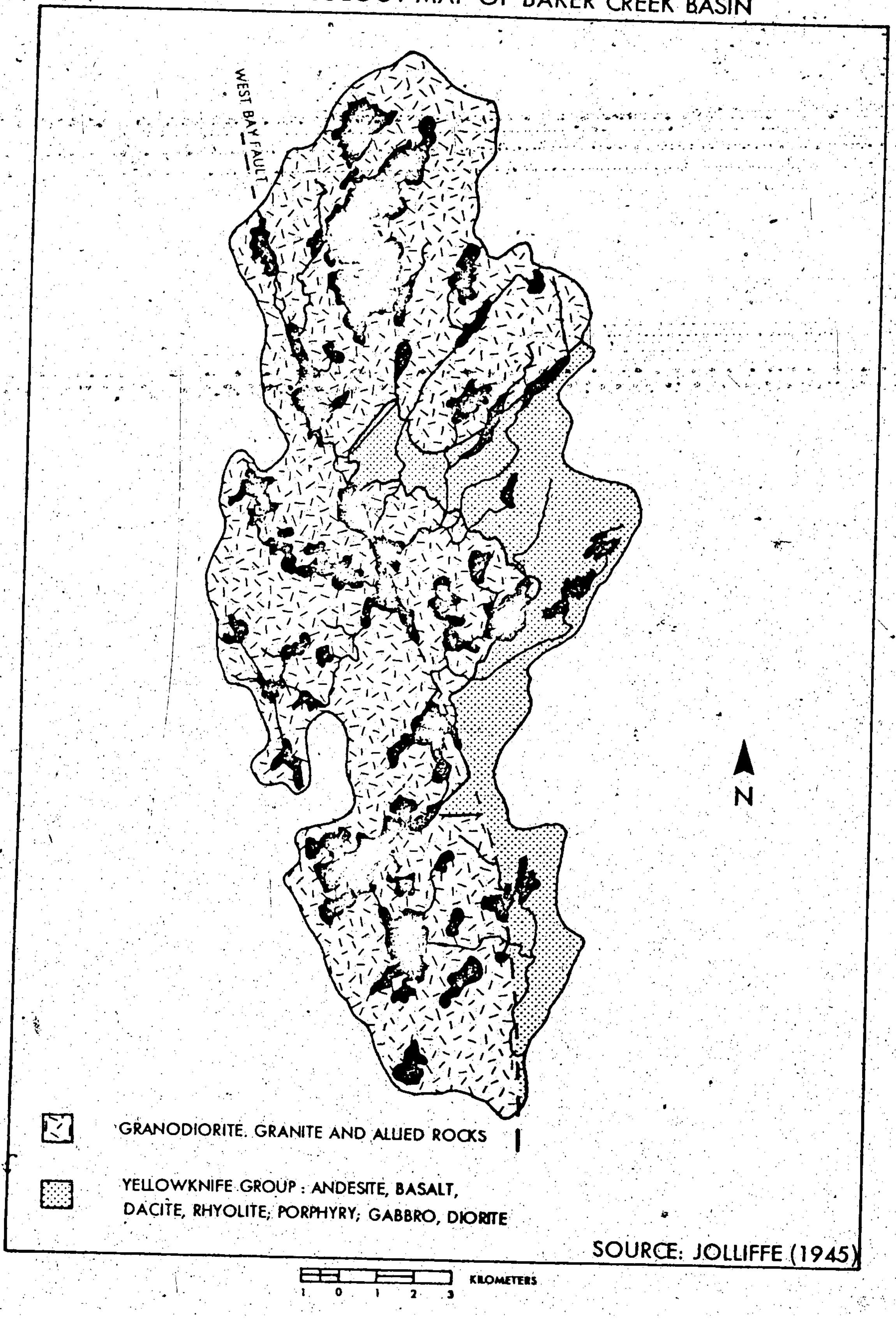


FIGURE 2-5

MEAN DURATION-INTENSITY WIND ROSES FOR YELLOWKNIFE AIRPORT 1957-1966

SOURCE: KAKELA (1969, p. 51)

FIGURE 2-6
BEDROCK GEOLOGY MAP OF BAKER CREEK BASIN



SOURCE: JOLLIFFE (1945)

divided into those which are deep and cold, and those which are shallower and thus will warm more in the summer.

There appears to be a genetic sequence connecting lakes with organic terrain. As vegetation encroaches upon the shallower lakes in the basin the lakes become smaller and shallower and, in time, will be covered with vegetation. At this stage the lake has become a sedge meadow. As more and more organic material is added to the depression, the water content decreases. Sphagnum becomes a major vegetational constituent and a subsurface layer of peat appears. With a much lower percentage of water present, permafrost is able to move into the area. Consequently the peat is thrust up into a hummocky elevated peat plateau which is better-drained than the previous peat bog. Black spruce may appear and, given time, a dense stand of these trees may replace the open peat area. There is widespread occurrence of each of these stages in the depressional areas within the basin.

BEDROCK GEOLOGY

The study area lies within the eastern portion of the Mackenzie River Basin. A recent study of the basin by Environment Canada (1972), includes the following description of the shield in this area:

> Its smooth, even horizon indicates an old, almost all-subduing erosion surface which at one time was at least in part buried under Paleozoic strata. The geologic time scale includes the development

> and partial dissection of a peneplain on the Archean rocks during Proterozoic times and then the subsequent burial and exhumation of this surface once, or perhaps twice during the Paleozoic era. Finally the area was scoured during the stage of Pleistocene glaciation (p. 25).

The importance of the bedrock geology to this study lies largely in the different albedo patterns of the major rock divisions, although its influence on landforms and soil parent material is also significant. As can be seen in Figure (2-6), the Baker Creek Basin is composed of two distinct rock groups. Approximately 85% of the area is underlain by granite and granodiorite of the Archean Age, while the remainder is formed of older rock in the Yellowknife Group. The latter consists of andesite, dacite, basalt, rhyolite, tuff and agglomerate. The area comprised of granodiorite and granite exhibits a much lighter tone and thus a higher albedo than does the area in the Yellowknife Group. This will tend to cause a reduction in the net radiation available to the ground surface in the greater part of the study area. The albedo factor in the water balance will be discussed in Chapter Five.

The presence of many faults in the portion of the basin underlain by granite and granodiorite should be noted, especially the West Bay Fault which trends northeast to southwest and divides the basin approximately in half. These faults are among the largest known steeply dipping displacements of the earth's crust (Campbell, 1948, p. 244). Many of the lakes in the basin are located in conjunction with the West Bay Fault and the drainage pattern of Baker Creek itself is largely controlled by it (Figure 2-7).

SURFICIAL DEPOSITS

The Baker Creek Basin was heavily glaciated by Keewatin ice moving westward toward the Mackenzie Mountains (Figure 2-8), and the present landscape is largely a result of this. Any soils or overburden which may have been formed during preglacial, early glacial or interglacial times would have been removed or altered by the Wisconsin ice advance. As a result, most of the surficial deposits in the study area are of glacial origin, either deposited directly by the ice or by glacio-fluvial or glacio-lacustrine mechanisms. The remainder were formed during the past 9,000 years (Prest, 1970, p. 706, Fig. XII-15).

The study area lies within what has been termed the 'driftless zone' (Wilson, 1939).

> The lack of drift over areas of thousands of square miles is a striking geological feature of the Territories that has been of great value to prospectors, for some of the most accessible regions are the least covered with drift. A zone of comparatively bare rocks, perhaps averaging fifty miles in width, extends along the north shore of Lake Athabasca, turns north along the east side of Slave River valley (there is silt to the river bank), rounds the eastern arm of Great Slave Lake, and stretches from the north arm to Great Bear Lake (Wilson, 1939, p. 125).

The reason for the minimal amount of drift in this area is thought to be because this was in the zone of dominant

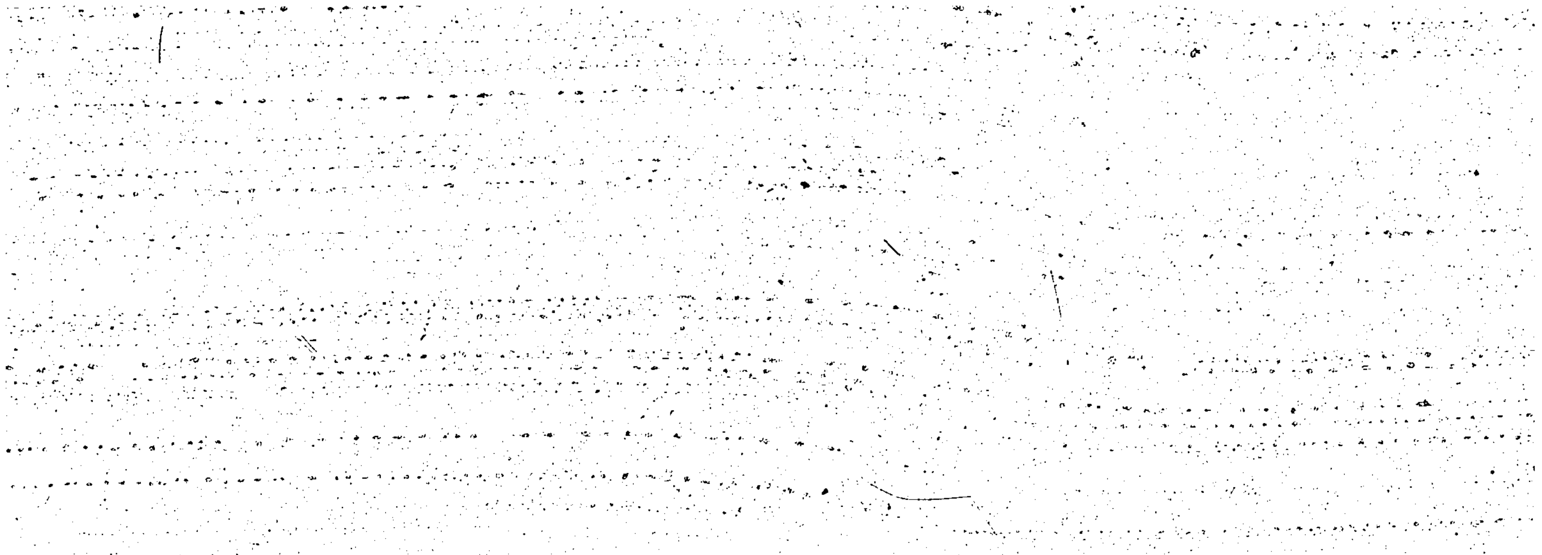
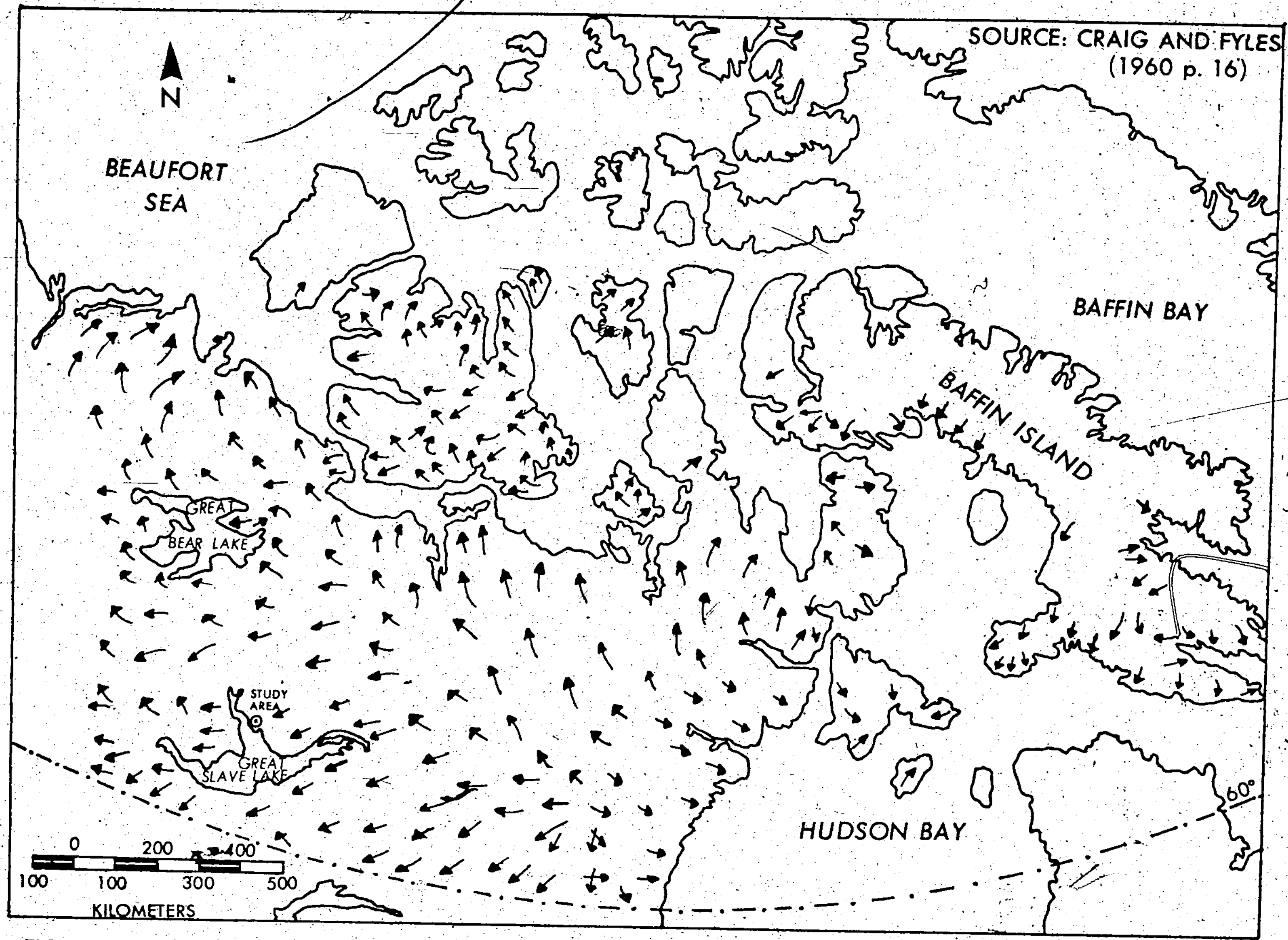


Figure 2-7: Northern portion of the Baker Creek Basin facing northwest. Duckfish Lake is in the center of the photo. Note fault lying across photo in bottom center and dividing the pink granite and granodiorite areas above from the grey rocks of the Yellowknife Group below.



SOURCE: CRAIG AND FYLES (1960 p. 16)

FIGURE 2-8 GENERALIZED DIRECTIONS OF GLACIAL FLOW IN THE NORTHWEST TERRITORIES compressive flow near the accumulation core of the Laurentide ice sheet. Therefore, erosion and transportation of material prevailed over deposition (Sugden, 1977, p. 38).

The drift which does exist is located, for the most part, in the numerous depressions typical of Canadian Shield topography. The glacially-scoured and rounded upland areas are mostly drift-free. A possible explanation for this is that the area was once covered by Glacial Lake McConnell which formed when the front of the Wisconsin ice sheet retreated beyond the area. At its maximum extent, this lake extended from Great Bear Lake through Great Slave Lake southeast to Lake Athabasca (Craig, 1965, p. 535). Jolliffe (1945), found beach deposits in the Baker Creek Basin at elevations over 73 meters above present levels of Great Slave Lake, while Lindsey (1952, p. 535), found them at 213 meters above present levels. Wave action would have washed much of the drift from the upland areas into the depressions. Lacustrine material consisting mainly of silt and clay would originally have been deposited as a layer over the entire study area. However, as lake levels fell, wave action would have swept clean the upper rock areas increasing the silt and clay content of the depressions. Today these sediments underlie most of the poorly-drained organic areas of the basin.

It should be noted that the present upland rock areas are not completely free of surficial material. They are characterized by numerous cracks and fissures, many of which have trapped glacial drift, lacustrine material, alluvium and aeolian deposits and given rise to pockets of soil where vegetation has established itself. This tends to increase detention storage and reduce runoff values from what would normally be expected in areas of more rounded and smooth bedrock (Wight, 1973, p. 17).

The valley of Baker Creek is comprised of several meters of gravels and sands resting on bedrock and overlain by thinly stratified lacustrine sediments. The gravels are considered to be of late Pleistocene age and the post-glacial history of Baker Creek has been one of dissection through the lacustrine deposits and locally through bedrock (Bateman, 1949, p. 8).

SOILS

The origin of the soils present in the Baker Creek Basin dates to the retreat of the Wisconsin ice front and subsequent lowering of Glacial Lake McConnell to levels approaching that of the present level of Great Slave Lake (151 m.a.s.l.). Their profile development has been limited, in part, by the subarctic climate and poor drainage conditions created by the presence of lacustrine sediments in the depressions (Raup, 1947, p. 19). The cold temperatures slow organic decay and prohibit the vertical movement of soil moisture necessary for profile development much of the year. Dickson (1947, p. 162), believes that in shield areas geology is the most important factor in creating the soil conditions due to the large amount of crystalline rock which is very resistant to soil-forming processes.

The combination of these factors have created soils which are classes as either intrazonal or azonal depending on the drainage situation (Bourne, 1963, p. 22). Zonal soils are rare if not absent from the study area. South of the southern limit of discontinuous permafrost in the Canadian Shield the dominant soils are podzolic (Hoffman, 1974, p. 216). The Baker Creek Basin is located in a broadly-defined zone of Orthic Gleysols (Clayton, *et. al.*, 1977, vol. 2, p. 232). For a delimitation of this zone and a detailed description of soil types see *Soils of Canada*, Canada Department of Agriculture.

The low-lying depressions are lined with fine, impervious clay and drainage from these areas is thus impeded, giving rise to intrazonal organic soils and large tracts of sedge meadow and muskeg, with great moisture storage capacity. As the study area was once part of the basin of Glacial Lake McConnell, the clays in these low-lying areas are lacustrine in nature and form part of rhythmite sequences. They possess a laminar structure normally consisting of alternating layers of silt or silty-clay (Leggett and Eden, 1960, p. 3).

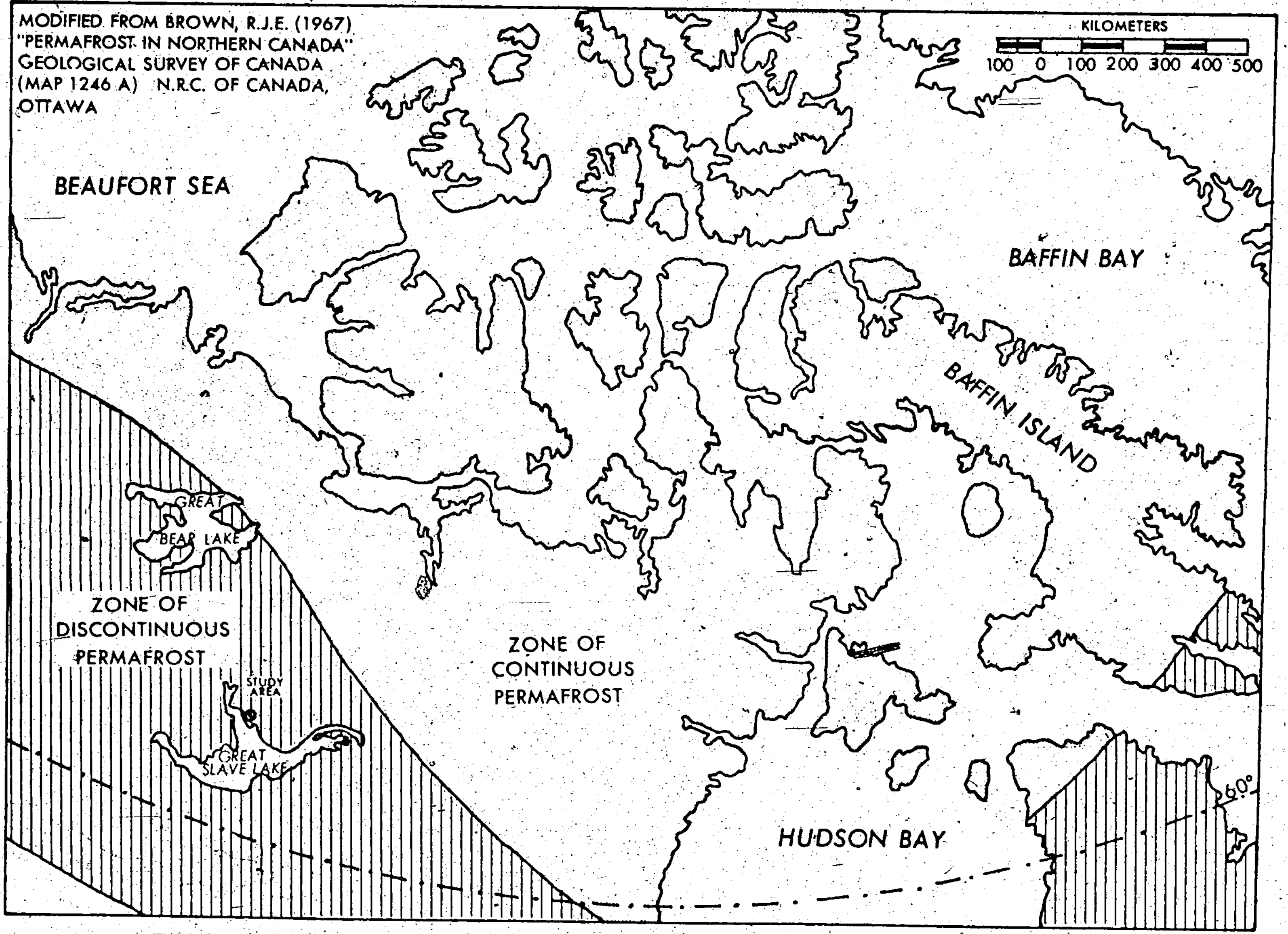
The upland rock areas have undergone considerable mechanical weathering. Frost action, as well as other rock fracturing processes, have created cracks and crevasses in the bedrock in which azonal soils may be found. These soils have a much lower moisture storage capacity than do the intrazonal soils and are not nearly as extensive within the basin.

Another limiting factor for soil development in the area is related to the fire history of the study area. Much of the basin has been burned over at least once. Fire can rapidly destroy the humus layer of zonal soils and, depending on the moisture content of the peat, burn for days or weeks in muskegs and peat plateaus. Replenishment of humus in subarctic areas is a very slow process due to the cold climate.

PERMAFROST

The study area lies within the zone of discontinuous permafrost (Figure 2-9). It is widespread, however, and its greatest extent is in the organic terrain where the active layer is about one meter thick (Brown, 1973, p. 28). Mean annual ground temperatures in the Yellowknife area range from -1.8°C to 1.5°C with the lowest temperature occurring in the peat bogs and the highest on the exposed bedrock (Judge, 1973, p. 120).

In a study of permaf[illegible]t occurrence in various types of terrain, Brown (1973, p. 29) tested eight sites in the Yellowknife area and found permafrost to be present in only two. It was not found in exposed bedrock, till, a beach ridge or a burned-over peat area. It was located in two peat bogs at 1.6 meters below a surface cover of <u>Sphagnum</u> and



MODIFIED FROM BROWN, R.J.E. (1967)
"PERMAFROST IN NORTHERN CANADA"
GEOLOGICAL SURVEY OF CANADA
(MAP 1246 A) N.R.C. OF CANADA,
OTTAWA

FIGURE 2-9 PERMAFROST IN THE NORTHWEST TERRITORIES lichen; and 1.68 meters below a ground cover of sedges and mosses. The thickness of the permafrost zone under these peat bogs was 50 meters and 30 meters respectively.

The Giant Mine of the Giant Yellowknife Mines Ltd., is located in the southeast portion of the study area adjacent to Yellowknife Bay. Areas of permafrost have been encountered in the upper levels of the mine above 76 meters. All of these areas of permafrost were found to be immediately below the valley of Baker Creek which has an insulating cover of from 15 to 18 meters of clay and gravel (Espley, 1969, p. 60).

Bateman (1949, p. 11), indicates that the permafrost may have had its origin in late glacial time and has been preserved by the insulation of clay, silt, sand and muskeg. This tends to produce a self-perpetuating situation as the organic terrain protects the permafrost underneath which prohibits internal drainage and creates conditions favorable to maintenance of organic terrain. Brown (1969, p. 25), believes that any area which was inundated by a glacial lake following Pleistocene glaciation, such as the study area, would lose any previously-formed permafrost due to the warmer water temperature. According to this view the permafrost located in the Baker Creek Basin would have had to have originated after the area was free of water from Glacial Lake McConnell.

The presence of permafrost has a major effect on the water balance patterns of an area. It limits root development and thus growth patterns of vegetation. If the roots of a tree are slowly enclosed by a rising permafrost table, the remaining root area will not be large enough to support the tree and it will die. If a plant cannot develop the root mass it normally possesses in non-permafrost areas, it will produce a stunted form.

Drainage is impeded by the presence of permafrost prohibiting groundwater flow. Approximately half of the basin is composed of exposed bedrock (Lord, 1951, p. 4). Depressional areas underlain by impervious clays and permafrost constitute the remainder. Because of these factors groundwater flow is not of major importance in the water balance of the study area.

HYDROLOGY

One effect of glaciation and subsequent inundation by Glacial Lake McConnell of the study area has been to create a deranged drainage pattern. Glacial deposition combined with a low topographic relief has fostered a situation of internal drainage into local depressions, many of which have no outlet and only contribute to Baker Creek drainage in those years in which they overflow. Depressional storage in Baker Creek Basin is thus very significant and detracts from annual runoff. Movement of water between lakes is often by interflow, slow seepage through organic terrain.

The drainage pattern of Baker Creek is controlled to a great extent by the West Bay Fault (Figure 2-10). Many tributaries flow in a southwest direction toward this fault. In a study of the evapotranspiration regime of the Baker Creek Basin, Wight (1973, p. 175), states:

> It is probable that Baker Creek owes its status as a significant flowing water body to the exceptional interconnection properties afforded by the West Bay Fault which dominates the spine of the basin. A short distance away from this narrow corridor it is likely that many semi-permanent internal drainage basins dominate the drainage area.

Although groundwater flow is not of major significance within the study area, it is not absent. Groundwater movement does occur in the bedrock in fault zones and in areas of extensive jointing and rock fracturing (Brandon, 1965, p. 20). In a study of gold deposits in the Yellowknife area, Boyle (1961, p. 171), comments on the origin of groundwater encountered in the local mines:

> The chemical and physical facts such as temperature, pressure and elemental content of the waters suggest that they are meteoric waters which have penetrated deep into the rocks along late faults and fractures. In time, these meteoric waters became impounded and reached a chemical equilibrium with the rocks and minerals with which they are in contact. They start to flow only when underground workings intersect the fractures and faults, and in some cases their flow continues only until the reservoirs along the late faults and fractures are drained. In other cases they probably receive continuous additions from the surface and maintain a fairly constant flow.

Groundwater flow is also restricted by the presence of permafrost within the study area. Standing or moving water inhibits the formation of permafrost and contributes to the

Figure 2-10: Baker Creek Basin at night. Ryan Lake is in foreground. Note general alignment of lakes along West Bay Fault from lower center left to upper center right of photo.

degradation of that already present. Due to the heat storage capacity of water, its presence indicates an excess of thermal energy (Johnston, et. al., 1963, p. 41). Consequently there is no permafrost below water bodies or wet depressions within the Baker Creek Basin. As noted above, however, these areas inhibit groundwater recharge due to the presence of a clay or silty-clay layer.

Variations of lake size within the basin create real differences in net annual water loss or gain from their surfaces. The amount of evaporation from waterbodies in subarctic regions is partly a function of their depth. The rate of evaporation from free-water surfaces is determined by the vapor pressure difference between a body of water and the air above the water surface. This relationship is known as Dalton's Law and was first recognized in 1802. In 1915, V. K. Meyers proposed a modification of Dalton's Law based on the premise that the effect of atmospheric pressure is compensated for by the change in vapor pressure with change in altitude (Veihmeyer, 1964). The expression of these theories in equation form may be found in Appendix A.

The vapor pressure of a water body increases with the temperature of the water. A shallow body of water may become ice-free and have its temperature raised more quickly in the spring than a deeper water body. This is due to several factors. The lower albedo of water compared to ice and snow increases the amount of net radiation absorbed by the surface and this contributes to melting and warming. Once the ice has melted, light is able to penetrate to the shallow lake bottom. That, combined with some heating from below and the lack of spring overturn which brings colder water from below to the surface in the deeper lakes, raises the surface temperature. Thus more evaporation is able to take place from shallow lakes at this time.

During the late spring and early summer, deep lakes will experience vertical convection currents which tend to distribute the surface heat to the lower layers. The result is that their volume remains relatively cool compared to shallower lakes and less evaporation will occur (Chow, 1964, pp. 23-17).

In the fall and early winter, however, a deep lake will usually remain ice-free longer than a shallow one. This is partially due to the vertical convection currents which bring the now relatively warm sub-surface waters to the surface. The result is that if ambient air temperatures are lowered considerably, large amounts of evaporation can take place. Also the lower albedo of open water as compared to ice and snow increases the effectiveness of any solar radiation which is present. It should be noted that this albedo difference is of greater significance in May and early June when the deeper lakes are still ice-covered than in October because of the much greater net radiation in the earlier months.

Evaporation from free-water surfaces occurs when the vapor pressure of the water is greater than that of the adjacent air. As the temperature of a liquid is increased, more kinetic energy is imparted to its molecules and thus more are able to escape from the surface, and evaporation increases until saturation of the overlying layer of air is approached. Conversely, if more molecules of water are entering the water surface from the adjacent air than are escaping, condensation is taking place.

In subarctic regions large water bodies can stay ice-covered well into, if not throughout, the month of June. This means that ambient air temperatures can be quite high and condensation on the ice is a common phenomenon. Annual evaporation is usually expressed as a net value which would be decreased by any condensation. Because of this and earlier reasons, the larger lakes would have a lower net annual evaporation.

VEGETATION

The Baker Creek Basin flora is composed of plant species which have adapted to poor growing conditions. Long periods of extreme cold and physiological drought, shallow infertile soils, a short growing season, sporadic permafrost and poorly-drained, acidic muskegs all detrimentally affect the growing conditions.

Conifers are the dominant tree type found in the basin. They are cold-hardy and due to their evergreen nature, except for the larch, they are able to carry on photosynthesis in the spring and fall when the deciduous trees have no leaves.

Thus they are able to more effectively make use of the limited solar radiation available. Their needles are also advantageous in that they have a waxy coating and a small surface area which contribute to the prevention of dangerous water loss from the plant.

The most common conifer in the basin is black spruce. It is less frost-tolerant than white spruce, which is also present, but is able to occupy a larger variety of sites. Although it is normally situated in wet acidic muskeg depressions, it was frequently found in crevasses on upland rock areas within the basin. It has a wide, shallow rooting system which enables it to cope with high permafrost tables.

White spruce was not found to be a common species within the basin but is a major species in most subarctic areas of the world. It demands a better-drained habitat than does black spruce and is found in great numbers on the sandy beach deposits outside the study area.

Jack pine is the dominant conifer on the well-drained upland areas. It has a deeper taproot than do the previous two species and grows best on sandy beach deposits where the permafrost table is quite low or absent. In the basin it is found predominantly in the fissures and hollows of the upland rock areas which it shares with white birch and, to a lesser extent, aspen poplar. Jack pine is important as a primary colonizer in recently burned-over areas. It, along with black spruce, possesses serotinous cones which open to permit distribution of its seeds only after the ascent of water to the cone has ceased with the death of the tree. In the case of jack pine it is thought that fire initiates the opening of the cones by burning off coatings of resin (Daubenmire, 1974, p. 327).

The remaining coniferous species in the study area is larch. As with the spruce, it has a shallow spreading root system which enables it to cope with the permafrost condition. It is found in the poorly-drained depressions along with black spruce. Larch rarely occurs in large stands and is not an important species quantitatively within the basin.

Of the deciduous species, only white birch was found in large numbers within the study area. It also has a shallow root system and although it is able to grow in a variety of sites, it prefers well-drained sandy soils. It is the dominant deciduous species on the upland rock areas, sharing these locations with jack pine.

An important adaption to northern climate which white birch possesses is a thin chlorophyll layer just under the bark which enables it to carry on photosynthesis in the spring before its leaves have appeared, or in the fall after they have been dropped.

While aspen poplar is an important deciduous species in the north, extending to the treeline in many areas, it was found to be sparse in occurrence in the Baker Creek Basin. It was present in large stands, however, in the sandy beach deposits south and east of the study area. Balsam poplar also occurs rarely within the basin, usually along water courses.

Willow and alder, while technically tree species, are treated here as shrubs. They are extremely widespread and exist on almost every type of site. Many species of the willow family are phreatophytic and are found along water bodies. In sufficient numbers they can add substantially to the evapotranspiration of an area by drawing upon water which would otherwise be lost to the system as runoff.

Understory vegetation consists of a variety of healthy shrubs, low herbaceous plants, grasses, sedges, rushes, mosses and lichens. A complete list of species will be found in Appendix C and a discussion of the plant associations is developed in Chapter Four.

Lichens are prevalent on the rock outcrops. The most common are the green and black crustose lichens which are primary colonizers and aid chemical and mechanical weathering in breaking down the rock structure. <u>Cladonia spp.</u>, commonly known as reindeer moss, is a fruticose lichen which forms mats on depressions in the rock surface and acts as a sponge in retarding runoff.

Mosses, especially <u>Sphagnum</u>, are widespread in the basin in depressional muskeg sites. They are also found overlying fissures in the rock areas which collect water during snow melt or after rains.

CHAPTER THREE

LITERATURE REVIEW

INTRODUCTION

A number of studies have been performed by people in a variety of scientific disciplines involving the subject of soil moisture storage. For example, botanists have been interested in the amount and availability of water to plants in general, under various soil and climatic conditions. Agronomists and agricultural engineers have been more specifically interested in the practical aspects of crops and cropping patterns and, not surprisingly, the majority of vegetation studies dealing with soil moisture retention have been carried out for this purpose. Soil scientists are involved with the physical relationship between soil water and such factors as size and type of soil particles, structural arrangement, porosity, soil suction and soil temperature. Hydrologists have been concerned with the movement of water in the soil, the effects of the soil surface on runoff and, in studies such as the present one, of the variation in amount of water stored in soils and its effect on the water balance.

This chapter is a consideration of the findings of some of these studies as they relate to the present thesis. It is divided into three areas; soil factors, plant factors and climatic factors. Related studies in subarctic areas, though not specifically dealing with soil moisture storage, are included, especially those involved with the role of lichens and mosses in the water balance.

In this thesis the emphasis is placed on water stored in the unsaturated zone of the soil, i.e., that portion above and not including the groundwater table. Remson and Randolph (1962, p. D-2), divide the unsaturated zone into three parts; the capillary fringe, the intermediate zone and the belt of soil water. In the capillary fringe, the lowest layer, the pressure is less than atmospheric so that capillary water is able to extend above the ground water table against the force of gravity. This water is continuous with the ground water. In the uppermost layer, the soil water zone, moisture is available to the roots of plants and/or is susceptible to evaporation from the soil. The role of the intermediate zone is basically one of gravity transfer of excess moisture from the soil water zone to and beyond the capillary fringe.

The concept of field capacity is applicable here and is described as "the amount of water held in a soil after excess has drained away and the rate of drainage has become slight or zero, a state usually reached in two or three days after rain or irrigation on pervious soils" (Penman, 1963, p. 46). Detention storage refers to the water over and above field capacity which will be lost to drainage. Retention storage is the amount of water up to and including the field capacity of a given soil less the amount below the wilting point. In practice some of the water in detention storage is available for evapotranspiration on its journey through the zone of soil water (Laycock, 1967, Appendix B, p.1.), and this tends to make precise measurements of field capacity difficult. The wide occurrence of poorly-drained, intrazonal, organic soils in the Baker Creek Basin also confuses the use of the field capacity concept. Many of these areas are underlain by impeding layers of permafrost and/or bedrock. After a period of precipitation there is often considerable surface detention storage, much of which will be eventually evaporated rather than contributing to the runoff. This problem will be developed later in this chapter.

Another term usually associated with field capacity, wilting point, denotes the lower limit of retention storage. It is defined as the moisture content of the soil at which plants are no longer able to extract sufficient water to sustain growth (Linsley and Franzini, 1964, p. 387) and as such is a botanical concept and only partly related to soil or hydrological conditions. Plants will lose turgor and wilt because they have exhausted the supply of readily available water surrounding their root zone and are unable to create enough osmotic pressure to oppose the force of gravity and/or of colloidally-bonded particles holding the remaining water in the soil.

There are many factors which affect the amount of moisture held in the unsaturated zone of the soil. They include such soil properties as texture, structure, depth, amount of organic matter present, stratification and temperature (Kelley, 1954, p. 78). Vegetation effects are depth and structure of rooting, extent of cover and differential transpiration rates, although the latter is a controversial subject.

In addition to those determinants of soil moisture storage, studies of climatic elements involved in potential and actual evapotranspiration are discussed. Such factors as solar radiation (the energy supply available for the evaporation and transpiration of moisture), temperature, precipitation and albedo of different surfaces are included.

SOIL FACTORS

> The capacity of soils to absorb and retain precipitation is the prime regulator of the response characteristics of any watershed. Comprehensive and quantitative knowledge of this capacity is a prerequisite for successfully predicting the hydrologic performance of watersheds in a natural state or influenced by man's activity.
>
> England and Stephenson (1970, p. 89).

Texture

The mineral portion of a soil is composed of a variety of particle sizes. For convenience, these particles have been arranged into size classes known as soil separates.

Texture is an expression of the relative porportion of soil separates in a given soil. Soil separates vary in size from gravel, with a diameter greater than 2 mm., to clay with a diameter of less than 0.002 mm. Most soils are composed of the soil separates sand, silt and clay, with subsidiary gravel components. The texture of a soil has an important effect on that soil's water-holding capacity and in at least one study, Salter and Williams (1965), the conclusion is that texture is the single most important factor determining the moisture characteristic of soils.

Field capacity of soils can vary greatly depending upon texture. It may be as low as four percent (by mass) in sands while clay can retain as much as 45% and some organic soils may contain over 100% (Hillel, 1971, p. 164). Salter and Williams (1965), studied the available water capacity in the upper two feet (the belt of soil water described by Remson and Randolph, 1962), of twenty-seven soils. Their results indicate that the field capacity increases as the texture becomes finer but the medium-textured soils contain the largest volume of available water. The following are their findings of the field capacity and available water capacity in the top 30 centimeters of the three soil materials most relevant to the present study:

Material	F.C. (%H_2O)	A.W.C. (cm.)
Sand	6.7	2.0
Clay	39.4	4.9
Peat	156.8	9.2

(modified from Salter and Williams, 1965, p.312)

Millar, Tuck and Foth (1965, p. 85), agree with this concept but state it slightly differently; fine-textured soils have the highest total water-holding capacity but soils of medium-texture have the greatest available water-holding ability, i.e., that above the wilting point.

Jamison and Kroth (1958, p. 192) also found that the available water storage was greatest in soils with a high silt (medium texture) content and decreased with higher sand and/or clay percentages. From highest to lowest water storage potentials the mineral grain size is coarse silt, fine silt, clay, fine sand, and coarse sand. A loam, however, is characterized as possessing a greater available water capacity than any well-sorted textural class, as is demonstrated in Table 3-1. Chang (1968, p. 198) is in agreement with this but simply makes the observation that the usable water for plants is greater in clay soils than in those with a coarse texture.

This sequence can be divided even more, as Hillel (1971, p. 164) found that the type of clay present in a soil has a definite bearing on its water retention ability. The greater the percentage of expanding lattice clay minerals in the soil the more hygroscopic water will be absorbed by the particles, and thus held in the soil. However, most of this increased water content is held so tightly by colloidal bonding that the wilting point rises and much of the water is not available to vegetation.

Almost all clay found in natural soils is colloidal and

Table 3-1: Available water storage and air capacity of soils with different textures (based on moisture release between 1/3 and 15 atmospheres tension), (Jamison, 1956, p. 465).

Soil Type	Available Water Capacity	Air Capacity
	ml/100ml	ml/100ml
Lakeland Sand	3	26
Hiwassee Sandy Loam	5	18
Commerce Silt Loam	16	24
Sharkey Clay	14	6
Lloyd Clay	15	15

most colloidal clay is crystalline (Donahue, et. al., 1971, p. 53). Clay crystals are sheetlike in structure and contain a negative electrical charge. When wetted montmorillonite, for example, expands so that additional space exists between the plates in which cations and water molecules can be absorbed (Gardner, 1977, p. 405). Kaolinite, another important clay mineral, does not have this ability to expand.

Smectite is the name given to all minerals formerly classified as the montmorillonite group of expanding lattice silicates. The smectites are responsible for nearly all of the shrinking and swelling that takes place in soils (Dixon and Weed, 1977, p. 293). Included in this group is bentonite, a term which is often misused as being the equivalent of montmorillonite. Bentonite is an altered deposit of volcanic ash normally found in prehistoric lakes which possesses a very high silica content essential for smectite formation (Dixon and Weed, 1977, p. 308).

Ward (1967, p. 197), states that the main forces involved in holding moisture in the soil are absorption, osmotic forces and capillary forces. The texture of a soil is instrumental in the application of these forces. As indicated above, most clay particles are colloidal and thus have the highest absorption ability of the soil separates. In addition, because they are fine-textured the range of pore space sizes in a clayey soil is much greater than in a predominantly sandy or silty soil. Thus there is a higher percentage of small pores in which soil water can be retained at high suctions, whether capillary or osmotic, than in coarse-textured soils which tend to hold water in large pores at low suctions only. Suction in the soil increases as the size of the pore space holding water decreases and as the total moisture content in the soil decreases (Table 5-1).

Structure

The moisture-holding capacity of a soil is not only related to the surface area of the soil separates (texture), but also to the pore space volume. The latter is a function of the structure of a soil (Millar, Turk and Foth, 1965, p. 54). Structure refers to the arrangement or aggregation of the individual soil particles into compound particles separated from adjoining aggregates by surfaces of weakness. Penman (1969, p. 50), describes a well-structured soil at field capacity as consisting of saturated aggregates surrounded by completely drained pore spaces. Plant roots will absorb the water from the aggregates causing one of two situations to occur. Either the displaced water will be replaced with air and therefore leave the soil structure basically unchanged, or the soil particles will be drawn together as water is removed, thus causing a tighter packing of the particles and affecting the structure until rewetting takes place. Most soils will react somewhere between these two extremes.

Development and improvement of structure inceases the permeability and air capacity of a soil but decreases its water-holding ability (Jamison, 1955, p. 466; Jamison and Kroth, 1958, p. 192). After a period of precipitation, a well-structured soil will admit more water initially than a poorly-structured clay or silt soil, but that water will also tend to drain beyond the soil water zone more quickly. Aggregation increases the volume of large, easily drained pores but decreases the volume of the smaller moisture-storing pores.

Another factor which can markedly affect the field capacity of a soil is the presence of impeding layers in the substrate (Jamison, 1956, p. 463; Peters, 1965, p. 280). These strata range from those which slow the drainage and simply increase the time required for that soil to reach field capacity, such as clay and sand lenses, to those which form impenetrable barriers to downward percolation. The latter are represented by bedrock and a high permafrost table, and are especially relevant to the present study area.

Most azonal soils in the Baker Creek Basin are found mainly in the upland areas. They are shallow, underlain by bedrock, and often located in small depressions in the rock. A period of rain in the summer can quickly saturate the soil and create surface storage. The soil will remain saturated until the excess water, that above the normal field capacity of that soil, is depleted either by evapotranspiration or slow drainage through the rock. Miller (1973, p. 108), found that if the underlying bedrock is fractured to the point of permitting some water to drain by gravity flow, the situation is very similar to one in which a soil is underlain by coarse materials.

Intrazonal soils found in the extensive muskeg areas within the Baker Creek Basin are mostly underlain by permafrost. The permafrost table acts as an effective barrier to downward percolation of soil water. This impenetrable layer, combined with the extremely high absorption ability of peat and the lack of transpiration by lichens and mosses, often results in periods of standing surface water on these organic soils.

The consequence of these conditions is that the concept of field capacity is often not applicable in subarctic areas in general and specifically in the Baker Creek Basin. The determination of moisture storage capacity for these soils is thus complicated and this factor must be taken into consideration when calculating the water balance for the basin.

Organic Material

Thick accumulations of organic matter in muskegs and sedge meadows within the Baker Creek Basin are extremely significant in the water balance because of their large moisture storage capacity and because of the poor moisture transfer from a saturated sub-layer to the air above. The greatest percentage of peat deposits in Canada occurs in the discontinuous permafrost zone (Brown and Williams, 1972, p. 3), in which the present study area is located. Poor drainage is a characteristic necessary for peat formation and the numerous depressions in the shield bedrock, overlain by clay which acts as a sealant for the smaller fractures, have created the essential conditions.

Brown and Williams (1972, p. 4), indicate that peat can hold as much as fifteen times its weight of water. This fact alone would seemingly explain the great moisture-retention ability of muskegs and peat plateaus. The relatively high value has much less significance, however, when the low volume weight of dry peat is considered (Feustel and Byers, 1936, p. 7).

Other factors of importance, then, are the depressional sites, the insulation properties of the peat which maintains cool subsurface temperatures, retarding evapotranspiration and protecting the underlying permafrost table, and ponding of water on the surface. Brown and Williams (1972, p. 4), explain that in poorly drained organic terrain, surface water from rain or snowmelt in the spring remains near the surface or floods it, causing most of the energy from solar radiation to be used in evaporation and not in warming the soil. At the beginning of the summer the soil beneath a layer of peat can remain frozen until rain water saturates it (Budyko, 1974, p. 471).

Feustel and Byers (1936, p. 7) showed that sphagnum moss peat had the highest moisture-holding percentage of any materials used in their study and was as much as three times higher than other peats. This is especially significant in the Baker Creek Basin where most of the organic terrain areas were found to be composed of sphagnum peat (Landals, 1970, p. 33; Wight, 1973, p. 26).

The movement of water varies with depth in peat bogs. Brown and Williams (1972, p. 5), observed that the moisture content of the surface area of sphagnum responds quickly to an input of precipitation. The water moves by convection in the water-filled pores, by gravity along the division between the surface cover and the saturated peat below, and by vapor diffusion under unsaturated conditions. Water in the saturated, partially-decomposed peat below is virtually stable and varies little annually.

Dingman (1966, p. 757), in a study of runoff characteristics from a watershed in central Alaska, found that the response of streams to a period of precipitation was extremely slow as compared to similar situations in the mid-latitudes. He felt that the reason was partially due to the long distances that the water had to travel through mosses and organic surfaces before reaching the stream channel.

Patric and Stevens (1968, p. 175), studying soil moisture levels in various soils near Juneau, Alaska, disputed the idea that muskegs are unfailing sources of streamflow in dry weather. Their studies showed that muskegs often behave as ponding areas for water from adjacent upland reaches. During dry periods muskegs are simply an extension of streams, the unsaturated upper layer acting as a wick conducting water from adjacent upland areas to stream channels.

Large tracts of muskeg with impeded drainage make considerable use of surface detention storage but retention storage capacities are rarely utilized (Laycock, 1967, Appendix B, p. 5). In a study of the response to runoff of small watersheds with considerable organic terrain, Bay (1969, p. 101), found that from the perched bogs water yield occurred during wet periods but that perennial storage was not available for discharge during dry periods. Low peak flows and extended recessions, however, indicated that the bogs did store short-term runoff, especially after summer drying periods when the watertable was low.

Organic matter is also effective as a retainer of water when it is present in mineral soils. Humus has colloidal properties, as does clay, and is able to hold water molecules by ionic bonding. Therefore the addition of humus to most soils will increase their retention storage capacities. However, the amount or organic matter present in most mineral soils is too small to show much of an effect (Hillel, 1971, p. 164).

VEGETATION FACTORS

Rooting Behavior

The moisture-holding capacity of a soil depends, in large part, on the texture, structure and depth of the soil. Mather (1961, p. 253), found that it varied from just a few millimeters of water in a shallow sand to over 400 mm on a deep, well-aerated silt loam. He also noted that the depth of rooting of vegetation seems to partially compensate for the wide range of moisture-retention abilities of different soils. For example, sand, which stores the least amount of water, permits the deepest penetration of root growth so that although the soil near the surface drys out more quickly than does that of silt or clay, the plants can draw upon water at lower depths. Roots, in themselves, act to hold moisture in a soil by their suction pressure. Thus deeper rooting in sand increases its storage capacity.

Muller (1966, p. 282), in a study of reforestation on the Allegheny Plateau in New York State, showed that the depth of the rooting zone is initially governed by the growth habits of plants, so that for the same soil type the retention storage capacity can differ according to vegetation and land cover types. Muller points out, however, that rooting depths may be strongly modified by the soil environment and perhaps even the availability of soil water.

Penman (1963, p. 46), describes root behavior as a foraging for water rather than an ability to draw water from more remote areas by suction. Ayers (1968, p. 6), also indicates that the root systems of annual species of vegetation seek out the available water from the time of germination throughout the life of the plant. Rooting characteristics of plants of the same species growing in the same soil conditions can vary from year to year depending on the rainfall pattern. He also found that perennial vegetation exhibits the same variance.

Thornthwaite and Mather (1955-B, p. 350), showed that shallow-rooted crops growing in a sandy soil have an available water storage capacity of only 2.5 to 5.0 cm., whereas deep-rooted crops on a fine-textured soil have from 15.2 to 20.3 cms. of water available. The amount of water storage must be determined from both the rooting structure of the crop and the soil characteristics.

The concept of the root constant was introduced by Penman (1950) and refers to the amount of accessible water in the soil within the root zone, plus an inch to allow for water just below the depth of rooting and upon which the plant can draw. Penman (1969, p. 55), notes that in using this generalized term one must recognize that rooting structure and depth are not constant and can vary from soil to soil and with time for a given plant in the same soil. However, the concept is considered useful and can be used in either specific cases where the depth and structure of plant roots are known or generally, such as in the statement that the root constant for trees is greater than that for grasses (Ayers, 1968, p. 7).

In the Baker Creek Basin most of the soil is located in poorly-drained lowland areas, or in upland depressions in the bedrock. Soils found in the latter category are mainly shallow with the bedrock ranging from a few centimeters to rarely more than a meter below the soil surface. Jamison (1956, p. 464), reports that while rooting depth and moisture storage are limited by soil depth and while fractures in a shallow bedrock layer will tend to drain the soil above, the roots of plants may be able to penetrate the fissures and seek out moisture below. This may well be the case with stunted black spruce in the upland sites within the present study area.

The lowlying organic terrain within the basin is, for the most part, poorly-drained. In a study of water deficits in tree species, Zahner (1968, p. 237), indicates that excess water and poor soil aeration have as marked an effect on root systems as does water deficit. Soils with these water-logged conditions support trees with superficial, shallow root systems. In dry years such trees will suffer considerable damage and disease if their root system can't rapidly penetrate to lower moist zones. Knight (1965, p. 110), discusses similar conditions for growth and notes that with the pore spaces in the plant root zone saturated the roots become oxygen-starved while the soil becomes acidic with anaerobic microorganisms prevalent.

A further problem associated with growth of plants in saturated peat has been described by Jamison (1956), and Lutz (1956). Much of the water held in organic matter is in the tension range above wilting and thus so tightly bound that vegetation can't remove it and is susceptible to wilting (see Table 3-2).

Another study which should be mentioned is that by Thames, Stoeckler and Tobiaski (1955), concerning soil moisture under forested and non-forested sites in Wisconsin. They found that the forested sites maintained a higher moisture storage than the cleared cropland. The reason was partially due to the soil compaction of the treeroot channels in the surface layer of cleared cropland. This compaction destroyed the porous structure of the soil, thereby increasing its density and lowering its moisture storage capacity.

Vegetation, then, is indicative of long-term soil moisture conditions. There is not much information in the literature concerning water availability to many herbaceous plant species, either wild or domestic, or to coniferous and deciduous trees (Ayers, 1968, p. 7). The rooting characteristics and site preferences of some of the species found in the Baker Creek Basin are documented, however.

Rodda, Downing and Law (1976, p. 145), report that approximately 90% of the roots of herbaceous plants are contained in the top 15 cm. of soil, and that 99% are found in the top 60 cm. Linsley, Kohler and Paulhus (1949, p. 170),

Table 3-2: Typical moisture capacities for various soil textures (Linsley, et al., 1975, p. 197).

	Percent Dry Weight of Soil		
Soil Texture	Field Capacity	Wilting Point	Available Water
Sand	5	2	3
Sandy Loam	12	5	7
Loam	19	10	9
Silt Loam	22	13	9
Clay Loam	24	15	9
Clay	36	20	15

observed that the root systems of most annuals are located in the upper 30.4 cm. of soil but that close-growing perennials such as alfalfa, may have root systems which penetrate as much as 12 meters.

The concentration of the root mass of most plants, even the deeply-rooted species, in the uppermost portion of the soil may not be a result of necessity to absorb water from that particular layer. Hoover, Olson and Greene (1953, p. 150), believe that there are probably many more roots in the surface soil than the plant species needs to efficiently remove water. Instead, the abundance of roots in this area is more likely due to the more favorable conditions for root growth. These include favorable drainage and root aeration, advantageous soil textures caused by weathering of the mineral soil and readily available nutrient supplies from the decomposition of organic material on or close to the surface. In an area such as the Baker Creek Basin which is characterized by frequent rain showers in the growing season, the upper root zone of the soil will contain a concentration of available soil moisture. Plant roots located in this upper soil zone will thus have access to abundant moisture and will not be required to exert high suction pressures in order to absorb it.

Information on the rooting habits of tree species is more readily available. Under better soil conditions than are found in the study area, Linsley, et al., (1949, p. 170), found that pine, which has a deep taproot, can penetrate 3 to 6 meters below the surface while spruce rarely reaches down more than 1.5 meters. Aspen roots are able to descend to 1.8 m. below the surface (Croft, 1950, p. 15).

Several studies which have been performed in subarctic areas similar to the Baker Creek Basin contain data on the rooting habits and site preference of vegetation species. In one of the first studies of far northern flora, Pulling (1918, pp. 226-232), found that black spruce, larch and white birch have a rigid, shallow root system, white spruce has a flexible and shallow root habit, and jack pine has a deep, rigid one. Stoeckler (1952, p. 8), studying Alaskan trees, shows that the root mass of white spruce is quite shallow, in some cases less than 30 cm. deep. Because of this, the white spruce is able to grow in very shallow soils, although a stunted form will result. Black spruce was also found to have an extremely shallow root system of 30 cm. Larch had a broad, shallow root mass and it was noted that nearly always it was found in soil which was saturated, fine-grained and cold, the permafrost table being 30 to 45 cm. below the surface. Aspen grew best on unfrozen fairly moist soils with a sunny, south-facing aspect, although it was able to exist under very dry soil conditions. In a later study, Stoeckler and Curtis (1960, p. 894), examining soil moisture conditions in southwestern Wisconsin, noted that the soil moisture was twice as high in all cases on north-facing slopes than on south-facing ones. This is due mainly to the higher annual incidence of solar radiation on south-facing aspects which dries the soil more effectively and provides more energy for vegetation growth and moisture use.

One of the perplexing problems encountered in the field by the author was the apparent lack of site discrimination by two species in particular, jack pine and black spruce. Previous experience outside subarctic regions created an expectation that these species would be found in dry upland sites and depressional wet sites, respectively. Although this was the observed general trend, there were many exceptions where jack pine was found on the margins of organic terrain and black spruce located in seemingly xeric sites on rock outcrops. According to the literature, however, this is not unusual.

Gaertner (1963, p. 367), in a study performed in northern Ontario, found jack pine growing on very wet sites with black spruce. Fraser (1954, p. 410), reported black spruce as a co-dominant with jack pine on xeric sites in northwestern Ontario. It is thought that an intolerance to shade might be the factor which forces each species to edaphic extremes.

Larsen (1971, p. 151), notes that while white spruce seems to prefer a rather narrow range of soil conditions, black spruce occurs over a very wide range of substrate types in Ft. Reliance, N.W.T. Ritchie (1956, p. 558), found that in northern Manitoba jack pine occasionally occurred with black spruce in hydric sites (muskeg) and that its tolerance range must be as great as that of black spruce.

Moss (1953, p. 222), in a study of forest communities located in northwestern Alberta, states:

> It may be noted here that black spruce does occur apart from the two associations already described. Especially in the more northern parts of our region, black spruce is rather common in pine and other wooded stands on many kinds of terrain. For example, near the Alberta - N.W.T. boundary black spruce was found, on rather sandy soil and level terrain, in pure stands and also intermixed in various proportions with aspen poplar and jack pine. Such vegetation seems to defy recognition of communities, whether in terms of tree dominants or of associated species.

It has been suggested that in northern Alberta the black spruce found in xeric sites is a different genotype than that occupying the muskegs (North, 1976, p. 38).

The rooting behavior of plants, then, is an important factor influencing both the moisture capacity of a soil and site preference among vegetation species. While there are several exceptions to the latter in the Baker Creek Basin, in most cases species location conforms to generally predictable soil environment conditions.

Transpiration

Transpiration may be regarded as a necessary evil to a plant. It is true that the movement of water from the roots to the leaf surface is responsible for dissolved nutrients in the soil solution being distributed throughout the plant. But more transpiration at the leaf surface than absorption at the roots can dehydrate the plant and eventually kill it. Vascular plants must carry on photosynthesis to live and the photosynthetic process requires the stomata to be open for the intake of oxygen and carbon dioxide. More plants have been killed or injured by transpiration exceeding water absorption than by any other means (Kramer, 1969, p. 297). Subarctic areas possess their own special complications in this regard. The presence of permafrost and large areas of organic terrain in association with vascular species may well create special adaptations in the transpiration rates of plants in these areas due to the detrimental effect of cold temperatures at root levels.

The role of transpiration in vegetation is a controversial issue among researchers (Gates and Hans, 1967). Some say that the plant has little or no control over the passage of water through it and that water moves from the soil to the atmosphere by way of the plant's conducting vessels much like a pipe, responding only to limitations encountered in the soil and air environment (Thornthwaite, 1948, p. 60; Van Wijk, et al., 1953, p. 35; Penman, 1956, p. 26; Hobbs and Krogman, 1968, p. 502). Others claim that because the plant is a living organism it does exert a control over its transpiration rate and must be considered (Slavik, 1965, p. 157; Baier, 1968, p. 155; Kramer, 1969, p. 298; Burgy and Papazafiriou, 1971, p. 315; Ekern, 1929, p. 739; Gray, 1973, p. 3.39). Swanson (1970, p. 36), observes that there are times when a tree does act as a pipe and there are times when it does not. Part of the reason for this apparent disagreement concerning the role of the plant in the evapotranspiration process may lie in different definitions of transpiration. For example, some definitions include plant respiration requirements and others do not. Another factor contributing to the controversy may well be the location of the various studies. Pruitt (1971), indicates that Penman may have downgraded the effect of crop roughness on evapotranspiration because his experiments were conducted in England, characterized by a high humidity and cool conditions, while work in hotter and drier environments have endorsed a higher significance to this effect.

Root Absorption

During and after a period of precipitation water enters the soil and, drawn by gravity, percolates downward through the larger pore spaces and channels. It also moves laterally by capillary action to fill the smaller pore spaces between soil particles and is in part absorbed by those particles. If the soil becomes saturated the water will continue to drain out of the soil moisture zone until the retention forces equal the gravity force and the soil is at field capacity. If no vegetation is present the soil moisture will remain relatively unchanged except in the surface layer which will be affected by evaporation.

If plant roots permeate the soil they will begin absorbing water in the process of transpiration, and will continue until the soil suction, acting to hold the film of water about each soil particle, equals the root suction. Transpiration effectively stops at this time and the plant is said to have reached the wilting point.

Most natural cases of soil-vegetation interaction fall between the two extremes of no roots and total permeation. Species differ in their rooting characteristics and extent of ground coverage so that the assumption of complete occupance of the soil by roots is often not the case. Even allowing for these factors to be equal, transpiration rates are not the same for all species. Rider (1957, p. 192), warned that the idea of equal transpiration for all crops should be carefully examined. He found that different crops growing on plots of several acres are able to modify the general weather affecting them so that real differences in water loss from different crops take place. He did not elaborate on the methods of weather modification by crops, however. Kramer (1969, p. 339), notes the role of advection in causing higher transpiration rates in open, well-ventilated plant communities compared to dense, closed stands.

Stomata, found in the leaves of most vegetation, act as doors to permit the entrance of CO_2 for photosynthesis, and also as an escape for water vapor from the cell walls of the leaf. These stomata respond to light, temperature and water content of the leaves, and variations in these factors can cause them to open or close, thus permitting or curtailing transpiration in the plant. The physical reaction of the stomata to various amounts of the above parameters differs in various plants. Therefore, the results of studies on transpiration rates and associated phenomena of vegetation are important for the determination of variance of soil moisture storage.

According to Baier (1968, p. 170), the distribution, both horizontal and vertical, of moisture within a soil at less than field capacity is irregular, and usual methods of measurement of soil moisture do not indicate the proximity of water to the distribution of plant roots. Roots have been described above as seekers of water rather than relatively fixed, absorbing bodies. Root systems of various species are not uniform and the uptake of water by vegetation is proportional to the length of roots in a given soil volume (Gardner, 1960, p. 70). It should be noted, however, that plants will often operate at less than full efficiency due to a limited availability of energy. In this case a longer root system would not necessarily provide greater water uptake.

Slavik (1965, p. 152), discussed the mechanics of water absorption by roots. One of the most important factors of the availability of water to a plant for transpiration is the size of the absorbing root surface, which is itself determined, in part, by the velocity of root growth. While vertical development is a function of many factors, most notably the characteristics of the species itself, permeability of the soil, need for the plant to reach downward for water and the presence or absence of impeding layers in the soil, horizontal extension is basically determined by competition.

Root environment is an important aspect in the proliferation of subarctic muskegs. Luthin and Guymon (1974, p. 240), in a study in Central Alaska, found that the roots of black spruce experienced reduced respiration as a result of the anaerobic condition of the soil and therefore transpired very little. Other factors which favor the preservation of muskegs include a high permafrost table, the presence of an insulating peat surface and the acidic condition of the peat which discourages peat-reducing micro organisms.

Stomata and Plant Response

Water is absorbed by the plant's root system and transferred to the leaf cells by means of conducting vessels. The water, still in liquid form, is then evaporated, conditions being favorable, from the cell walls into the intercellular spaces which are connected to the stomata opening. The final transfer of the water from the plant to the surrounding air is a process of molecular diffusion of water vapor (World Meteorological Organization, 1967, P. 8).

The amount of water vaporized at any given time is determined by the nature of the surrounding atmosphere, the soil environment and the degree of stomatal opening. All three parameters must be taken into consideration when estimating transpiration rates (Swanson, 1970, p. 34).

Kramer and Kozlowski (1960, p. 295), mention several plant factors affecting transpiration rates including leaf area. If other things are equal, plants with larger leaf surface areas will transpire more than those with smaller areas. But, in an earlier publication Kramer (1952, p. 95), states that while plants of different species have different transpiration rates, leaf structure is not a reliable indicator because plants with thin leaves have lower rates than those with thick cutinized leaves.

Baier (1968, p. 170), in describing the transpiration process, states that a point is eventually reached when soil suction becomes greater than the suction in the plant leaves and, in response, the leaf cells lose turgor, closing the stomata. This point depends on root distribution, the P.E. rate and characteristics of the soil, but also differs with the species. Kramer (1969, p. 339), assigns degrees of stomatal control over transpiration to differences of water loss among species.

King (1961, p. 67), discusses variations in stomatal behavior of plant species. Most species fall into one of three categories: a) those which have their stomata open during the day, closed at night and, depending on the moisture conditions, may partially close them at midday, an example of which is alfalfa; b) the potato type, in which the stomata are open all the time except for three hours after sunset and only close during the day if the plant is badly wilted, and c) those which are closed at night and open rapidly during the day, never being open fully more than two hours at a time, such as barley.

It can be seen from the literature mentioned above that the evidence supports the concept that vascular plants do control, to some extent, their rate of transpiration and thus the loss of moisture from the soil. But while plant capacities for transpiration may vary, these capacities are rarely fully utilized, the limiting factor being the energy supply available for evapotranspiration. During long hot spells of weather transpiration from plants may reach or approach maximum capacity. In the Baker Creek Basin, however, these weather conditions are exceptions to the normal situation. In most cases during the growing season vegetation in the study area must compete for incoming solar radiation and the soil-moisture available to it is more than that required for the growth possible at the lower temperatures.

However, all plants are not vascular and therefore are not able to transpire. This fact has immense ramifications in subarctic regions, such as the Baker Creek Basin, where lichens and mosses make up a considerable percentage of the flora. The following is a review of studies concerned with the special role of lichens and mosses in northern areas.

Lichens and Mosses

The Thornthwaite water balance formula minimizes the effects of different evapotranspiration rates for different plant types, and Brown (1965, p. 20), feels that this is particularly objectionable for subarctic regions where lichens and mosses ~~are so~~ widespread. *Sphagnum spp.* and other mosses are extremely hygroscopic and can lose large amounts of water quickly. Lichens, on the other hand, can have completely dry surfaces while their basal areas are quite wet.

In a study carried out at Norman Wells, N.W.T., Brown (1965, p. 25), found that although the ambient air temperature in summer often rose above 27°C, the temperature just below the surface of lichen and mosses remained near 0°C.

These data indicate that covers of lichen and mosses are effective in insulating their below-surface areas from heating by solar radiation. Thus the water/air interface within the organic mat of a lichen and/or moss cover is cold, vapor-pressure gradients are shallow and moisture transfer to the surface is limited.

Regardless of the process involved, the result is that evapotranspiration from subarctic regions cannot be considered similar to that from areas to the south where the vegetation is mostly vascular. Evapotranspiration estimates and procedures used for broad areas in other regions cannot be accurately applied to the subarctic.

Rouse and Kershaw (1971, p. 291), note that it is a well-known fact that in subarctic areas ground lichen creates a resistance to passage of soil water into the atmosphere because of its inability to transpire and because of the mulching by non-living plant matter of the surface. They found that lichen-covered surfaces yielded considerably more summer runoff, both surface and subsurface, than did burned-over areas, mainly due to the higher evaporation rate of the latter. In a later study it was found that Cladonia alpestris created a physical barrier to water vapor flux across the atmospheric boundary surface (Rouse and Kershaw, 1973, p. 1315).

Lichens differ among themselves in their rate of water loss. Addison (1972, p. 290), explains that structural morphology is the main reason for this difference. Fruticose lichens, because of their vertical and branching nature, have a greater evaporative surface area and consequently a higher evaporation rate than do crustose lichens. When the surface is dry, however, crustose lichens are able to sustain a higher evaporation rate than bare soil because the lichen acts as a sponge, drawing water from the soil and evaporating it, while in the bare soil moisture must move through increasingly deeper layers to reach the surface.

Heatwole (1966, p. 153), in a study of various species of Cladonia spp. including Cladonia rangifera, the dominant in the Baker Creek Basin, found that dead and living thalli absorbed water from vapor at basically the same rate until differences occurred after 10-12 hours. The significance of water uptake from vapor was thought to lie in the fact that during the night lichens are able to become hydrated and carry on photosynthesis in the early morning hours before being dried out again. Thus growth and reproduction of Cladonia spp. is basically independent of soil moistureand precipitation if dew is abundantly available.

In a comparison study of water loss from a moss, Dicranum scoparium, and a fruticose lichen, Cladonia subtenuis, Klepper (1968, p. 19), found that the moss had a faster rate of loss than the lichen but that the initial value of water content was so great that even after a period of drying the moss was wetter than the lichen. This difference is not understood but possible explanations are that the tufted surface of the moss is structurally a better evaporating surface, that the two species may differ in resistance to water loss or in the vapor pressure at different water contents.

Natural and Man-Induced Disturbances

Vegetation in the Baker Creek Basin has been subject to a long history of fires which, unless threatening the Yellowknife townsite, have been basically allowed to burn unchecked. Because of the numerous water bodies and relatively bare bedrock areas, these fires usually burn themselves out before destroying large areas of vegetation. Over the years, however, much of the study area has been burned at least once. Lightning strikes account for most of the fires but many in the southern portion of the basin were purposely started several decades ago by prospectors to expose underlying bedrock formations. Landals (1970, p. 38) refers to an organic mantle, which took thousands of years to produce, that was destroyed by prospectors to save a few hour's work.

Past burns affect the soil moisture regime in several ways. Spring runoff is greater here because of the destruction of a portion of the organic mat, which normally would retain greater amounts of moisture (Landals, 1970, p. 39). Regeneration of a vegetation cover can be a slow process in subarctic areas, and runoff patterns can be affected for a long period of time.

Rouse and Kershaw (1971, p. 303), in a study of the effects of burned-over lichen-dominated surfaces in the subarctic, found that there was substantially less summer runoff from burned areas, both surface and sub-surface, than from unburned lichen mats. They also observed that measured soil moisture under a mature lichen woodland was forty percent greater than that under older and recently burned lichen-dominated surfaces, indicating less resistance to evaporation of burned areas (Rouse and Kershaw, 1971, p. 291).

Another important effect of burning is that of raising the albedo of a surface. In a study of albedo patterns over subarctic surfaces, Davies (1962, p. 144), found that burned-over lichen surfaces had higher albedos than those untouched by fire. This is explained by the light color of spruce trees with no bark and the predominance of deadfall, creating an effective reflective surface. A lower albedo means a higher net radiation regime and a greater drying of the ground surface.

Finally, fires tend to destroy the climax vegetation of an area, clearing the way for successional species. In this way much of the white spruce population in the Baker Creek Basin has been destroyed. Tree species with serotinous cones, i.e., those which open slowly after having been subjected to intense heat, have the advantage in recolonizing burned areas. A muskeg which has been burned will usually return to a black-spruce cover because of the semi-serotinous cones of that species (North, 1976, p. 64). Jack pine will tend to recolonize the more xeric upland sites for this reason. A change in species content of an area can effect the soil moisture regime, especially the storage values.

Fires are not the only means by which portions of the Baker Creek Basin have lost a part of their vegetative cover. Arsenic pollution from the local gold mine operations has been in evidence since the start of operations several decades ago. Its effects on surrounding vegetation have yet to be studied extensively, but destruction of some lichen and moss covers and the sparseness of trees in close proximity to the mines can be observed today.

Clearing of land for timber and fuel near Yellowknife in the southern portion of the Basin has also been effective in removing tree species, especially white spruce.

CLIMATIC FACTORS

The significance of soil moisture storage to the water balance of the Baker Creek Basin lies not only in the amount of water which will be retained by various surfaces at field capacity or even surface storage, but also in how quickly that moisture will be depleted to make way for a new supply during the next period of precipitation. Thus the climatic factors important to actual and potential evapotranspiration should be explored. The following is a brief review of the findings of some studies on solar radiation, temperature, albedo and precipitation.

Solar Radiation

According to Thornthwaite (1948, p. 60), if there is an adequate supply of water to the root zone the amount transpired by vegetation is more a function of the amount of solar energy incident to the surface and the resulting temperature than on the type of vegetation present. Water loss from areas of adequate soil moisture is determined, then, by the climate, especially by the radiative energy input (Sellers, 1965, p. 168). It is influenced by the heat available for evaporation and the movement of water vapor in the lower air layers, which itself is a function of wind velocity and of saturation deficit. According to experimental data, temperature lags behind radiation by about a month, giving credence to the assumption that incident solar radiation is the principal cause of evapotranspiration (Van Wijk, De Vries and Van Duin, 1953, p. 37).

Reifsnyder and Lull (1965, p. 79), expand upon this concept by stating that solar radiation is the immediate source of energy for evapotranspiration when its channels of energy, incident to the leaves of vegetation, are divided and a portion is directed into latent heat. Solar radiation is the ultimate source when energy stored in leaves, wood, air and soil is transformed into latent heat. The input of energy to vegetation comes from direct solar radiation, radiation reflected and reradiated from the surfaces of adjacent soil and vegetation surfaces, and advective heat from surrounding areas (Kramer, 1969, p. 300).

Net radiation is the difference between incoming and outgoing radiation and equals the total amount of energy available from the radiative processes (Lemon, Glaser and Satterwhite, 1957, p. 464). Net radiation values in high latitudes and subarctic continental climate conditions have an annual march comparable to that in middle latitude continental climates. Although these values are slightly higher in the high latitudes, the period of time with positive values is less than that to the south (Budyko, 1974, p. 200). During the daylight hours when evapotranspiration occurs, radiation liberates energy at the surface of the earth and can be divided into three components which evaporate water, heat the air, and heat the soil (Halstead and Covey, 1957, p. 462).

Morton (1968, p. 1), mentions a complication in the analysis of the cause and effect relationships in evaporation. The amount of insolation available for evaporation is determined by the water-vapor content of the lower atmosphere, which, in turn, is influenced by the evaporation rate. Consequently evaporation has an effect on its own cause.

Aspect is an important factor in the amount and intensity of solar radiation incident upon the earth's surface. In a study of mountain watersheds Lee (1963, p. 33), notes that natural landscapes are actually composites of a variety of insolation climates. Insolation is not precisely vertical to most surfaces and the inclination of slopes may either increase or decrease the solar energy received per unit area of surface. The two-dimensional land area of a watershed is always less than the three-dimensional area of its surfaces. In northern latitudes south-facing slopes tend to be more xeric than north-facing exposures, because of the difference in the amount and intensity of radiation impinging upon them.

Reid (1973, p. 319), indicates that although the total annual difference in evaporative water loss between slopes of different aspects is not great, over an extended period of time they become important in changing the gross hydrological balance.

Temperature

It is generally accepted that potential evapotranspiration will differ according to amount of heat supplied. This heat can come from three sources; solar radiation, advection and heat stored in the evaporating body. Since land surfaces, including vegetation, soil and rock, have low heat storage capacities compared with water bodies, stored energy is a relatively insignifcant factor.

The amount of energy available for evapotranspiration at any surface can be shown by the formula:

$$H = R_I \ (1 - r) - R_B$$

where H is the heat available, R_I is the incoming shortwave solar radiation, r is the albedo or reflection coefficient of that surface, and R_B is long-wave re-radiation back into the atmosphere (Penman, 1963, p. 35). The amount of incoming solar radiation is dependent upon the angle of the sun, the degree of cloudiness, and the slope and aspect of the particular ground surface.

Temperature is important as an index to PE, according to Thornthwaite and Mather (1955-A, p. 18), due to the relationship between the net radiation used for heating and that used in the evaporative process when the potential rate can be achieved. This relationship varies with latitude and water, snow and frost distribution patterns. The rate of transpiration increases with increasing temperature within the tolerance range of plants (K[illegible] and Kozlowski, 1960, p. 287). Leaves in direct sunlig[illegible] tend to be warmer than the ambient temperature but can rapidly cool below it if a breeze occurs or a cloud obscures the sun.

In a study of evapotranspiration from alfalfa, Hobbs and Krogman (1966), found a strong temperature-evapotranspiration relationship which supported the use of temperature in estimating evapotranspiration for medium to long periods of measurement from the Thornthwaite formula.

In subarctic regions one of the most important relationships in the heat and water balance is that between solar radiation and covers of mosses and lichens on organic terrain. Rouse and Kershaw (1971, p. 299), show that evaporation over lichen-dominated surfaces in the subarctic is greatest during the high sun period when the direct solar beam is able to penetrate the lichen mat and reach the underlying soil moisture reserves. They found that the lichen cover at all other times inhibits evaporation and the daily heat flux normally never exceeds 70% of the available radiation heat energy under the most favorable conditions. Nebiker and Orvig (1958), found that a Cladonia spp. cover at Knob Lake incurred water losses which were only a third of those theoretically possible with the net radiation available.

Williams (1968, p. 181), studying the heat balance over areas of saturated sphagnum moss noted that in two earlier studies it was found that the net heat gained at the saturated moss surface was largely lost by evaporation and, in measurements in a peat bog, actually exceeded the measured net radiation by nearly 50%. Approximately 30% of the heat needed for evaporation was gained from the air by convection. This, however, could not apply to larger areas.

In a later publication Williams (1970, p. 200), attributed the drainage of cold air into peat bogs as the main reason for the air temperature to be lower over the bogs than at the nearby weather station. The main factor creating the colder peat soil temperatures compared to the adjacent mineral soil was that the heat from radiation and convection was used to evaporate water from the saturated sphagnum rather than for warming the soil.

Bavina (1967, p. 359), found that the temperature regime of bogs is associated with the thermal characteristics of the upper peat layers. The surface heats more during the day and cools more at night than mineral soil. Brown and Williams (1971, p. 5), explain that the process of heat transfer in the uppermost layers of organic areas is complicated by the extremely variable water content and the porous structure of sphagnum. In saturated peat, conduction accounts for the majority of heat transfer while in porous sphagnum, heat is transferred by conduction, convection or transfer of water vapor. Net radiation through moss is greater than through lichen (Brown, 1965, p. 29).

Hoffman and Gates (1971, p. 365), discuss the thermal environment of lichens growing on rock. Rock surfaces are good daytime heat sinks. Because of the conductive propertie of solids, a rock surface will be warmed slowly during the day and cool slowly at night. This creates a cooler environment for lichens growing on the surface than would be the case for lichens elsewhere. A large rock is much more effective in this manner than a small one (Landsberg, 1958, p. 142).

Albedo

Albedo, the measurement of the reflectivity of a given surface, is not in itself a climatic element. However, because it is an extremely important factor in the determination of net solar radiation it is considered here. It is vital to water balance studies and is a measure of the reduction of solar energy available for evapotranspiration (Davies, 1962, p. 138).

As can be seen in the previous formula, albedo is a very important factor in determining the amount of heat supplied to a surface. The two major surficial variables are color or tone and configuration. A surface with a darker color will absorb more and reflect less shortwave radiation than will a lighter-colored surface. A rough surface will absorb more energy due to aspect than will a smooth surface. A quiet water body, for example, will tend to produce specular reflection like a mirror. Thus lighter-colored and/or smoother surfaces will re-direct varying amounts of energy away from themselves and reduce heating from net radiation available for evapotranspiration. Because of this, for example, a heavy snow cover can effectively prolong itself well into the late spring.

In subarctic regions such as the study area the latitude is such that the sun is never directly overhead, even on June 21, when it is at an angle of 51° 03' above the horizon. Budyko (1974, p. 53), found that when the sun's altitude is low, the albedo of most surfaces increases. The reason is that reflectivity of surfaces increases with lower sun angles. Also, the energy received from the sun increases in wavelength and decreases in frequency at lower sun angles. Longer wavelengths are prone to MIE scattering and their heating efficiency is reduced. MIE scattering occurs when the atmosphere contains larger particles such as dust and water vapor whose diameters are of similar size to the wavelengths of the incoming radiation. These larger particles tend to be concentrated in the lower atmosphere

(Barrett and Curtis, 1976, p. 20). The effects of a low sun angle then, should not be overlooked in any study of evapotranspiration from subarctic areas.

One of the most important aspects of the energy balance and the water balance in the subarctic open boreal forest zone, in which the Baker Creek Basin is found, is that the solar radiation maximum occurs in the months of April, May and June. During much of this time there is a snow cover on the surface and consequently a high albedo. Thus much of the solar energy which could be used for melting the snow and contributing to plant growth is instead reflected away from the surface, leaving it relatively cool (Hare and Ritchie, 1972, p. 352).

Conifers tend to have lower values of albedo than do deciduous species and it is commonly thought that this is due to the darker green color of the coniferous foliage. Monteith (1959, p. 390), however, believes that the reason may be due to the more efficient trapping of radiation between coniferous trees, on a large scale, and between needles on individual trees.

As can be seen from Table 3-3, values for the same feature vary according to the different studies conducted. These variations are valid, as albedo patterns change with different sun angles. All of the studies noted are for subarctic regions with the exception of Landsberg, whose albedo values are averages based on readings from a variety

Table 3-3: Average albedo values for various surfaces

Evergreen Forests – 7

Deciduous Forests – 9

Lakes and Rivers – 7-9

Fresh Snow – 80-90

(Landsberg, 1958, p. 122)

Stable snow cover in high latitudes (over 60°) – 80

Forest with stable snow cover – 45

Unstable snow cover in spring – 38

Unstable snow cover in autumn – 50

Forest with snow cover in autumn – 30

(Budyko, 1974, p. 55)

Shrub sphagnum bog – 16

Highmoor landscapes in summer – 14-16

Sedge microlandscapes – 19-20

Reed-grass-rush microlandscapes – 21-22

(Bavina, 1967, p. 359)

Lichen woodland – 12

Lichen woodland (snow covered) – 22

Bog and muskeg – 8

Bare rock and lichen – 8-12

Open water – 12

(Jackson, 1960, p. 199)

Tundra – 14.9

Open woodland – 12.2

Bog and muskeg - 11.0

Ice - 20.9

Snow - 34.0

Water - 7.6

(Davies, 1963, p. 143)

of latitudes. Low sun angles increase reflectance from natural surfaces and thus also increase albedo values. Because the angle of the sun, and thus the angle of incidence of solar radiation, varies not only with latitude but also with season and time of day, it is difficult to find exactly-correlating studies in the literature. It is probably more important to compare relative albedo figures within a particular study than to attempt to compare values of the same feature for various studies.

Precipitation

Precipitation is, of course, a major component of any water balance study. It is mentioned here, however, only because several studies indicate that there is a possible problem associated with measured values in northern regions.

Neff (1977, p. 218), found that wind was a serious problem in the gauging of rain at meteorological stations. Rain gauges exposed to windy conditions collected from 5 to 15% less precipitation than did pit gauges or other ground controls. A 5 to 15% error in gauging precipitation in a hydrological network providing quantitative input to an intensive hydrologic investigation may be larger and more damaging to the study than any other error component.

Hare and Hay (1971, p. 90), in a study of annual water balance over northern North America, state that they believe precipitation to be undermeasured in northern countries, mainly because of the undermeasurement of snow. They feel that the problem is serious enough to cast considerable doubt on attempts to budget precipitation against P.E. in order to predict actual evapotranspiration, soil moisture and water surplus.

The U.S.S.R. Interdepartmental Committee for the I.H.D. (1967, pp. 1-2), having reviewed the results of rain and snow gauging from stations throughout the Soviet Union, and having compared them to precipitation norms for those areas, suggested that the following correction factors be employed where locally-tested corrections were not available:

> For liquid precipitation, the average correction necessary to the rain gauge reading varies between 12% and 22% (it is usually between 14% and 16%); for solid precipitation, between 20% and 100% (usually between 40% and 60%); and for annual totals between 17% and 56% (usually between 20% and 30%).

Kakela (1969, p. 225), studying a portion of the Baker Creek Basin, believed these Russian I.H.D. recommendations to be of the right magnitude and suggested that the 25-year mean snow precipitation as measured at the Yellowknife airport, should be increased by fifty percent, and the rain precipitation by fifteen percent. Wight (1973, p. 281) expressed concern that Kakela had over-estimated the precipitation adjustment. His research in the Baker Creek Basin indicated that the nature of the evapotranspiration and runoff data collected supports a precipitation correction factor of lesser magnitude.

Another contribution by Kakela (1969) was his emphasis on the relocation of snow by drifting. In the spring when snowmelt is important to the soil moisture regime, more exposed surfaces will have been swept clean of snow and sheltered areas will have collected this excess snow, sometimes amounting to double the mean winter snowfall for the general region (Kakela, 1969, p. 86). For this reason, the exposed surfaces will be subject to an early summer deficit while accumulation areas will be fully recharged and still provide a surplus of melt-water for evaporation or runoff.

Landals (1970), conducting a pilot study of the influence of environmental factors on the spring snowmelt regime, found that patterns of runoff were dependent upon the complex interactions of a variety of physical and climatic parameters. The climatic conditions during the time period immediately preceding active layer freezeback in the fall were found to be extremely important in determining spring runoff patterns, but the critical factor was found to be the difference in moisture storage capacities of different types of surficial cover (Landals, 1970, p. 109).

Ferguson, O'Neill and Cork (1970, p. 1631), believe that condensation on vegetation and ground surfaces has not been given enough consideration. It may be a significant factor in the water budget, especially over snowy surfaces and for time periods of less than a month.

REMOTE SENSING OF NATURAL SURFACES

Air photo interpretation of vegetation types and distribution patterns is a valuable tool in any study of physical geography. Its value in studies of vegetation is obvious, but since vegetation is an excellent indicator of other physical phenomena such as soils, surficial geology, geomorphology, permafrost distribution and hydrology patterns, knowledge of these relationships and skill in interpretation techniques is a definite asset in a wide range of studies. For this reason a separate bibliography of remote sensing has been included in this study.

As the discipline of remote sensing gains increasing acceptance by scientists in a variety of fields, and as techniques become more sophisticated, the amount of literature on the subject has enjoyed a similar increase. Some of the better general texts are listed in the bibliography as well as works on more specific applications. In addition to these, forums for remote sensing studies such as the proceedings of the annual international symposia on remote sensing of environment sponsored by the Environmental Research Institute of Michigan (ERIM), the proceedings of the Canadian Symposia on remote sensing and the journal <u>Photogrammetric Engineering and Remote Sensing</u> published monthly by the American Society of Photogrammetry.

Finally, it should be mentioned that the Alberta Remote Sensing Center in Edmonton provides free of charge unlimited access to the Remote Sensing On-Line Retrieval System from

Ottawa. With this service one can choose from a variety of key words regarding his interest, in some cases combining two words to more nearly delimit his subject, and in a matter of minutes have a print-out of the literature titles correlating with his input. Those articles desired can be quickly ordered and received at no cost to the user. This and other services, including free use of very sophisticated interpretative devices, make the Alberta Remote Sensing Center an invaluable asset to studies of all types. These services provided by the A.R.S.C. are unique within Canada, and possibly within the world. The author knows of no other institution of this type which offers comparable services to the public regarding equipment use and advice.

CHAPTER FOUR

RESEARCH METHODOLOGY

INTRODUCTION

In this chapter the techniques used for vegetation sampling in the field and for air photo analysis in the laboratory are discussed. The criteria for site selection of the nine smaller areas chosen for detailed investigation within the Baker Creek Basin are explained. Analyses of aerial photography of the basin at several scales show a variety of surficial patterns. Methods used to discriminate between these patterns are presented.

The very basis of this thesis is the mapping division of the Baker Creek Basin into a series of surficial cover categories which possess distinctly different water storage values. In this chapter the category divisions are defined and assigned storage values. The multistage sampling technique is employed in which smaller-scale photography is examined for surficial patterns already defined on large scale photos. Satellite imagery from LANDSAT I and II is interpreted for gross patterns related to those found on conventional photography in order that the findings of this study may be applied in other parts of subarctic Canada.

SITE SELECTION CRITERIA

Nine smaller areas within the Baker Creek Basin were chosen for detailed analysis. These study sites are each approximately 3900 square meters in area. Initially a large number of possible study sites was selected from the air photographs before travelling to the Baker Creek basin. Once in the study area the author was able to choose from among the original number those which best exhibited the bedrock and vegetational patterns found in the Basin as a whole. Together these smaller study areas are representative of the entire basin; four are underlain by granite and granodiorite, one by rocks of the Yellowknife Group and four are composed of a mixture of both types, with more than half of each area in the Yellowknife Group. One study site includes lacustrine beach deposits. The vegetation patterns displayed in these nine areas are representative of the entire basin, including both upland rock types and depressional organic terrain associations.

The difference in tone of the two types of bedrock make differentiation between them on the air photos quite a simple procedure. Gross vegetation patterns, i.e., large stands of conifers, relatively bare rocky upland areas, major depressional organic terrain containing sedge meadows and peat plateaus, and smaller depressions within basically bare bedrock were also easily located on the photographs. Because of this, initial investigation of the air photos insured that the smaller study sites were representative of the entire Baker Creek Basin.

Within each study site two transects were delimited. These transects were chosen to pass through areas containing a variety of vegetation types, especially possible problem areas. To facilitate execution of each transect in the field and to insure correct orientation, they were selected to begin and end at some recognizable feature on the ground, usually a lake. This was later found to be a sound procedure as the presence of ore bodies throughout the study area caused incorrect readings to be made on the compass.

VEGETATION SAMPLING

The method used for sampling the vegetation was the Curtis Transect, with several adaptations designed to improve its use in the study area. It was chosen because it is relatively free of bias, simple to implement and statistically reliable. The procedure begins with the selection of a transect route. Near the beginning of that line a tree is selected and its species and height are noted. The tree must be at least 2.4 meters in height to qualify. With that tree as the center, the area is divided into four equal quadrants. The species of the nearest tree meeting the height requirement in each sector is noted along with its height and distance from the center tree. The lower vegetation species found in a line running from the center tree to the nearest tree in each of two opposite quadrants is recorded. This process is repeated every 90 meters.

The Curtis Transect was developed in Wisconsin to be used in a forest situation. The distance between sampling sites is given as 40 meters, or 40 stops per mile (Kuchler, 1967, p. 177). For this study it was felt that due to the openness of the terrain and the relative sparsity of densely-treed areas, 90 meters would be more appropriate.

At each stop or sampling area along a transect, several items of information are obtained. The species and height of five trees, as well as the distance between them are recorded. Thus the density of tree growth can be inferred. The understory vegetation representative of that particular area is also identified.

In addition to the data gathered on vegetation several other types of information were collected at each point on the transect. First, the moisture condition of the top fifteen centimeters of soil at the center of each stop was noted. A scale of five values from saturated (1) to dry (5) was employed. The simplicity of this method was considered adequate since only an estimation of relative moisture properties, not exact percentages, was required recognizing temporal effects or variations due to precipitation.

Second, at each stop a soil probe was used to test for the presence of, and depth to, permafrost. The probe was 0.9 meters long so any permafrost tables below that depth were not recorded. However, familiarity with the conditions under which permafrost could be expected to occur enabled estimation, in some cases, of a permafrost table just beyond the probe's limits (Brown, 1973, pp. 28-29).

The depth of soil as determined by the use of a soil probe at each stop was noted as was the amount of deadfall. Considerable amounts of dead trees living on the surface can have a pronounced effect on the net radiation of an area. Deadfall can intercept solar radiation before it reaches the ground and thus reduce the energy supply available for evapotranspiration from the soil and vegetation below.

In addition to collection of data regarding the species of low strata vegetation at each location, a judgment was made as to the density of that vegetation. Each sampling site was rated as sparse, sparse due to the presence of considerable bedrock, average or prolific.

And finally, an overall impression of each area was recorded. Anything which might aid in identifying that precise location on the air photos and applying that information to other areas within the study site was included. On four of the transects ground photographs were taken of each stop to further facilitate correlation between transect data and air photo interpretation. A sample survey sheet used in the field may be found in Appendix B.

In the laboratory the stops, ninety meters apart, were plotted for each transect on the air photos. Adjustments were made to correct any inaccurate compass bearings from one stop to another. Upon completion of each transect study, each point on a transect would have been described in a variety of ways and each could be located precisely on the air photographs. Familiarization with tone and texture patterns and relative location for each point enabled comparison with other similar areas not sampled, and correlations could then be made.

AIR PHOTO ANALYSIS

Two scales of air photographs were used for interpretation of the study area patterns. The larger of the two, 1:12,000, contained adequate detail for interpretation of the nine smaller study sites. The interpretation was done on black and white panchromatic photos with reference to black and white near-infrared photos at the same scale. The near-infrared photographs were found to be better for differentiation between some of the category types. It is not recommended, however, that they be used alone as a base for photo interpretation. For one thing the effects of stereo vision are not as pronounced on near-infrared imagery as on panchromatic, thus the heights and depressions are not as easily discernable.

The second photo scale used was 1:31,680. This smaller scale of black and white panchromatic photographs permitted a broader overview of the entire Baker Creek Basin. Information gathered from these photosaided in interpretation on the larger scale.

The two major bedrock areas, granite and granodiorite and rocks of the Yellowknife Group are easily differentiated on the air photos. The granites appear much lighter in tone than the Yellowknife rocks as can be seen in Figure 2-7. Organic terrain tends to mask the bedrock in places but divisions of the rock types follow rather broad patterns and can be inferred where covered.

The appearance of bodies of water on air photos provide several different types of information depending upon whether panchromatic or near-infrared photos are used. Infrared radiation will not penetrate more than several centimeters into a water body before it is absorbed. Thus black and white near-infrared photos will show a lake or river as black unless there is a suspended sediment load within the water which will scatter the radiation and produce a lighter tone, or vegetation floating upon it which will usually produce tonal variations. The near-infrared photos were valuable in locating and determining the degree of cover of floating aquatic vegetation on lakes in the study area. The presence of vegetation cover will have a slightly negative effect on evaporation from a lake by decreasing the water/air interface area. This effect occurs both because of decreased open-water area and because floating vegetation tends to reduce wave action and thus the area of water surface exposed to the air. With the panchromatic photographs it is possible to see a certain depth into the water, and these were used to differentiate between shallow and deep lakes.

The use of near-infrared photography as a reference proved most beneficial in the interpretation of the vegetation cover. Two species of trees, jack pine and white birch, while easily separated on the ground are most difficult to distinguish between on black and white panchromatic photography taken during the summer when the foliage of the latter is still green. Since they both prefer the upland rocky sites the problem of photo interpretation is pronounced. The near-infrared photography was found to show the two species as quite distinct from each other in appearance.

The key to understanding the differences in response between the two types of imagery lies, in part, in the nature of the internal structure of the leaves. Radiation between the wavelengths of approximately 0.5 and 0.6 microns, or the color green which our eyes perceive, is preferentially absorbed less by plant pigments than are red and blue wavelengths. Thus we see most healthy leaves and needles as green. Although in most cases needles are a darker shade of green than leaves, on black and white panchromatic photography where colors translate to differences in grey tone, the difference is not great enough to separate the two.

Reflected infrared radiation, between approximately 0.7 and 3.0 microns, is not affected by the palisade layer but instead passes through to the area known as the spongy mesophyll which is composed of pillowlike cells with the air spaces between them. In a healthy leaf these cells are turgid and by means of the Fresnel Effect, the infrared radiation is highly reflected by the intercellular spaces, resulting in a good return, or light tone, on the infrared photography (American Society of Photogrammetry, Vol. I, p. 104). It should be noted that the sensitivity of IR film only extends to wavelengths of approximately 0.9 microns. Conifer needles possess little or no spongy mesophyll. so that only a small amount of infrared radiation is reflected, creating a darker tone on the photos.

Another major factor contributing to the darker tones of conifers on infrared film is the arrangement of their needles permitting a greater amount of radiation to reach the ground and become absorbed by the soil. Although radiation is reflected from both needles and leaves, there are dark or shadowed spaces between. When viewing a tree from the ground the radiation from the leaf or needle is greater than the darkness of the space between. But from a distance such as that represented by an air photo, the combination of all the spaces between the needles or leaves can cause an overall darker tone. Since leaves tend to overlap, thus reducing the dark spaces between, the radiation from their surface creates a relatively lighter tone on the photo than does that from a conifer where the inter-needle distance can be quite large (Howard, 1970, p. 57).

For these reasons the near-infrared photographs were consulted whenever an area of mixed jack pine and white birch were encountered, and differentiation was quite easily accomplished.

Near-infrared photography was found to be inferior to panchromatic in several areas. The latter were much better in distinguishing deciduous trees from low-lying herbaceous vegetation. The high reflection from both areas on the infrared photos made separationdifficult. The lighter-toned granitic areas tended to blend with the deciduous vegetation on infrared photography, but could be separated on the panchromatic photos. The reason for this is that radiation from vegetation in the visible portion of the electromagnetic spectrum is less than that from the infrared zone, as noted before.

Sedge meadows often occur adjacent to peat plateaus. Sometimes difficulty was encountered in trying to determine the boundaries between the two on near-infrared film, but on panchromatic film the distinction between types was easily made.

SURFICIAL CLASSIFICATION SYSTEM

The amount of water that can be held by the soil in a given location depends upon several factors; the type and condition of the soil and the species and density of coverage of any vegetation present being the two most important. The colloidal fraction of the soil, composed of clay particles, humus and sesquioxides, is extremely efficient in increasing the water storage capacity. The greater surface area of the smaller particles plus the electro-chemical charge which is characteristic of colloids provides more opportunity for water molecules to attach themselves to these particles with a stronger bonding force than is true of other soil components. Organic matter is able to hold up to nine times its own weight of water (Daubenmire, 1974, p. 25). Thus soils with a large clay content and/or considerable organic matter will be the most efficient in water storage. Since the depressional soils of the Baker Creek Basin are characterized by having both of these properties, moisture storage will be higher there than ~~on~~ the uplands. Water held by the colloids will be relatively unavailable for evapotranspiration, however, due to the extremely powerful electro-chemical bonding of these particles to water.

Given a constant supply of water, differences in vegetation type would have minimal influence on evapotranspiration rates (Thornthwaite, 1965, p. 168). Under this condition variations in albedo patterns would prove to be the differentiating factor. In the Baker Creek Basin areas with a consistently abundant supply of water are unusual or of very limited extent, and vegetation does play an important role in evapotranspiration patterns.

Variation in the amount and depth of rooting of vegetation species are important plant factors contributing to differences in evapotranspiration patterns. Transpiration from the leaves creates a stress or pressure in the water stream of plants and a demand for water at the root surface. If present in sufficient amounts, soil water will move into the zone of absorption around each active root system and be incorporated into the plant. In the case of a large colloidal component in a given soil, the pressure gradient in the plant must be greater than the colloidal bonding in the soil in order for the soil water to be available for use. It is possible for a plant to wilt and die from dessication while its roots are surrounded by colloidally-bonded water. The more root surface area a given species of plant possesses the more insurance that available soil moisture can be tapped and the greater ability of that plant to sustain itself during water deficit situations.

Normal rooting structure of plants will adapt to meet the needs of their environment. A plant species with a typically deep vertical root system, for example, may have to develop horizontally in order to create enough root surface to survive if it encounters a barrier to downward growth. In the Baker Creek Basin, environmental limits to rooting depth of natural vegetation include high permafrost tables and the presence of bedrock close to the surface.

For these reasons both site condition and vegetation type were considered in creating the surficial cover categories. It is believed that important differences in evapotranspiration will be more correctly determined from an analysis oriented toward these criteria than any other.

Table 4-1 lists the category types used for interpretation of the surficial cover of the study area along with their assigned moisture storage values. These values were estimated from previous work carried out in the Baker Creek Basin and consultation with Dr. A.H. Laycock (Landals, 1970, p. 100; Wight, 1973, p. 232).

The water bodies in the study area were divided according to depth and temperature. The warmer, shallower lakes were judged to evaporate water at the potential evapotranspiration rate plus one-half the annual water deficit; and the deeper, colder lakes at the potential evapotranspiration rate only. Temperature is the key here, a slight increase causing a significant difference in the amount of evaporation. Shallow lakes open earlier in the spring, have limited flow within and are warmed throughout during the summer. Deeper lakes experience spring and fall overturn, maintaining a colder temperature throughout their volume.

Sedge meadows are divided according to the amount of standing water present during the summer. Some of these areas are adjacent to lakes which keep them saturated most of the warm season. Others are in areas more removed from the lakes and are dependent upon summer rains or overflow lake drainage. Some will dry up in years of less than normal precipitation or when runoff from snowmelt evaporates in mid-summer. Determination of these sedge meadow types on air photos is augmented by observations of the vigor of growth of the associated vegetation.

Table 4-1: Surficial Cover Categories

Category	Description	Map Symbol	Storage Value
Water body	Deep, cold	WB1	No limit
	Shallow, warm	WB2	No limit
Sedge Meadow	Wet, standing water most of summer	SM1	15 cm.
	Intermediate	SM2	10 cm.
	Relatively dry	SM3	5 cm.
Willow/Alder/ Leatherleaf	Dense	W1	25 cm.
	Open	W2	15 cm.
Black Spruce	Dense Stand	BS1	25 cm.
	Intermediate	BS2	15 cm.
	Sparse	BS3	10 cm.
Open Peat Plateau	Few if any trees	P	5 cm.
Birch/Aspen	Dense Stand	B/A1	15 cm.
	Open, rocky-marginal	B/A2	10 cm.
	Open, rocky-upland	B/A3	5 cm.
Jack Pine	Dense, stand over 50% cover	JP1	15 cm.
	Sparse, rocky site 15-50% cover	JP2	10 cm.
	Sparse, rocky site 2-14% cover	JP3	5 cm.
Bedrock	Moderate- high # depressions	R1	5 cm.
	Few depressions	R2	1.3 cm.
Peat Hummocks/ Standing Water		P/S	10 cm.

Some areasadjacent to lakes in the study area, or between two lakes where there is seepage of water, are characterized by shrubby vegetation consisting of species such as willow, alder and leatherleaf. In these areas there may be standing water over which the branches of the shrubs spread. In other places the always abundant water is hidden by grasses and roots of the shrubs.

Black spruce is traditionally an indicator of wet depressional sites. In the Baker Creek Basin it can also be found in pockets within bedrock where water can collect and be held for a period of time, but this is the exception rather than the rule. For these category divisions the density of black spruce cover determines the degree of moisture storage.

Peat plateaus within the study area are relatively small compared to those found in Manitoba and Saskatchewan. They appear to be a stage in the transformation of lakes to woodland. It is only conjecture at this time, but judging by the presence in some areas of a shallow drying-up lake fringed by a sedge meadow which, in turn, is surrounded by hummocky peat areas, there seems to be a sequence in development from shallow lake to peat plateau.

Peat plateaus can be categorized as either open or treed, the latter mainly with black spruce. To avoid confusion with black spruce areas, only the open peat plateaus were given a separate category, the treed areas forming part of the black spruce sites depending on density.

The birch/aspen areas often corresponded with the jack pine areas but the two were given separate categories. The reason for this is that areas of relatively dense birch and, rarely, aspen were found in lower, well-drained parts of the basin but jack pine were not. The latter has dense and prolific growth in the sandy beach deposits just outside of the study area but is limited mainly ~~to~~ the rocky uplands within it. Thus the birch/aspen covers were divided according to their location, those in the lower sites being denser and those in the higher areas were more open and sparse. The jack pine areas were all found to contain a moderate to sparse tree growth which rarely provided more than 50% cover.

Differences in bedrock have been explained in Chapter Two. For the purpose of water storage categories these areas were divided as to surface characteristics. Relatively smooth, bare bedrock with or without a lichen cover and with few cracks or depressions was given a lower moisture storage rating. Areas of rock with a moderate to high number of pockets for water detention were given a higher storage rating.

The only remaining areas not truly fitting into a previous category are those in which raised peat hummocks are surrounded by standing water. The upper peat surface is relatively dry, contributing little to evapotranspiration while the water is evaporated at the rate of a shallow water body. Although the water is quite cold due, in part, to a high adjacent permafrost table, it is usually very shallow and solar radiation is often able to penetrate to the bottom. The ten centimeter storage capacity assigned to these areas represents an averaging of the values assigned to the two components.

The permafrost table was encountered in peat plateaus, black spruce areas, peat hummock/standing water sites, some sedge meadows and some willow, alder and leatherleaf areas. Since permafrost is degraded by moving water it will not be found under water bodies and may or may not be present under sedge meadows or willow, alder and leatherleaf areas adjacent to water bodies.

Examples of each of these category types will be found in Figures 4-1 to 4-10. A list of low-strata vegetation associated with each surficial category type will be found in Appendix C.

MULTISTAGE SAMPLING TECHNIQUE

Detailed interpretation of surficial cover categories was performed on photographs at a scale of 1:12,000. At this scale and with the aid of field checking, accurate interpretation was facilitated. It is not always possible to obtain large scale photography such as this, however, and when it is, the cost can be high. In order to provide maximum application of the results of similar studies, an attempt should be made to determine the smallest scale of imagery which can be effectively used.

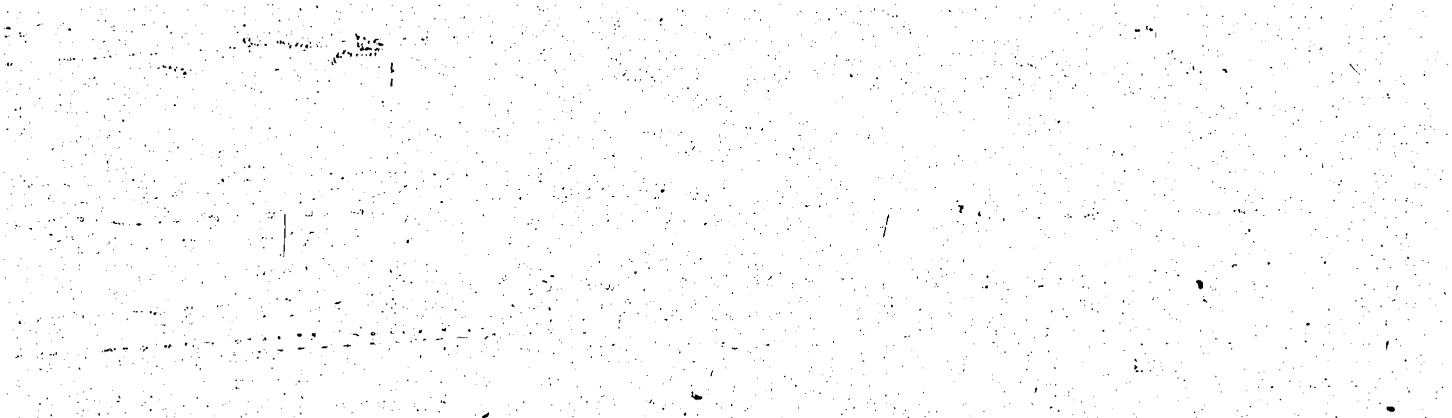
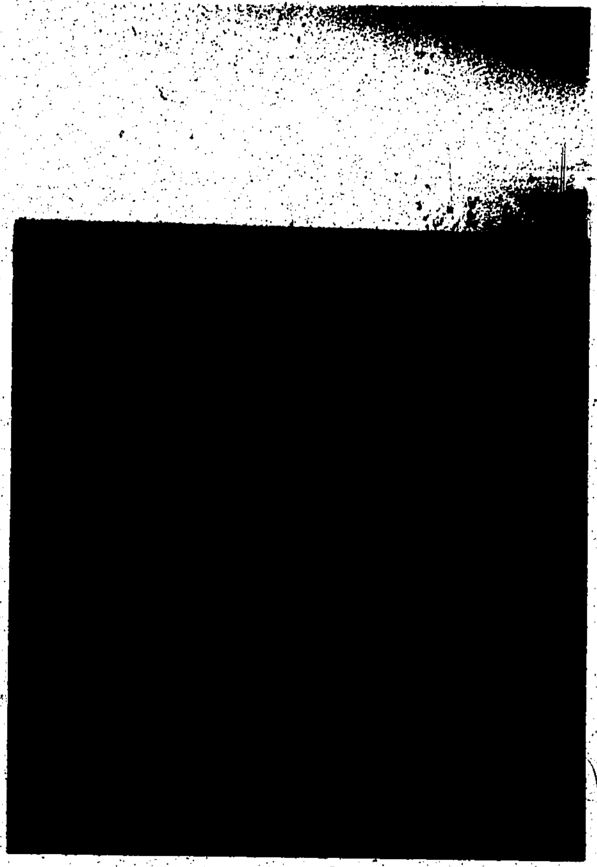


Figure 4-1: Water Body - WB 1
(Cold and deep)

Figure 4-2: Water Body - WB 2
(Warm and shallow)



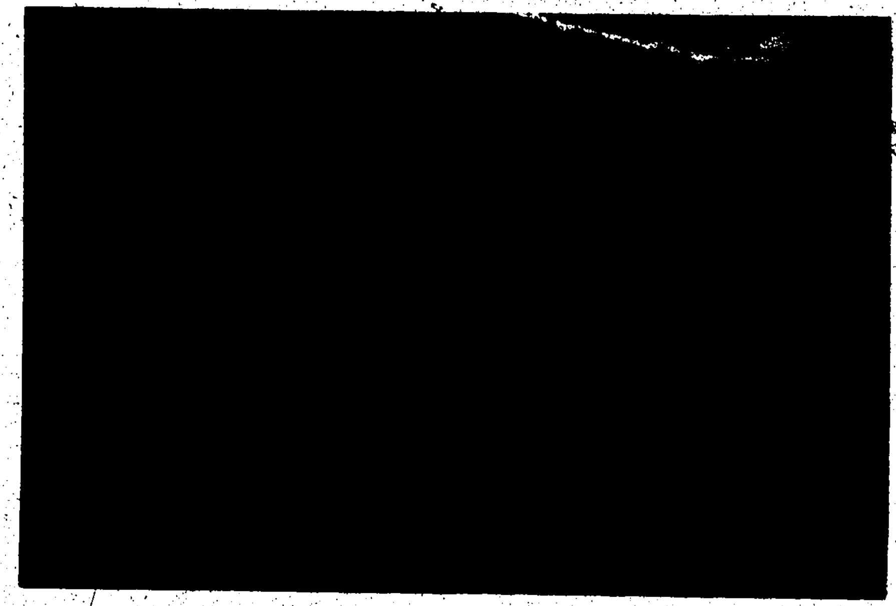


Figure 4-3: Sedge Meadow - SM 2
(Intermediate)

Figure 4-4: Willow/Alder/Leatherleaf - W 1
(Dense)

Figure 4-5: Black Spruce - BS 3 in foreground (Sparse) BS 1 in background (Dense)

Figure 4-6: Open Peat Plateau - P (in center)

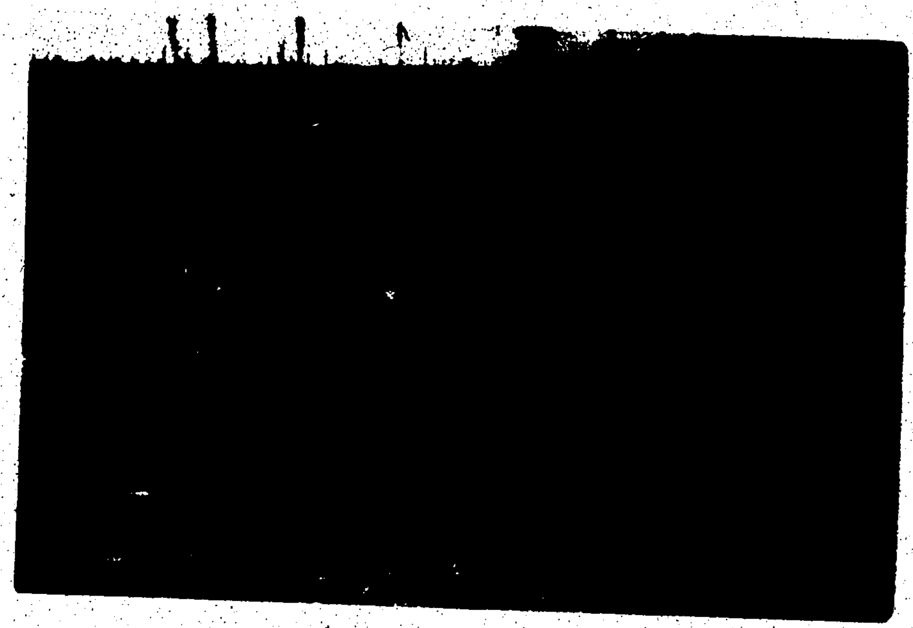
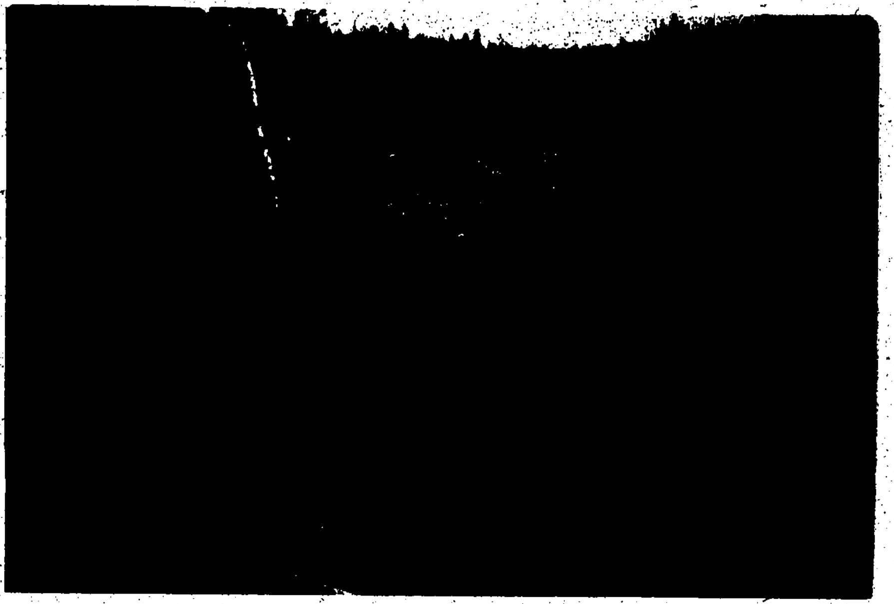


Figure 4-7: Birch/Aspen -B/A 2
(Open, Rocky-marginal)

Figure [redacted]: Jack Pine - JP 2
(Sparse, rocky site 15-50% cover)



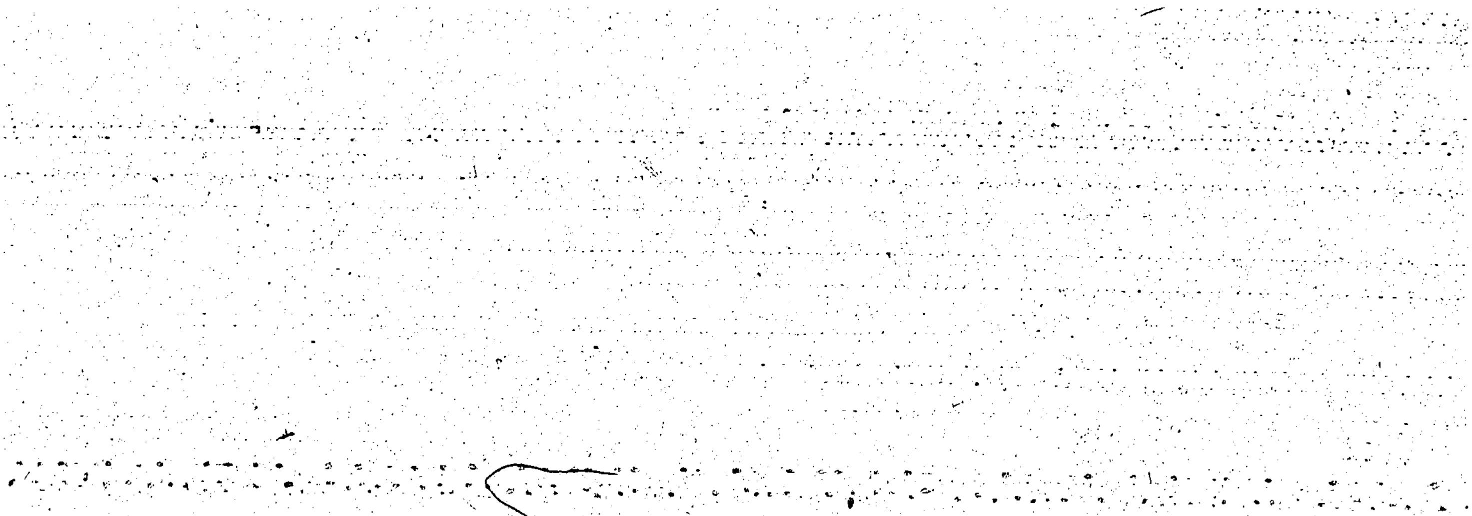


Figure 4-9: Bedrock - R 1
(Moderate - high # depressions)

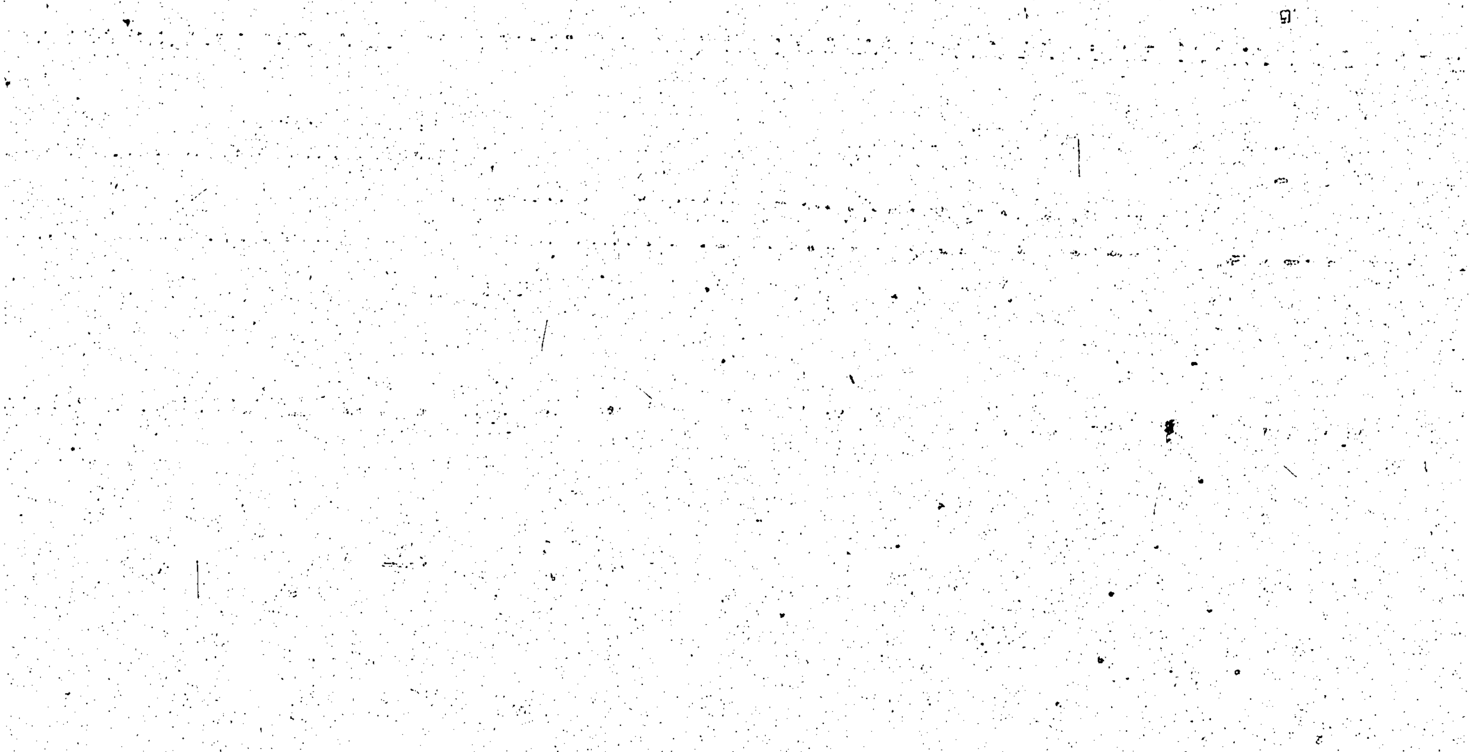
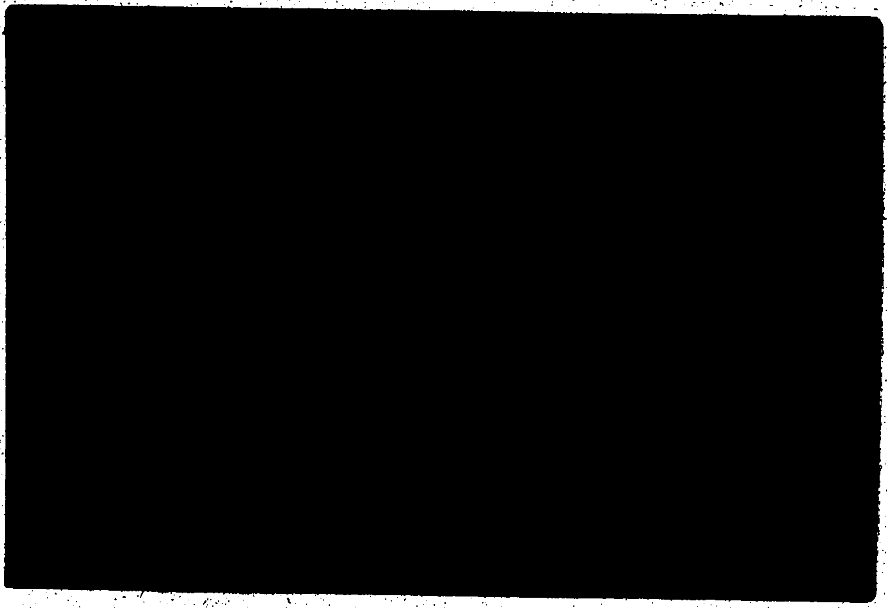
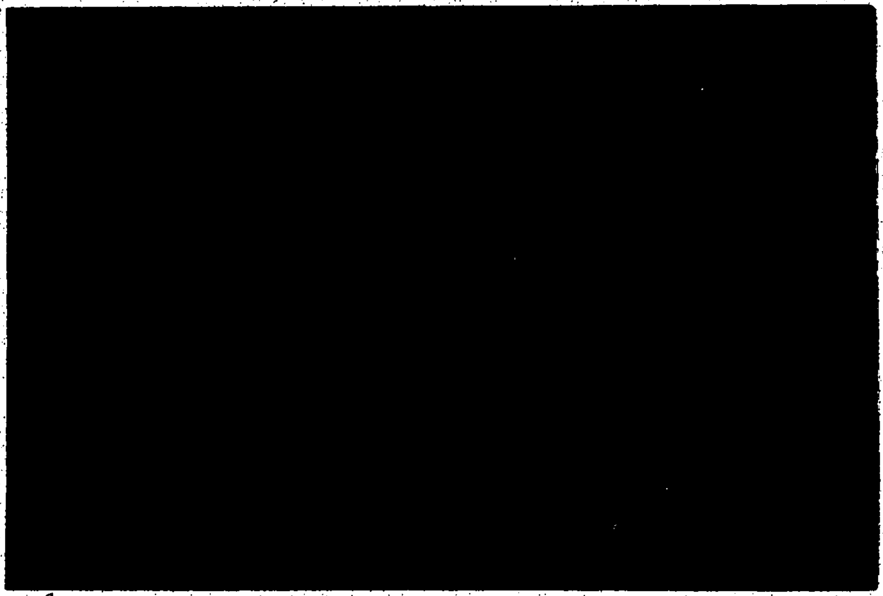


Figure 4-10: Peat Hummocks/Standing Water - P/S





Multistage sampling is a process by which information gathered from large scale photographs is applied to photos of smaller and smaller scales. Only the broadest of patterns may be seen on very small-scale images, but in most cases the step-by-step procedure must be adhered to in order to recognize these gross patterns. In this study three scales were used. Very little loss of detail in pattern recognition occurred when photographs of the study area at a scale of 1:31,680 were used (Figure 4-11). In an area such as the Baker Creek Basin the same patterns of surficial cover are found to occur frequently. Once one becomes adept at interpreting these features on photos as a scale of 1:12,000, they are relatively simple to pick out on the smaller scale of 1:31,680.

The smallest scale used is from the LANDSAT I and II satellite images (Figure 4-12). At 1:1,000,000 it is a great jump from the previous 1:31,680. The reason these very small-scale images were used is that they provide an inexpensive and continual coverage of subarctic Canada. If even the largest of patterns can be recognized on these satellite images, the potential application of a study such as this is increased immensely.

A satellite image containing the Baker Creek Basin area has been taken every eighteen days since LANDSAT I was first launched in July of 1972. When LANDSAT II was placed in orbit on January 21, 1975, the study area could be imaged every nine days, as LANDSAT I was still operable. Because of the relatively high latitude of the study area, side-lap of the images is large and the basin is actually covered more than two times every eighteen days.

The interpretation of surficial cover types on each scale of photos or images, along with maps created from these interpretations will be found in Chapter Five.

Figure 4-11: Portion of an air photo at a scale of 1:31,680, showing study areas A and B in relation to city of Yellowknife. (Roll No. CR250, Line 2, Frame 5, imaged 9/9/67)

Figure 4-12: LANDSAT image of the northern arm of Great Slave Lake showing the relative position of the Baker Creek Basin.
(CCRS E-1780-18171, Orbital Path No. 50, Frame image No. 16, Band No. MSS-6, imated on September 11; 1974)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CHAPTER FIVE

ANALYSIS: SOIL MOISTURE STORAGE IN THE BAKER CREEK BASIN

INTRODUCTION

In this chapter the water balance of the Baker Creek Basin is calculated according to the Thornthwaite water balance equation. Parameters of the equation are defined and discussed, and the results of previous calculations for the study area by Kakela (1969), and Wight (1973) are examined. Moisture storage values for each of the nine intensively studied areas within the basin are compiled and an average value for the entire study area is computed. This value is then used in the water balance equation and the result is compared to results of previous studies, and with recorded stream flow data of Baker Creek. Possible sources of error in the computations and measurements are discussed.

The Thornthwaite procedure for calculating water balance was employed in this study for several reasons. It was developed and refined over a considerable period of time using data from a great variety of climatic and soil regimes. The variables associated with the Thornthwaite water balance equation are latitude, precipitation, temperature and soil moisture storage capacity, all relatively easy to determine (Thornthwaite and Mather, 1957). Two previous studies in the Baker Creek basin (Kakela, 1969; Wight, 1973), employed the Thornthwaite technique and these data are readily available.

Armstrong and Stidd (1967, p. 263), believe that any successful determination of actual evapotranspiration from a natural environment must include the effects of seasonal deficiency in soil moisture storage, and found the Thornthwaite method to be the only one known to them which did this. Although Landals (1970), devised moisture storage values for selected surfaces within a portion of the Baker Creek Basin, they have not been refined and expanded to be applicable to the basin as a whole. The present study is an attempt to accomplish this using new data collected on surficial cover types within the Basin.

THE THORNTHWAITE WATER BALANCE EQUATION

The concept of water balance involves the quantitative budgeting of water relationships in the hydrologic cycle. The method was developed in the early 1940's, and first published in 1948 (Thornthwaite, 1948)[illegible] The major parameters are average monthly air temperatures, precipitation totals and a daylength adjustment to correct for season and latitude. With this information, the researcher can calculate the monthly and yearly water balances of an area by using the formula;

$$P = PE - D + S \pm SC$$

where: P = Precipitation
PE = Potential Evapotranspiration
D = Deficit
S = Surplus
SC = Storage Change

In effect the equation represents a balance between the incoming precipitation of a given area in the form of rain, snow and condensation at the earth's surface, and outgoing water consisting of surface runoff, groundwater discharge, surface evaporation and transpiration from plants. The outgoing portion of the equation is further affected by addition to, or removal from, the soil moisture in storage. A more detailed description of each term in the water balance equation and possible sources of error in measurement will serve to better explain its function.

PRECIPITATION

Theoretically a precipitation gauge records the same amount of rain and/or snow which would reach the ground in that precise area of measurement had the gauge not been there. In practice there are a number of problems associated with precipitation measurement which reduce its reliability. In addition to the relatively minor problems of evaporation losses, gain or loss due to splashing and improper levelling of the device, the wind factor is the most serious (Bruce and Clark, 1966, p. 67). Wind speeds can increase over the collecting orifice of the precipitation gauge and often reduce the amount of rain drops or snowflakes entering, thus misrepresenting the actual amount of precipitation. The nature of convective or frontal storms is such that winds are often associated with their occurrence. Steps can be taken to reduce the possible error of measurement, such as keeping the rain gauge low to the ground where winds are reduced. However, as of yet no device or precaution has been developed to entirely eliminate error.

In most water balance calculations moisture which has condensed on cool surfaces from saturated or nearly saturated air is included with precipitation or it may be omitted on the assumptions that it is either small and can be ignored or largely compensated for in underestimates of evapotranspiration. The amount of condensation is determined not only by the atmospheric conditions but also by the nature of the surface upon which condensation takes place. Generally speaking, the cooler the surface the more condensation which will occur. Because of this variability, measurement or estimation of this factor for a large area, such as the Baker Creek Basin, is unreliable. For a previous discussion of precipitation patterns see Chapter Three.

POTENTIAL EVAPOTRANSPIRATION

Potential evapotranspiration, or P.E., is the amount of moisture which will be transferred to the atmosphere from the land surface (including water bodies), if a constant supply of water is available. It includes both evaporation from surfaces and transpiration from plants. The amount of P.E. increases with intensity of solar radiation.

Thornthwaite (1948), devised a method of estimating P.E. in which it was expressed as a function of the mean monthly air temperature with a daylength adjustment to correct for season and latitude. His original formula and that expressed by Hare in later works is as follows:

$$e = 1.6b\ (10t/I)^{a}$$

where e = monthly PE in cms.

t = mean monthly temperature in ^{o}C

a = cubic function of I

b = correction factor for difference in daylength between months

and

$$I = (t/5)^{1.514}$$

where I = monthly heat index

t = mean temperature of the given month in ^{o}C

Although widely employed for the temperate, continental climate of North America, where it was originally devised, Thornthwaite's P.E. formula has drawn criticism for application in other parts of the world, especially in latitudes above 50^{o}N. Chang (1968, p. 198), discusses several problems associated with assumptions made by Thornthwaite in his P.E. equation.

First, air temperature is not necessarily a good indicator of the amount of energy available for evapotranspiration. In subarctic regions such as the study area, much of the solar radiation, especially in the spring and early summer, is used to melt the snow and ice and to heat the air. Thus while the ambient air temperature may be relatively high, it will not be indicative of the amount of energy available for P.E. In lower latitudes there is a much higher correlation between radiation and air temperature.

Secondly, estimates of P.E. based on the Thornthwaite equation tend to lag behind measured values because an increase in solar radiation precedes a rise in air temperature. This factor would then cause the P.E. to actually be higher in the spring months of May and June and lower in September and possibly October. The effects would be a larger deficit in moisture storage for the spring and a smaller value in the fall.

A third source of error with the Thornthwaite P.E. equation is that daily averages of temperature are used. Quite often in the fall or spring months the daily temperature in the study area will rise above freezing but the daily mean will be below. Thus evapotranspiration will be underestimated. It has been proposed that the maximum daily temperature in marginal months, i.e., those in which the temperature fluctuates above and below the freezing point, be used in Thornthwaite's P.E. equation rather than the mean (Mather, 1961).

Another very important problem with the Thornthwaite equation for determining P.E. in the northern hemisphere is that the correction factor for duration of sunlight by date and latitude extends to only 50°N. For all areas above that latitude the 50°N correction factor must be used. There is no evidence to suggest that variability in the correction factor ceases at precisely 50°N latitude. The result is that P.E. values computed from Thornthwaite's equation in subarctic areas, such as the Baker Creek Basin, are inherently error-prone.

Despite these problems in application of Thornthwaite's P.E. equation, it is still more widely used than any alternative. Admittedly, the equation is empirical and only raw values are initially obtained. But numerous corrections and modifications to account for the aforementioned error sources have been introduced by various authors and the end product is at least as good as that obtained from intensive physical measurements using Penman's and other procedures.

For an empirical procedure such as Thornthwaite's water balance equation to be applicable over a wide range of latitudes and climates adjustments must be made for such parameters as precipitation, temperature, evapotranspiration and areal differences in soil moisture storage levels (Wiche, 1977, p. 71). A major objective of the present study is to better define the vegetation-related distribution patterns of variation in storage levels.

DEFICIT

When P.E. is greater than precipitation after soil-moisture storage has been utilized there is said to be a moisture deficit. The importance of the deficit value is that when subtracted from P.E. the result is actual evapotranspiration, or A.E. Whereas P.E. is a theoretical value, A.E. represents the true situation for the area of study. In order to ensure reliable calculations of deficit, the soil moisture storage value for the area must be determined as accurately as possible, and it should reflect the variations in surficial cover response to moisture retention. The averaging of these moisture storage variations and degree of cover of each will result in a more reliable final deficit figure.

SURPLUS

Surplus refers to the value of precipitation minus P.E. after storage has been fully recharged. It includes surface runoff, interflow and ground water movement varying largely with the nature of the storage medium. In the Baker Creek basin, where groundwater movement is suspected to be minimal due to the resistence of the crystalline Shield bedrock, the calculated surplus for a given year has been presumed to be roughly equal to the discharge of Baker Creek.

Since water bodies comprise approximately ten percent of the study area their special function as collection areas for the runoff from surrounding land areas should be mentioned.

Theoretically the runoff from a given drainage basin is the amount of water which passes out of that basin by way of the stream or river which drains it. After a period of precipitation, lakes and ponds which have outlets will collect surrounding area runoff in addition to the precipitation which falls directly on their surfaces and the supply that is excess to storage capacity of these water bodies, after evaporation, will overflow and join the stream flow. In the Baker Creek Basin most of the lakes are depressions in the bedrock and are connected to other lakes, not by well-defined streams but by stretches of muskeg and/or sedge meadows. Consequently, if a given lake receives an excess of runoff it will tend to seep rather slowly through the organic terrain until it issues into another lake which may or may not expell an equal amount from its lower end. This process can take a considerable amount of time and the result is that a large percentage of the potential runoff can be evaporated in transit from either the muskeg or the lake surfaces. The basin discharge gauged near the lower end of Baker Creek after a storm, therefore, may not reflect the true total amount of local runoff.

Another problem associated with the reliability of streamflow values is icing in winter and early spring months. Ice can block the passage of water at the gauge site and cause lower than average readings to be made. Wight (1972,

p. 132), in consultation with A. H. Laycock, suggested that due to gauge blockage by ice conditions, in exceptionally cold winters perhaps as much as ten percent of measured discharge in the appropriate months should be added to the yearly total, and one to two percent in average winters. It may, however, be more a matter of winters with higher than average snowfall than with extremely low temperatures. The heavy snow cover on the lake ice may act to squeeze lake water into the outlet channel where it freezes and contributes to major blockage of the recording gauge (Laycock, personal communication, 1978).

STORAGE CHANGE

The storage change factor in the Thornthwaite water balance equation is the difference between the amount of moisture stored in the soil plus that present on the ground as snow and ice at the beginning of January in a given year and the amount of the same components at the end of December of the same year. This figure should be relatively free of error except that it is indirectly related to precipitation and P.E., the measurement of which, as noted above, is prone to error. If the storage value for the beginning of the year is larger than that at the end, there is said to be a loss of storage and the amount is subtracted in the equation. Conversely, a net gain of moisture storage for the year would be indicated by a higher December than January reading and this difference would be added in the equation.

SOIL MOISTURE STORAGE

Thornthwaite (1948, p. 60), suggested that if a variety of plant species were supplied with a constant source of water at the root zone, the amount of soil moisture used by the plants would be more dependent on amount of solar radiation available and the ambient air temperature than on individual differences in the species. In regions and seasons where there is not a constant supply of water at the root zone, i.e., when soil moisture fluctuates between field capacity and the wilting point, and perhaps even dries beyond the latter, the individual characteristics of different plant species become more important.

There is a difference of opinion in the literature about whether plants are able to transpire at a constant rate between field capacity and the wilting point. Veihmeyer (1927, p. 205), using tank-grown trees, found that per unit area of leaf surface there was no difference in transpiration rates above the wilting point. The conflicting opinion is that transpiration slows as the wilting point is approached (Penman, 1963, p. 47).

Individual species differ in their stomatal response to impending drought conditions at the root zone. In some species the stomata remain open until the wilting point is reached and thus will transpire at a constant rate until the water source is depleted. Others have adaptations which cause the stomata to begin to close if moisture supply at the root zone begins diminishing, thus conserving water and prolonging their life.

The amount of moisture stored within the soil at any given time and available to plants depends upon the type of soil, type and extent of plant cover, and time and amount of recharge. Given the occurrence of recharge, the most important factors are the texture of the soil and depth of root development (Laycock, 1967, Appendix B, p. 1), (Table 5-1). In the Baker Creek Basin large tracts of intrazonal organic soils, characterized by a high detention storage but low retention storage are common. Azonal soils located in cracks and fissures with the bedrock rarely occur as large groups but are scattered throughout the study area. These azonal soils often contain a high clay content of lacustrine origin and therefore have a high retention storage. Generally the water which is most readily available to plants is that in retention storage.

Soil depth varies considerably within the Baker Creek Basin. The organic terrain found in the extensive muskeg areas can be quite deep and the rooting depth of plants within such areas is limited only by the depth to the permafrost table or the nature of the particular plant species. Sedge meadows can attain even greater depths of rooting due to a lower permafrost table than occurs in muskeg.

In the upland rocky azonal soils the rooting depth of plant species is limited by the normally short distance to

Table 5-1: Water content (cm.) per 0.3 meters of soil depth

Soil Texture Class	Pore Saturation	Detention Storage	Field Capacity	Retention Storage	Wilting Point
Sand	12.7	10.4	2.3	1.3	1.0
Sandy Loam	12.7	8.1	4.6	2.8	1.8
Loam	12.7	5.8	6.9	4.1	2.8
Clay Loam	13.7	5.1	8.6	4.3	4.3
Clay	13.7	1.0	12.7	6.4	6.4

(based upon Colman, 1948)

bedrock. During months exhibiting a water deficit these azonal soils will be depleted of soil moisture while the water contents of intrazonal organic soils will remain far above the wilting point.

Because of these differences in soils and vegetation within the study area, it would appear that a more accurate method of computing water balance values for the Baker Creek Basin would be to differentiate among surficial cover types as these are related to soil moisture storage utilization. Until now this practice had not been employed. Kakela (1969, pl 209), assumed a 2.54 cm. average moisture storage for the basin for two reasons; 1) it was very close to the mean spring retention capacity for his study area, a relatively rocky portion of the Baker Creek Basin, and 2) the 25-year mean calculated runoff using a 2.5 cm. storage value was found to be relatively close to the mean discharge from the Yellowknife River Basin during the same period. Wright (1972, p. 266), used the same 2.5 cm. storage value but suggested that a more realistic figure would perhaps be 8.4 cm., this figure being more compatible with his other water balance parameters.

SOIL MOISTURE STORAGE CATEGORIES

The Baker Creek Basin is divided into surficial cover categories as described in Chapter Four and the storage values assigned to each surficial cover type are listed in Table 4-1. These storage values were decided upon in consultation with Dr. A. H. Laycock and are based upon preliminary studies by Kakela (1969), Landals (1970), Wight (1973), and Dr. Laycock and R. Steiner in the period 1968-1974, as well as studies in other parts of western Canada. They range from a low of 1.3 cm. in predominantly bedrock areas which exhibit few depressions and thus allow little infiltration of water, to unlimited storage in lakes which receive runoff from surrounding areas.

The bedrock areas provided a problem of interpretation. Bare bedrock of an areal extent large enough to differentiate on the air photos were rare. More often they occurred in smaller sites intermixed with jack pine or birch/aspen stands. In total, however, they constitute a fairly large percentage of the upland areas. Because they cannot be mapped separately they have to be included in another categoty. Due to the many small depressions and crevasses in the bedrock, some of which contain soil and vegetation, potential runoff from these bare bedrock areas may easily be trapped and stored for a period of time, thus contributing little to the runoff factor. The same is true in winter for snow drifting. The result is that these "islands" of bare bedrock intermixed with jack pine or birch/aspen stands react to periods of precipitation more like the storage category within which they are located than like larger expanses of bedrock itself. For this reason it is believed that the inclusion of bare bedrock areas within larger surrounding storage categories is justifiable.

Maps of surficial cover types and moisture storage categories for each of the nine smaller study areas within the basin can be found included in Figures 5-1 to 5-18. (For the location of each study area within the basin see Figure 1-4). These nine areas were chosen for intensive study because it was thought that they were representative of the entire Baker Creek Basin. Study area B, Figure 5-3, includes the largest percentage of low-lying organic terrain of the areas chosen and approximates the surficial cover for similar portions of the basin, notably the area just southwest of Duckfish Lake. Study areas H and I, Figures 5-15 and 5-17, exhibit the largest amount of upland rock area. The other study areas within the Baker Creek Basin range between these extremes. The following is a description of each soil moisture storage category.

<u>1.3 cm. Storage</u>

This soil moisture storage category is represented by only one surficial cover type, relatively bare bedrock areas with few depressions. The nature of the rock and the smoothness of its surface provides precipitation with little opportunity to collect and be retained. Rain falling on these areas will be subject to rapid runoff and in the winter snow will tend to be swept clear by winds so that this storage category does not contribute substantial amounts of spring snowmelt to the basin. Throughout the Baker Creek Basin these rock areas are covered to some degree with foliose, crustose and fruticose lichens.

Table 5-2: Photointerpretation Legend for Study Areas A-I

Map Symbol	Description
WB1	Deep, Cold Waterbody
WB2	Warm, Shallow Waterbody
SM1	Wet Sedge Meadow
SM2	Intermediate ~~Sedge~~ Meadow
SM3	Relatively Dry Sedge Meadow
W1	Dense Willow/Alder/Leatherleaf
W2	Open Willow/Alder/Leatherleaf
BS1	Dense Black Spruce
BS2	Intermediate Black Spruce
BS3	Sparse Black Spruce
P	Open Peat Plateau
B/A1	Dense Birch/Aspen
B/A2	Open, Rocky Marginal Birch/Aspen
B/A3	Open, Rocky Upland Birch/Aspen
JP1	Dense (over 50% cover) Jack Pine
JP2	Sparse (15-50% cover) Jack Pine
JP3	Sparse (2-14% cover) Jack Pine
R1	Bedrock (large no. of depressions)
R2	Bedrock (few depressions)
P/S	Peat Hummocks/Standing Water

Figure 5-1 Study area A — Surficial Cover
(R6519 5 - 176, June, 1968)

N

(For Legend see Table 5-2)

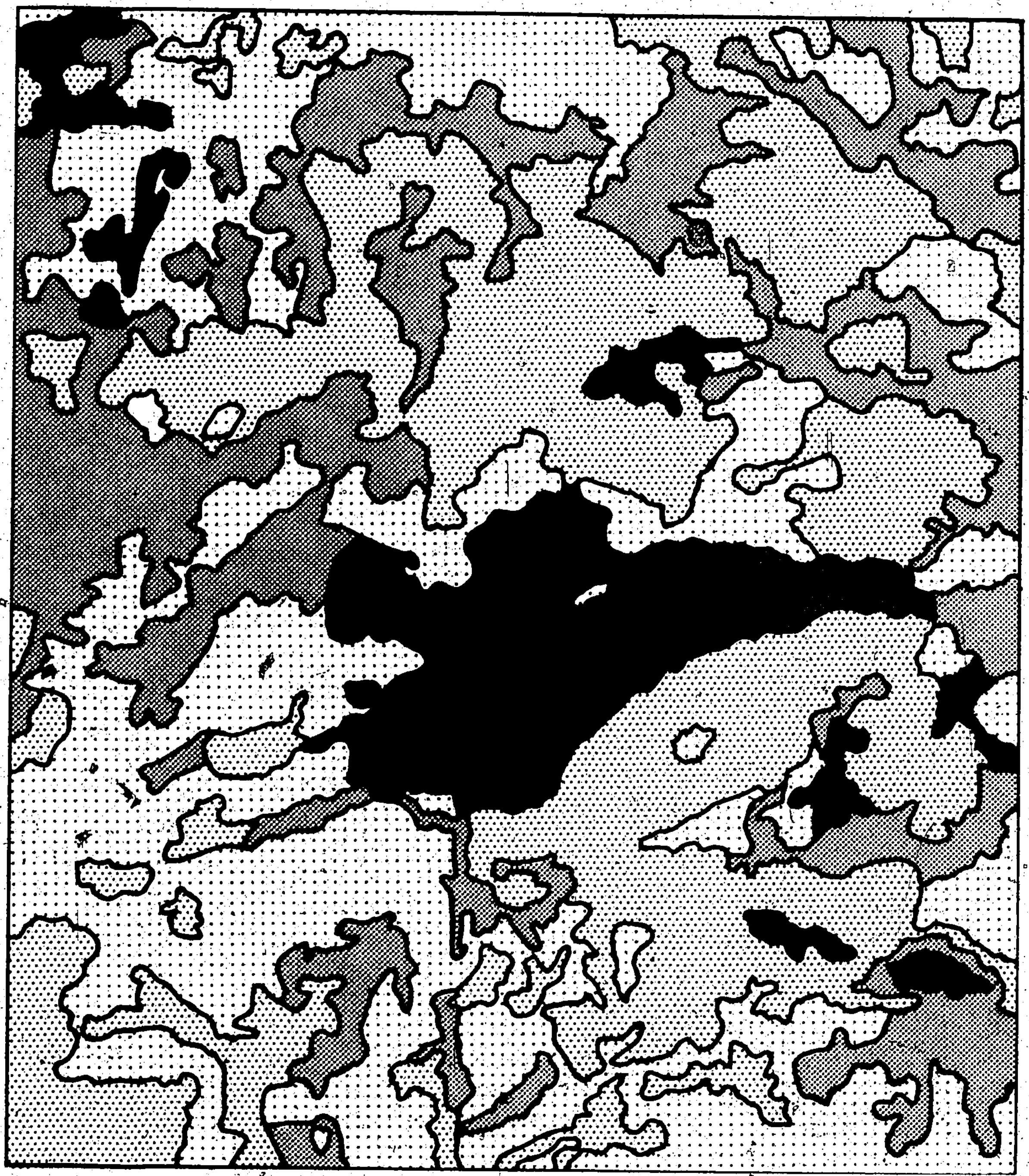

Figure 5-2 Study area A — Moisture Storage

LEGEND

░ 5 cm.

▒ 15 cm.

■ PE

□ 1.3 cm.

░ 10 cm.

■ 25 cm.

■ PE + ½D

Figure 5-3　Study area B — Surficial Cover

(R6519 5 - 181, June, 1968)

N

(For Legend see Table 5-2)

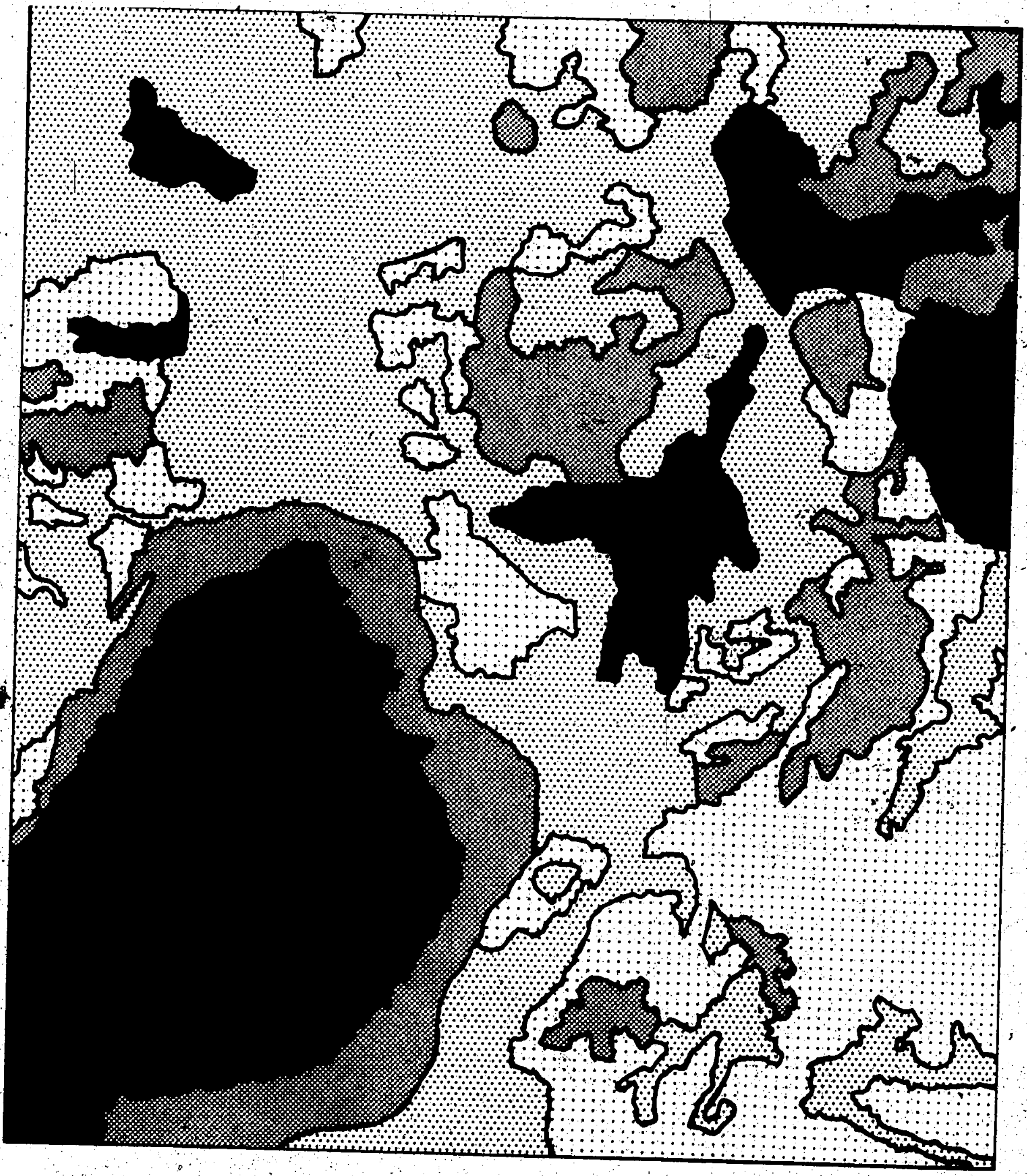

Figure 5-4 Study area B — Moisture Storage

LEGEND

		░	5 cm.	▒	15 cm.	▓	PE
☐	1.3 cm.	░	10 cm.	■	25 cm.	■	PE + ½D

Figure 5-5 Study area C — Surficial Cover
(R6519 6 - 241, June, 1968)

▲
N

(For Legend see Table 5-2)

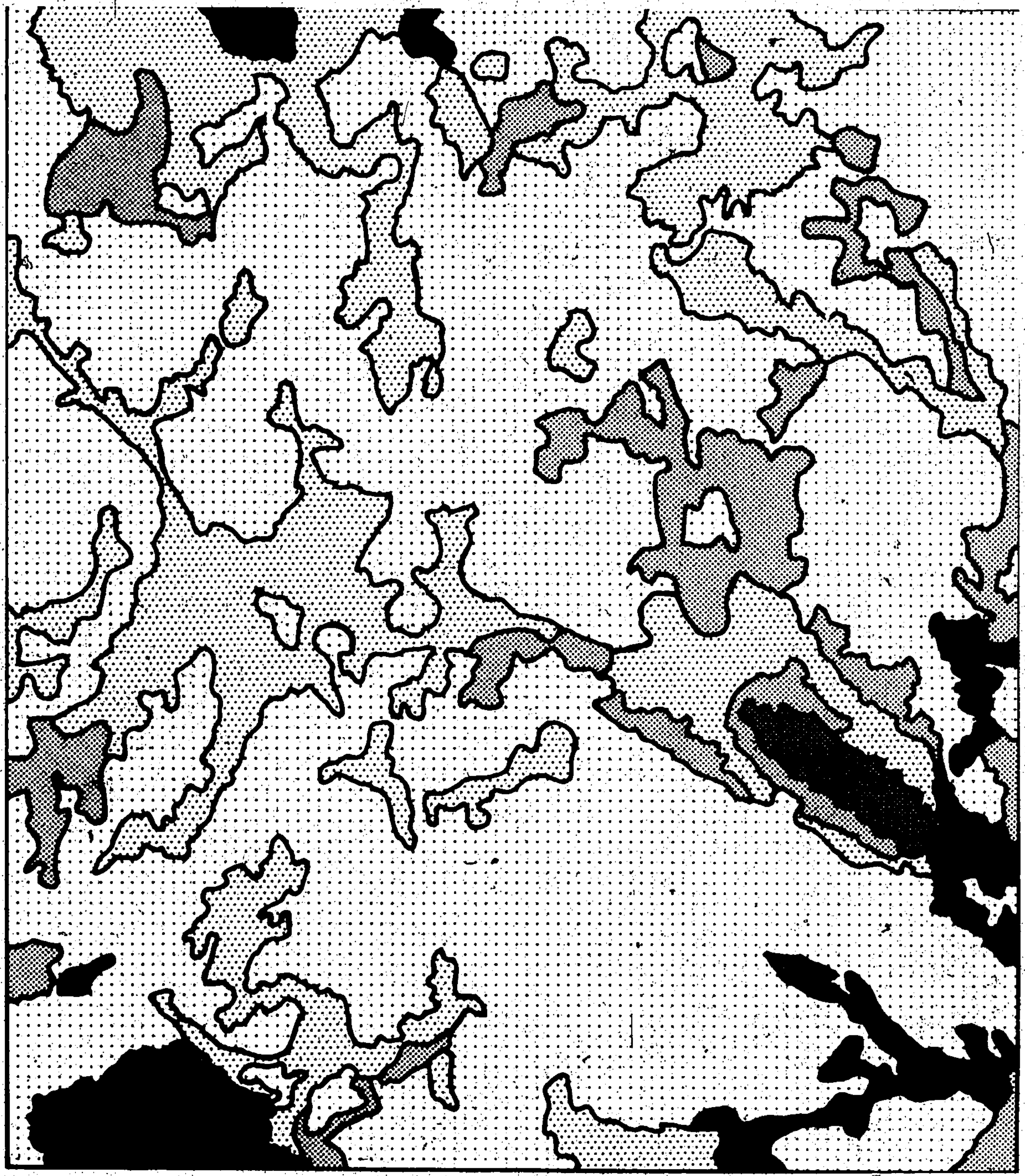

Figure 5-6 Study area C — Moisture Storage

LEGEND

⁙ 5 cm.

▒ 15 cm.

▓ PE

☐ 1.3 cm.

░ 10 cm.

■ 25 cm.

■ PE + ½D

Figure 5-7 Study area D — Surficial Cover

(R6519 6 - 232 June, 1968)

(For Legend see Table 5-2)

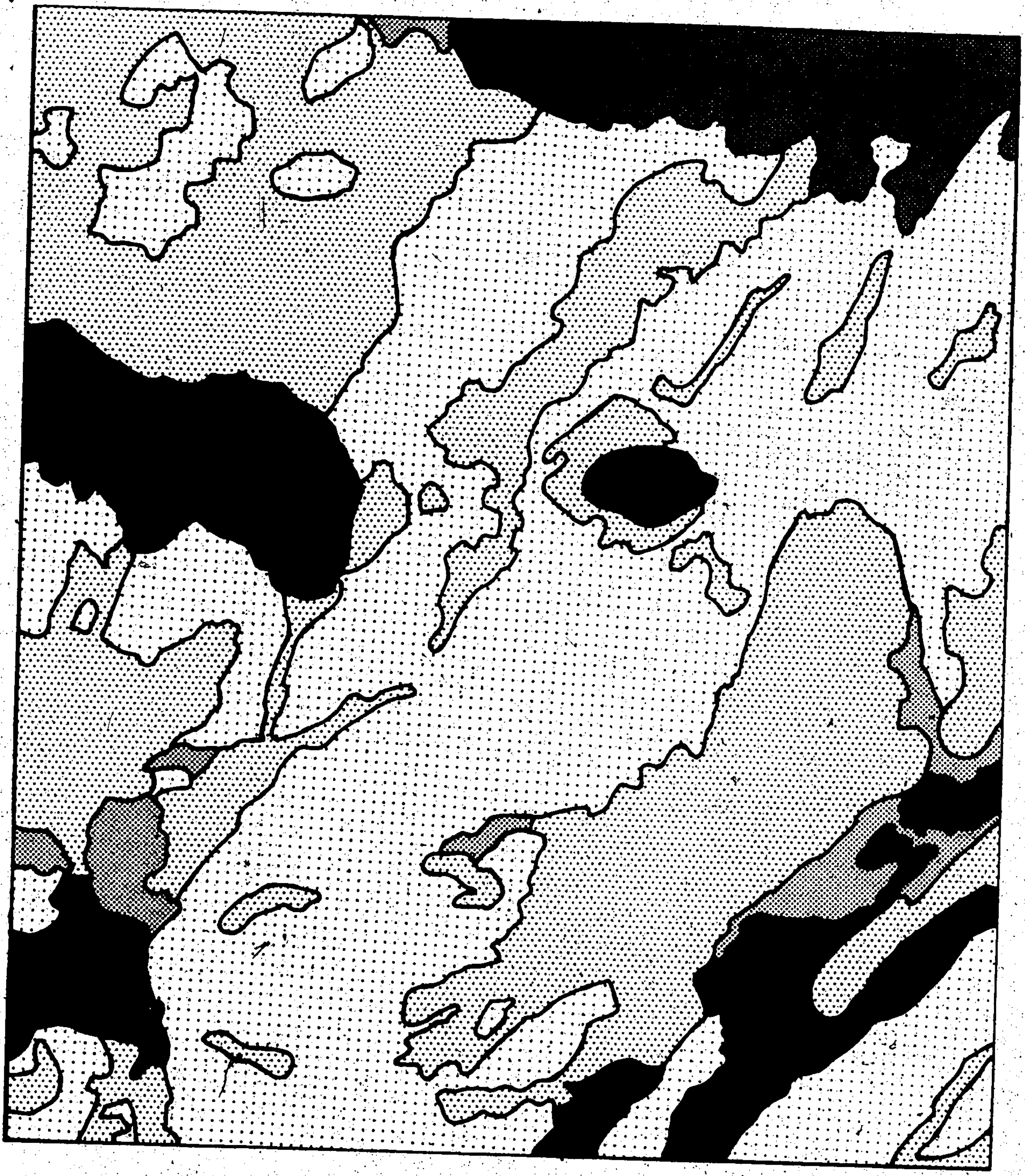

Figure 5-8 Study area D — Moisture Storage

LEGEND

☐ 1.3 cm.

░ 5 cm.

▒ 10 cm.

▓ 15 cm.

■ 25 cm.

▩ PE

■ PE + ½D

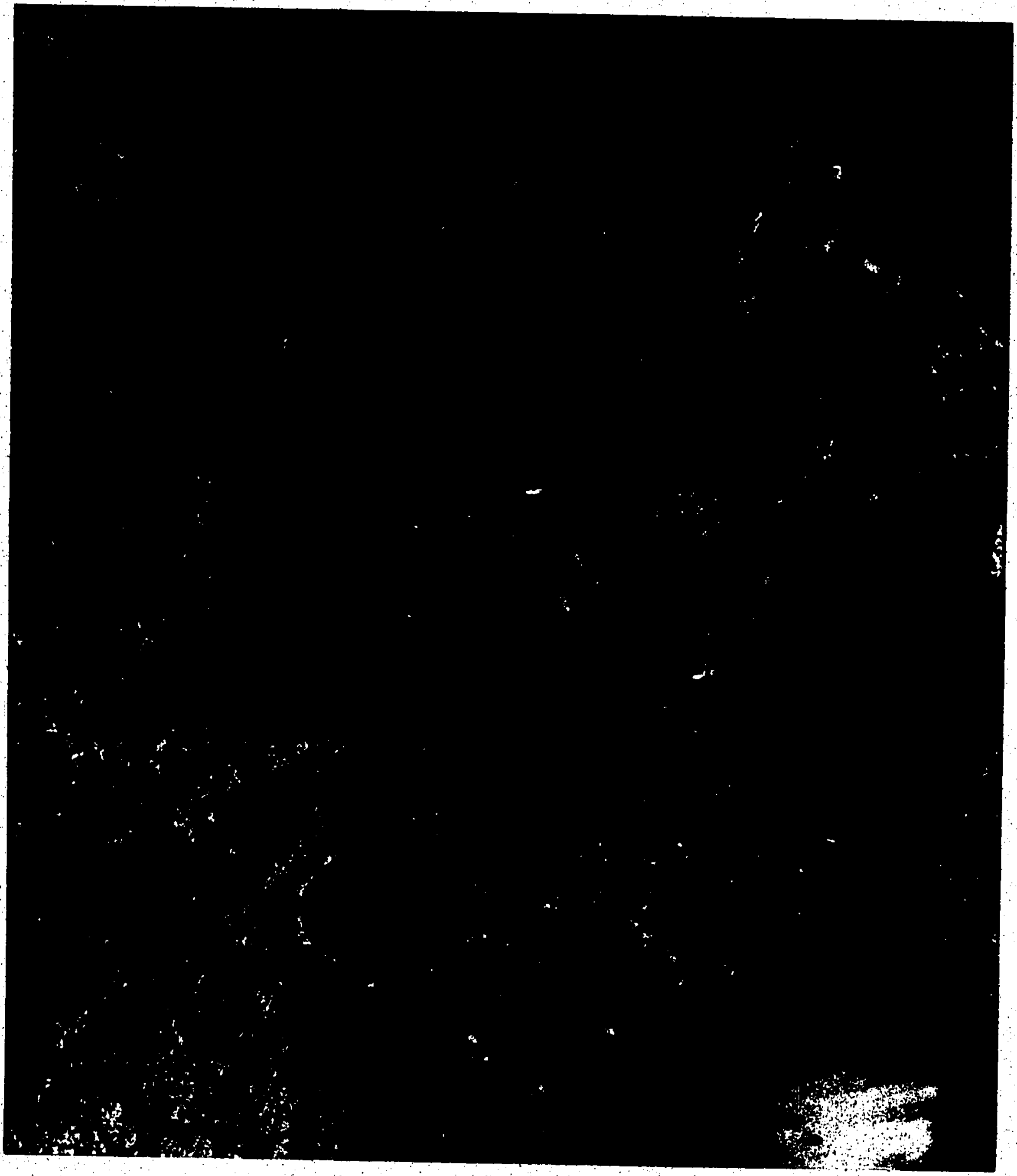

Figure 5-9 Study area E - Surficial Cover

(R6519 4 - 146 June, 1968)

(For Legend see Table 5-2)

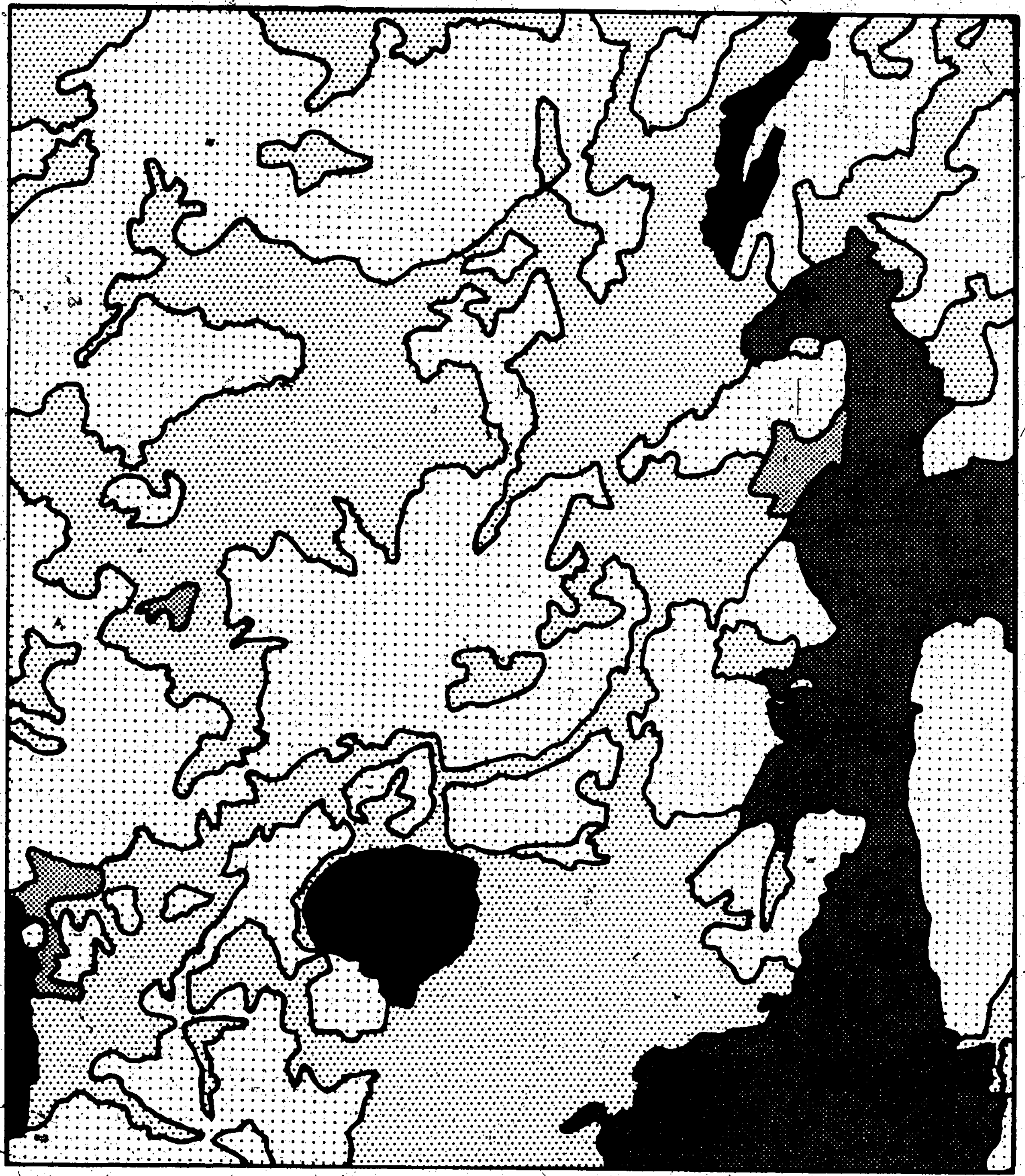

Figure 5-10 Study area E — Moisture Storage

LEGEND

⠿	5 cm.
▨	15 cm.
▩	PE
☐	1.3 cm.
░	10 cm.
■	25 cm.
■	PE + ½D

Figure 5-11 Study area F — Surficial Cover
(R6519 7 - 263 June, 1968)

(For Legend see Table 5-2)

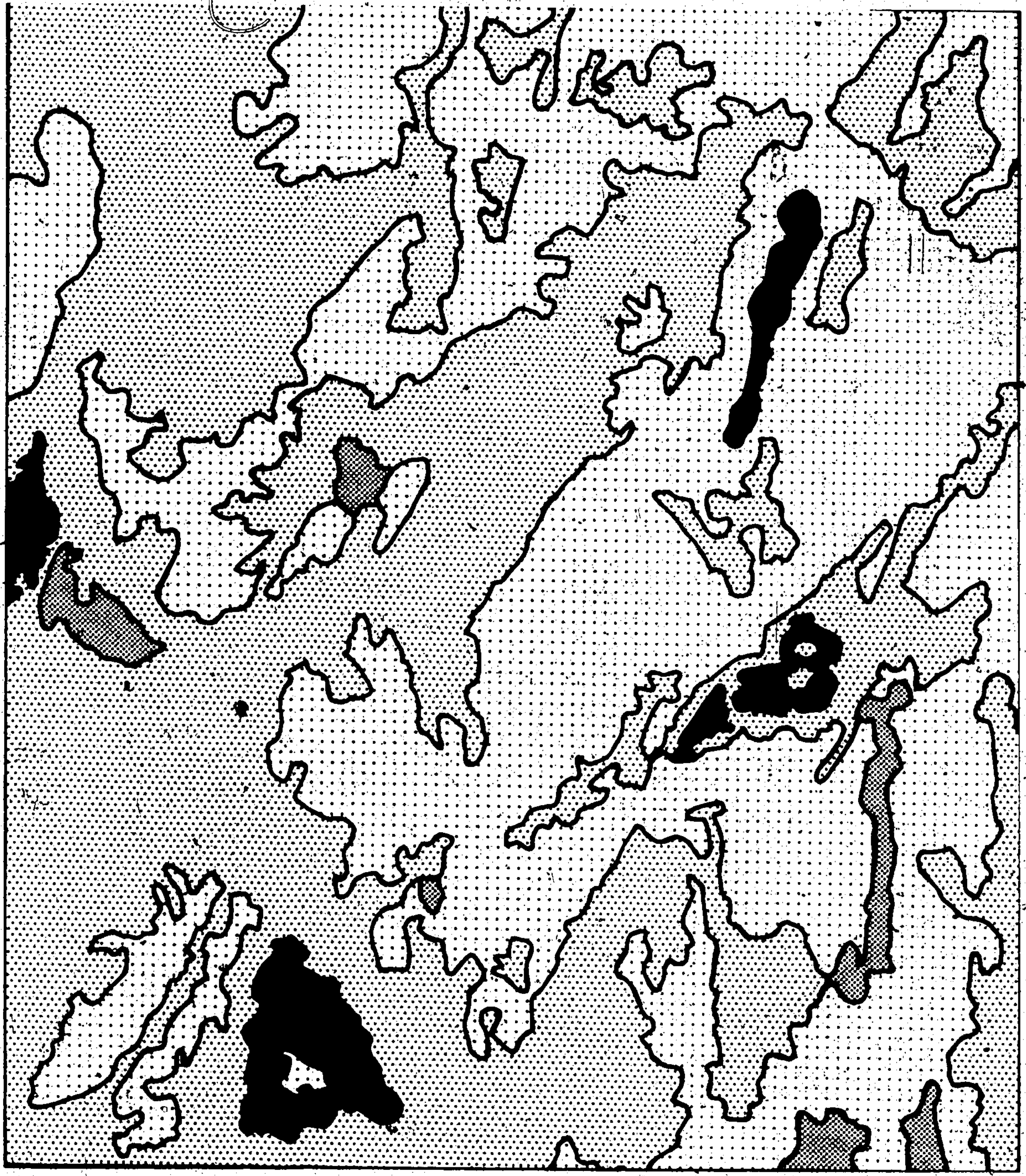

Figure 5-12 Study area F — Moisture Storage

LEGEND

☐ 1.3 cm.

▒ 5 cm.

▒ 10 cm.

▨ 15 cm.

■ 25 cm.

■ PE

■ PE + ½D

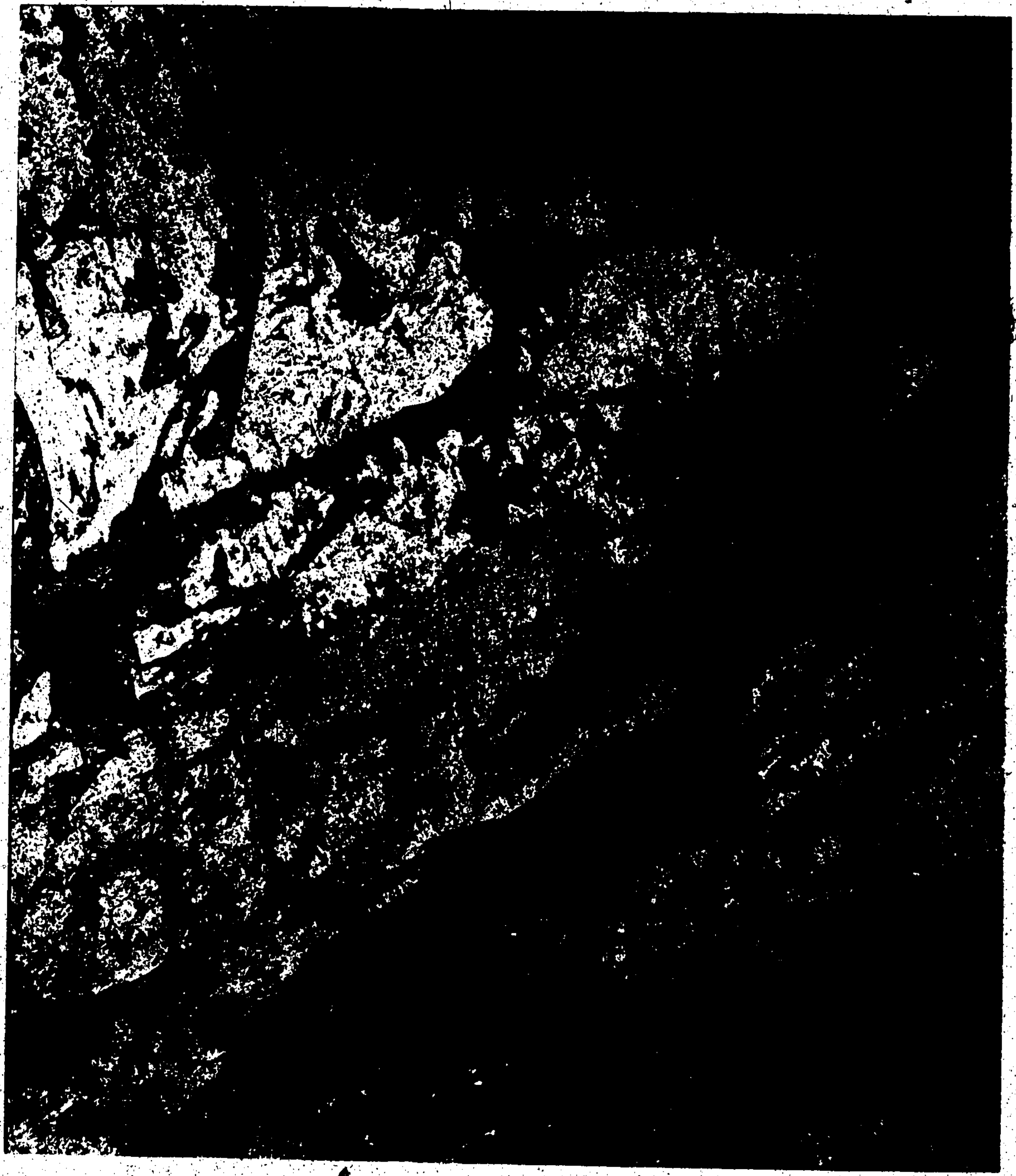

Figure 5-13 Study area G — Surficial Cover
(R6519 7 - 267 June, 1968)

(For Legend see Table 5-2)

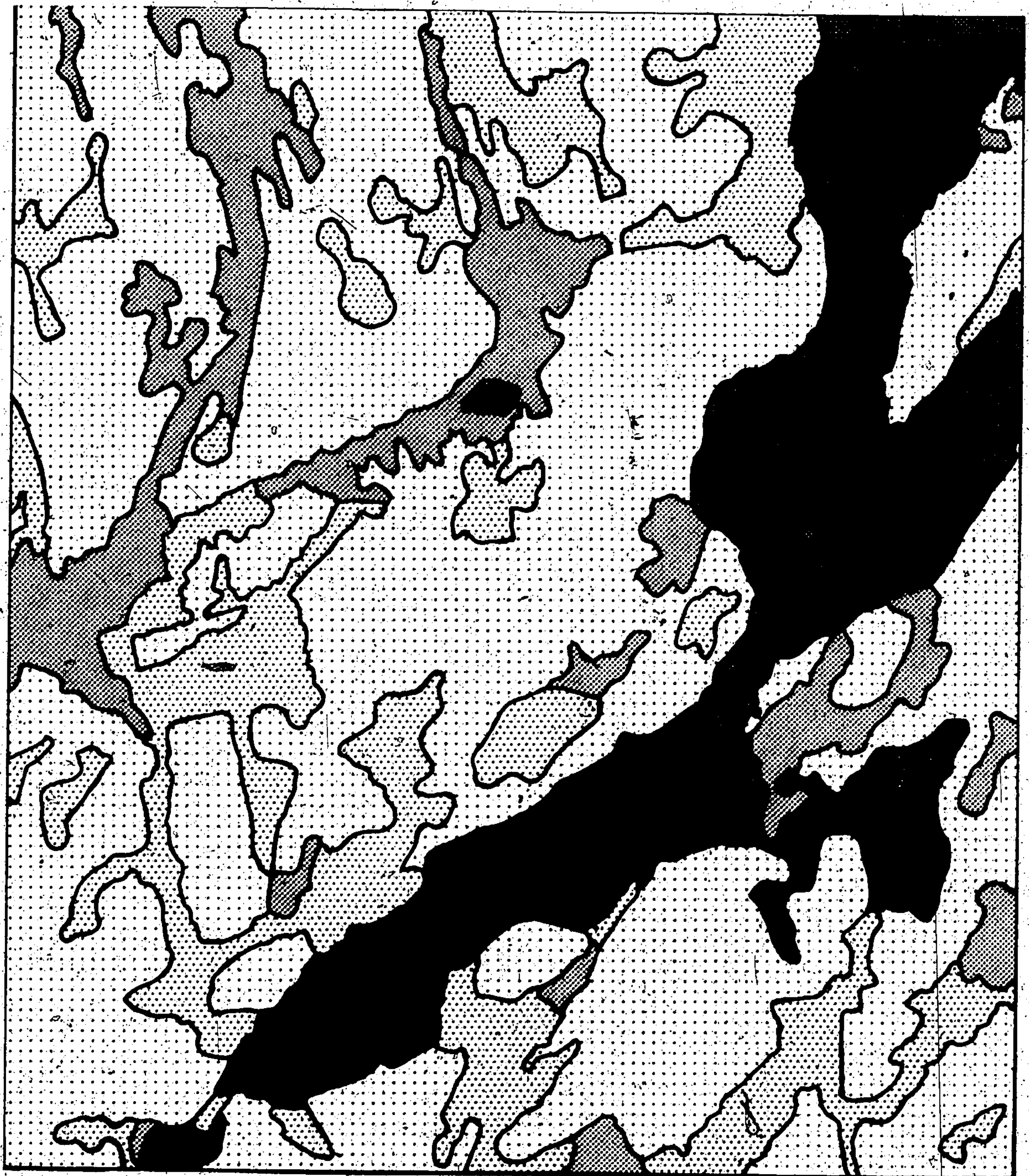

Figure 5-14 Study area G — Moisture Storage

LEGEND

▦	5 cm.
▨	15 cm.
■	PE
☐	1.3 cm.
▦	10 cm.
■	25 cm.
■	PE + ½D

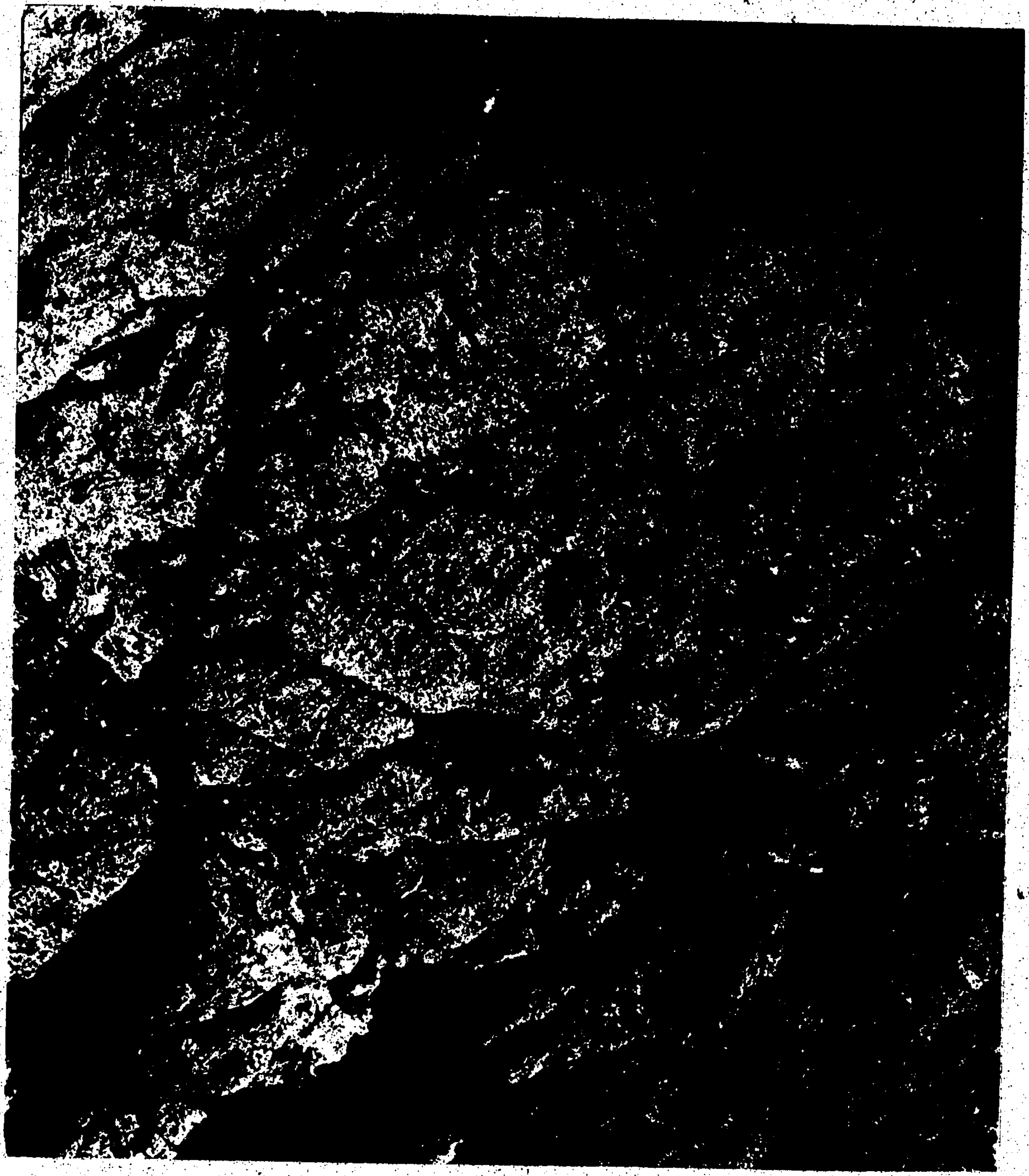

Figure 5-15 Study area H — Surficial Cover

(R6519 5 - 207 June, 1968)

(For Legend see Table 5-2)

Figure 5-16 Study area H — Moisture Storage

LEGEND

░ 5 cm.

▓ 15 cm.

■ PE

□ 1.3 cm.

▒ 10 cm.

■ 25 cm.

■ PE + ½D

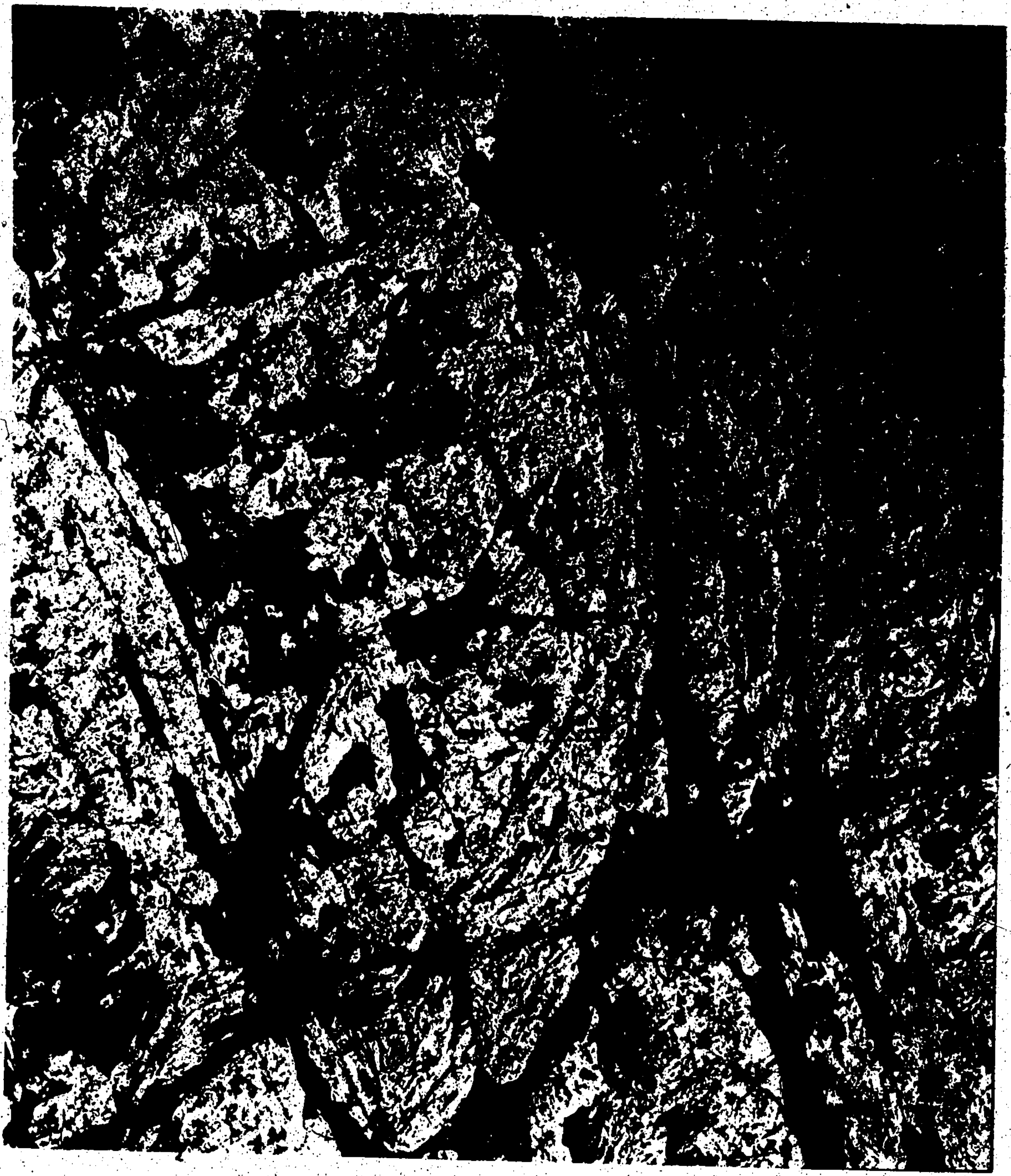

Figure 5-17 Study area I Surficial Cover
(R6519 5 - 213 June, 1968)

(For Legend see Table 5-2)

Figure 5-18 Study area I — Moisture Storage

LEGEND

5 cm.

15 cm.

PE

☐ 1.3 cm.

10 cm.

■ 25 cm.

■ PE + %D

5.0 cm. Storage

This category includes surficial cover types from both depressional sites and rocky uplands. The bedrock areas represented in this storage category are those which have a moderate to high number of fractures and depressions, and are thus able to retain more precipitation than those found in the 1.3 cm. storage. In most cases there will be vegetation growing in the larger depressions but the underlying bedrock is never far from the surface and this tends to limit plant growth to those species which either naturally have a shallow root system or can adapt to the existing conditions. These rock areas are also subject to coverage by lichens.

Two similar cover types placed in this storage order are the most sparse categories of jack pine and birch/aspen As discussed in Chapter Three these species are sometimes found within or on the margins of depressions, but normally they occupy the drier uplands. In a sense these two cover types represent the bedrock component of this storage category in which the fractures and depressions contain predominantly the respective species.

Understory vegetation is not well developed due to the small amount of soil available for growth. Representative species include the prickly rose (Rosa acicularis), bog cranberry (Vaccinum vitus-idea var. minus), bearberry (Arctostaphylos uva-ursi), arctic bearberry (Arctostaphylos rubra), grasses, possibly moss (Sphagnum spp.) and lichen (Cladonia spp.).

The depressional site cover types in this storage category are the organic peat plateaus and the relatively dry sedge meadows. These cover types are often found adjacent to each other in the Baker Creek Basin. It is thought that the drying-up sedge meadow is a transitory stage in the formation of a peat plateau. A common occurrence in the study area is the presence of a small water body surrounded successively by a wet sedge meadow, an intermediate sedge meadow, a relatively dry sedge meadow and a peat plateau.

The peat plateaus are characteristically hummocky and relatively dry compared to muskeg areas. Summer precipitation normally drains from these raised peat hummocks, the exception being that which is absorbed by the peat and living sphagnum. Because these peat plateaus are typically 0.5 meters above the surface of adjacent sedge meadow areas, they do not become saturated with standing water, except possibly during spring snow melt. Due to their surface morphology peat plateaus are collecting areas for snow in winter. The insulating properties of the peat result in its maintaining a high permafrost table.

Low strata vegetation foundon the peat plateaus is represented by species such as Labrador tea (_Ledum groenlandicum_), cloudberry (_Rubus chamaemorus_), bog cranberry (_Vaccinum vitus-idea_ var. _minus_), _Sphagnum spp_. and _Cladonia spp_. Although many peat plateaus are characterized by stands of black spruce of varying densities, for this study the peat plateau category includes only those which are relatively treeless. Any peat plateaus which possess stands of black spruce have been placed into one of the three black spruce categories, depending on density.

The sedge meadow cover type included in this soil moisture storage order is the driest of the three delineated, usually found on the outer periphery of the wetter types. It may receive a large input of moisture during spring snowmelt, or after a prolonged period of rain, but unless the center of the depressional area occupied by a water body or a saturated sedge meadow fills with water which encroaches upon this zone, it remains relatively dry with only enough moisture to support marginal growth of sedge. Typical vegetation species include sedges (Carex spp.), cottongrass (Eriophorum augustifolium) and other grasses.

10 cm. Storage

Included in this storage order are intermediate density stands of jack pine and birch/aspen as well as the sparsest category of black spruce, the intermediate category of sedge meadow and those areas characterized by peat hummocks surrounded by standing water.

The increased density of jack pine and birch/aspen stands indicates a better soil environment for growth. This may be due to either greater areal extent of soil or increased soil depth, or both. The result is more vegetation and a larger soil moisture retention capacity. Low strata vegetation species are basically the same as in the corresponding categories within ~~the 5~~ cm. storage order with several more inclusions: common juniper (Juniperus communis), creeping juniper (Juniperus horizontalis), shrubby cinquefoil (Potentilla fruticosa), northern gooseberry (Ribes oxyalanthoides), and Lapland rhodendron (Rhodendron lapponicum).

The least dense black spruce category incorporates sites in both upland and depressional areas. Sparse and intermediate stands of black spruce may be found in rock crevasses and small depressions within the bedrock, often mixing with jack pine and birch/aspen. In this situation the low strata vegetation will be the same as described for those species above.

The most favorable habitat for black spruce is the wet, low-lying depressions. As a tree species it has no rival in these preferred sites. Larch can often be found in similar conditions but usually the acidity of the peat is too strong for its tolerance level. If a stand of black spruce is sparse in these locations, the reason normally involves a water table which is too close to the surface for even these water-tolerant species. Lack of oxygen in the root zone, rather than too much water, is the limiting factor. A low water supply can also preclude extensive black spruce growth, but because of a poor level of competition with other species in these drier sites rather than a poor soil environment. Peat plateaus are often populated with black spruce, depending on the age of the plateau (Luff, 1978).

Low strata vegetation associated with black spruce sites on peat plateaus is the same as described in the peat plateau category. Black spruce found in wetter areas co-exists with Sphagnum spp. and sometimes with Cladonia spp.

The intermediate sedge meadow site is normally located between those of either extreme and represents a transition. However, it can also be found in upland depressions which receive and retain a nominal amount of runoff from higher rock areas. Vegetation associated with this category includes that described for the drier category plus Sphagnum spp. and some rushes (Juncus spp.).

The cover type designated as peat hummocks/standing water represents an intermediate situation between open water and organic terrain. In the field one can step from hummock to hummock and remain relatively dry, or from depression to depression and continually be in water. The placement of this cover type in the 10 cm. storage category indicates an averaging of the two extremes. The associated vegetation includes water-loving species such as cattail (Typha latifolia), rushes (Juncus spp.) and seaside arrowgrass (Triglochin maritima). Sphagnum spp. and grasses populate the peat hummocks.

15 cm. Storage

This storage order is represented by the wettest category of sedge meadow, [illegible], wet depressional areas of willow/alder/leatherleaf, intermediate black spruce and dense stands of jack pine and birch/aspen.

The wet sedge meadow site is usually found either on the margins of water bodies or in the center of depressions which collect and retain enough water for sedges and rushes to stand in for most of the growing season. In years with lower than average precipitation, however, these sedge meadows can dry considerably. In addition to the vegetation described for the other sedge meadow categories, the increased and sustained moisture content for these sedge meadows provides a favorable habitat for such species as dwarf birch (*Betula glandulosa*), water birch (*Betula occidentalis*), marsh cinquefoil (*Potentilla palustris*) and arum-leaved arrowhead (*Sagittaria cuneata*).

The open willow/alder/leatherleaf cover type is found in relatively flat depressions where the predominant vegetation is low and bushy. Sedges and rushes may be found in the understory, as may sphagnum moss. Because of their lowlying nature, and their surface morphology, these areas collect large amounts of snow in winter and release water slowly during the spring snowmelt. The water table is just below the surface so the vegetation behaves as phreatophytes except in the dryest of summers. In addition to the willow (*Salix spp.*), alder (*Alnus spp.*) and leatherleaf (*Chamaedaphne calycilata*) present, dwarf birch (*Betula glandulosa*), water birch (*Betula occidentalis*) and bayberry (*Myrica gale*) are typical species found in these areas.

Intermediate stands of black spruce are found on peat plateaus and on other depressional sites where the soil moisture content is not too pronounced. The vegetation is the same as indicated for the sparse black spruce in the 10 cm. storage category.

Dense stands of jack pine and birch/aspen are not prevalent in the Baker Creek Basin. They achieve their greatest extent in the sandy raised beach deposits near Yellowknife in the southern portion of the basin. The denser the stand the more soil occupance by roots ~~and~~, to some extent, the more soil moisture retained, thus accounting for the placement of this category in the 15 cm. storage order. The understory vegetation is the same as that described for lesser stands of the same species.

25 cm. Storage

Included in this category are cover types from depressional sites only. dense closed stands of willow/alder/ leatherleaf cover type are found on the margin of water bodies and stream courses, and in most cases the bases of the plants are covered by water in years of average to high precipitation. Evapotranspiration is high from these sites and the representative species tend to be much larger than in the open category described in the 15 cm. storage order.

The dense black spruce stands are most always found on peat plateaus. Because of the high permafrost table and the presence of saturated clay beneath the organic mat, the roots of the black spruce tend to spread outward, intertwining with each other, and thus form an efficient trap for liquid precipitation. Vegetation species associated with these areas are mainly mosses and lichens.

Lake Storage - P.E. and P.E. + ½D.

Both lake categories collect incident precipitation and runoff from surrounding upland areas. In addition they can act as temporary storage areas for water moving from the upper basin to the lower by means of an interconnecting muskeg and lake system. The reason for differentiating between cold, deep lakes (P.E.) and warm, shallow lakes (P.E. + ½D), involves the evaporation regime of each.

Warm, shallow lakes will experience a greater annual evaporation than will the deep, colder lakes. The warmer the temperature of the evaporating surface, the more evaporation that will occur, all other factors being equal. Solar radiation is able to penetrate to the bottom of many of the smaller lakes in the study area, and thus raise the average temperature of the entire water body more than in the deep lakes. With the average temperature higher, the surface layer can be heated even more, increasing the evaporation. Also, shallow lakes will become ice-free earlier in the spring, reducing the amount of moisture input by condensation of water vapor on the ice. This will permit earlier and greater heating during the period of maximum solar radiation and thus a greater evaporation.

For this reason the deep, cold water bodies were assigned a moisture storage value equal to the potential evapotranspiration of the 5 cm. storage class (average for the Baker Creek Basin), and the shallow, warm lakes were given a value equal to the P.E. plus half of the deficit, also from the 5 cm. storage category.

The shallow water bodies are easily discerned in the field and from aerial photos by the presence of extensive surficial plant growth and subsurface populations of zooplankton and phytoplankton, giving a cloudy appearance to the water.

This classification is preliminary and in need of a number of years of intensive testing beyond the scope and resources of the present study. As a first approach to, and basis for, mapping, however, it does provide a framework for testing anticipated yield patterns against streamflow and it is a contribution to a better understanding of regional water balance patterns and relationships.

CALCULATED RUNOFF FROM THE STUDY AREA

Given that the nine areas selected for intensive study are representative of the entire Baker Creek Basin, it was a relatively simple procedure to calculate the percentage of each storage category for all nine study sites and find the average. This average was then applied to the basin as a whole and the number of hectares of each storage category within the basin determined.

The water balance according to the Thornthwaite equation was calculated for each of the four years of the study. The water budget computations can be found in Tables 5-3 to 5-6. The following method was employed to complete these calculations. Temperature and precipitation data were gathered from the Monthly Record. The potential evapotranspiration figures for each month were calculated from Thornthwaite latitude conversion tables for solar radiation. The storage change for each month was computed by determining the difference between potential evapotranspiration and precipitation. Each storage category, except for lakes, was analyzed as to surplus or deficit for each month by determining the difference between amount of moisture storage needed to fill each category and the amount of storage change for that month. Any precipitation in or on the ground at the end of the previous year was carried over as surplus to the appropriate categories. Totals of surplus and deficit for the year in each category were calculated. The two lake categories were treated according to the proper formula, using the data from the 5.0 storage category (average for the basin).

From these balance sheets a single equation for each year can be determined (Table 5-7). This is a composite for the basin based upon Tables 5-3 to 5-6, times the respective areas involved.

If for each year the amount of moisture surplus, in centimeters, in each storage category is multiplied by the number of hectares in the basin covered by that storage category, and the resulting figure is divided by 100, the surplus in hectare/meters will be known. The total moisture surplus for the basin can then be found by adding the number of hectare/meters in storage categories 1.3 cm., 5 cm., 10 cm., 15 cm., and 25 cm., and subtracting that in the lake areas. The subtraction is necessary because these water bodies act as a runoff collecting area from the surrounding terrain and, in fact, subtract part of that runoff from the discharge of Baker Creek. In those years in which precipitation exceeds P.E. and/or P.E. + ½D, the lakes involved will have surpluses which may be added to basin totals. It should be stressed, however, that such surpluses are rare and occurred only in 1974-75 during the study period. Some of the lakes may have surpluses because of snow drifting in some years but this subject was covered by Kakela (1969).

The total surplus for each year can then be compared with the recorded discharge of Baker Creek for that year. The two figures should be approximately equal. In practice, however, they will rarely be equal due to the many possible sources of error in both the measurement of stream discharge and in calculation of the yearly surplus. These sources of error will be discussed later.

COMPARISON OF RESULTS WITH PREVIOUS BASIN RESEARCH

As noted above, both Kakela (1969) and Wight (1973) assumed a 2.54 cm. storage category in computing the water balance in the Baker Creek Basin. The values of the surplus component in their water balance equations can be compared to measured discharges from Baker Creek for the particular years of their respective studies as a rough check on the

Table 5-3: Water Balance Data for the Baker Creek Basin - 1973

	J	F	M	A	M	J	J	A	S	O	N	D	Year
Temperature °C	-25.3	-26.2	-17.0	-5.5	11.1	15.6	18.4	14.2	8.8	0.8	-15.3	-24.9	
P.E. (cm.)	0	0	0	0	8.1	11.4	13.6	9.5	4.9	0.7	0	0	48.2
PPT (cm.)	1.1	0.8	2.1	0.9	1.0	1.4	2.5	12.7	1.6	4.5	2.7	1.6	32.9
Storage Change (cm.)	1.1	0.8	2.1	0.9	-7.1	-10.0	-11.1	3.2	-3.3	3.8	2.7	1.6	
1.3 cm. Storage (1.3)	1.3	1.3	1.3	1.3	0	0	0	1.3	0	1.3	1.3	1.3	
Surplus (6.8 from 1972)	1.1	0.8	2.1	0.9	0	0	0	1.9	0	2.5	2.7	1.6	16.1
Deficit	0	0	0	0	5.8	10.0	11.1	0	2.0	0	0	0	28.9
5.0 cm. Storage (5.0)	5.0	5.0	5.0	5.0	0	0	0	3.2	0	3.8	5.0	5.0	
Surplus (3.8 from 1972)	1.1	0.8	2.1	0.9	0	0	0	0	0	0	1.5	1.6	8.7
Deficit	0	0	0	0	2.1	10.0	1.1	0	0.1	0	0	0	23.3
10.0 cm. Storage (8.8)	9.9	10.0	10.0	10.0	2.9	0	0	3.2	0	3.8	6.5	8.1	
Surplus	0	0.7	2.1	0.9	0	0	0	0	0	0	0	0	3.7
Deficit	0	0	0	0	0	7.1	11.1	0	0.1	0	0	0	18.3
15.0 cm. Storage (8.8)	9.9	10.7	12.8	13.7	6.6	0	0	3.2	0	3.8	6.5	8.1	
Surplus	0	0	0	0	0	0	0	0	0	0	0	0	0
Deficit	0	0	0	0	0	3.4	11.1	0	0.1	0	0	0	14.5
25.0 cm. Storage (8.8)	9.9	10.7	12.8	13.7	6.6	0	0	3.2	0	3.8	6.5	8.1	
Surplus	0	0	0	0	0	0	0	0	0	0	0	0	0
Deficit	0	0	0	0	0	3.4	11.1	0	0.1	0	0	0	14.5

* Circled numbers indicate surplus during freezing months to be carried over to next year

** P.E. (Deep Cold Lakes) - PPT. = P.E. - (S.C. + D - S)

32.9 = 48.2 - (0.7 + 23.3 - 8.7)

32.9 = 32.9

** P.E. + ½D (Shallow Warm Lakes) - PPT. = P.E. + ½D + S - (S.C. + D + ½D)

32.9 = 48.2 + 11.7 + 8.7 - (0.7 + 23.3 + 11.7)

32.9 = 32.9

** Data from 5.0 cm Storage (average for basin)

Table 5-4: Water Balance Data for the Baker Creek Basin - 1974

	J	F	M	A	M	J	J	A	S	O	N	D	Year
Temperature °C	-30.4	-27.4	-23.2	-6.4	4.3	14.0	16.0	12.3	-4.3	-6.2	-11.5	-20.8	
P.E. (cm.)	0	0	0	0	4.1	10.4	11.5	8.6	3.2	0	0	0	37.8
PPT. (cm.)	1.6	0.8	1.3	0.4	2.9	3.5	7.5	5.9	4.8	4.5	2.6	4.6	40.4
Storage Change (cm.)	1.6	0.8	1.3	0.4	-1.2	-6.9	-4.0	-2.7	1.6	4.5	2.6	4.6	
1.3 cm. Storage (1.3)	1.3	1.3	1.3	1.3	0.1	0	0	0	1.3	1.3	1.3	1.3	
Surplus (4.3 from 1973)	1.6	0.8	1.3	0.4	0	0	0	0	0.3	* 4.5	2.6	4.6	8.7
Deficit	0	0	0	0	0	6.8	4.0	2.7	0	0	0	0	13.5
5.0 cm. Storage (5.0)	5.0	5.0	5.0	5.0	3.8	0	0	0	1.6	5.0	5.0	5.0	
Surplus (3.1 from 1973)	1.6	0.8	1.3	0.4	0	0	0	0	0	1.1	2.6	4.6	7.2
Deficit	0	0	0	0	0	3.1	4.0	2.7	0	0	0	0	9.8
10.0 cm. Storage (8.1)	9.7	10.0	10.0	10.0	8.8	1.9	0	0	1.6	6.1	8.7	10.0	
Surplus	0	0.5	1.3	0.4	0	0	0	0	0	0	0	3.3	2.2
Deficit	0	0	0	0	0	0	2.1	2.7	0	0	0	0	4.8
15.0 cm. Storage (8.1)	9.7	10.5	11.8	12.2	11.1	4.1	0.1	0	1.6	6.1	8.7	13.3	
Surplus	0	0	0	0	0	0	0	0	0	0	0	0	0
Deficit	0	0	0	0	0	0	0	2.6	0	0	0	0	2.6
25.0 cm. Storage (8.1)	9.7	10.5	11.8	12.2	11.0	4.1	0.1	0	1.6	6.1	8.7	13.3	
Surplus	0	0	0	0	0	0	0	0	0	0	0	0	0
Deficit	0	0	0	0	0	0	0	2.6	0	0	0	0	2.6

* Circled numbers indicate surplus during freezing months to be carried over to next year.

** P.E. (Deep Cold Lakes) - PPT. = P.E. - (S.C. + D - S)
40.4 = 37.8 + 5.2 - 9.8 + 7.2
40.4 = 40.4

** P.E. + ½D (Shallow Warm Lakes) - PPT. = P.E. + ½D + S - (S.C. + D + ½D)
40.4 = 37.8 + 4.9 + 7.2 + 5.2 - (9.8 + 4.9)
40.4 = 40.4

** Data from 5.0 cm. Storage (average for basin)

Table 5-5: <u>Water Balance Data for the Baker Creek Basin - 1975</u>

	J	F	M	A	M	J	J	A	S	O	N	D	Year
Temperature °C	-33.4	-24.9	-20.4	-2.5	6.7	15.9	18.3	14.2	8.3	-2.4	-17.3	-25.8	
P.E. (cm.)	0	0	0	0	5.1	11.4	13.6	9.5	4.9	0	0	0	44.5
PPT. (cm.)	1.1	0.8	0.7	1.0	1.3	0.2	1.0	8.5	2.4	3.9	1.4	1.8	24.1
Storage Change (cm.)	1.1	0.8	0.7	1.0	-3.8	-11.2	-12.6	-1.0	-2.5	3.9	1.4	1.8	
<u>1.3 cm. Storage</u> (1.3)	1.3	1.3	1.3	1.3	0	0	0	0	0	1.3	1.3	1.3	
Surplus (11.7 from 1974)	1.1	0.8	0.7	1.0	0	0	0	0	0	*2.6	1.4	1.8	15.3
Deficit	0	0	0	0	2.5	11.2	12.6	1.0	2.5	0	0	0	29.8
<u>5.0 cm. Storage</u> (5.0)	5.0	5.0	5.0	5.0	1.2	0	0	0	0	3.9	5.0	5.0	
Surplus (8.3 from 1974)	1.1	0.8	0.7	1.0	0	0	0	0	0	0	0.3	1.8	11.9
Deficit	0	0	0	0	0	10.0	12.6	1.0	2.5	0	0	0	26.1
<u>10.0 cm. Storage</u> (10.0)	10.0	10.0	10.0	10.0	6.2	0	0	0	0	3.9	5.3	7.1	
Surplus (3.3 from 1974)	1.1	0.8	0.7	1.0	0	0	0	0	0	0	0	0	6.9
Deficit	0	0	0	0	0	5.0	12.6	1.0	2.5	0	0	0	21.1
<u>15.0 cm. Storage</u> (13.3)	14.4	15.0	15.0	15.0	11.2	0	0	0	0	3.9	5.3	7.1	
Surplus	0	0.2	0.7	1.0	0	0	0	0	0	0	0	0	1.9
Deficit	0	0	0	0	0	0	12.6	1.0	2.5	0	0	0	16.1
<u>25.0 cm. Storage</u> (13.3)	14.4	15.2	15.9	16.9	13.1	1.9	0	0	0	3.9	5.3	7.1	
Surplus	0	0	0	0	0	0	0	0	0	0	0	0	0
Deficit	0	0	0	0	0	0	10.7	1.0	2.5	0	0	0	14.2

* Circled numbers indicate surplus during freezing months to be carried over to next year

** P.E. (Deep Cold Lakes) - PPT. = P.E. - (S.C. + D - S)

24.1 = 44.5 - 6.2 - 26.1 + 11.9

24.1 = 24.1

** P.E. + ½D (Shallow Warm Lakes) - PPT = P.E. + ½D + S - (S.C. + D + ½D)

24.1 = 44.5 + 13.1 + 11.9 - 6.2 - 26.1 - 13.1

24.1 = 24.1

** Data from 5.0 cm. Storage (average for basin)

Table 5-6: Water Balance Data for the Baker Creek Basin - 1976

	J	F	M	A	M	J	J	A	S	O	N	D	Year
Temperature °C	-28.7	-25.6	-20.6	1.2	8.7	12.7	17.1	15.6	9.5	-0.7	-9.5	-25.8	
P.E. (cm.)	0	0	0	0.9	6.0	9.3	12.5	10.5	5.7	0	0	0	44.9
PPT. (cm.)	1.9	1.7	1.4	0.9	1.7	3.9	2.5	3.8	4.5	1.2	1.3	1.2	26.0
Storage Change (cm.)	1.9	1.7	1.4	0	-4.3	-5.4	-10.0	-6.7	-1.2	1.2	1.3	1.2	
<u>1.3 cm. Storage</u> (1.3)	1.3	1.3	1.3	1.3	0	0	0	0	0	1.2	1.3	1.3	
Surplus (5.8 from 1975)	1.9	1.7	1.4	0	0	0	0	0	0	0	*1.2	1.2	10.8
Deficit	0	0	0	0	3.0	5.4	10.0	6.7	1.2	0	0	0	26.3
<u>5.0 cm. Storage</u> (5.0)	5.0	5.0	5.0	5.0	0.7	0	0	0	0	1.2	2.5	3.7	
Surplus (2.1 from 1975)	1.9	1.7	1.4	0	0	0	0	0	0	0	0	0	7.1
Deficit	0	0	0	0	0	4.7	10.0	6.7	1.2	0	0	0	22.6
<u>10.0 cm. Storage</u> (7.1)	9.0	10.0	10.0	10.0	5.7	0.3	0	0	0	1.2	2.5	3.7	
Surplus	0	0.7	1.4	0	0	0	0	0	0	0	0	0	2.1
Deficit	0	0	0	0	0	0	9.7	6.7	1.2	0	0	0	17.6
<u>15.0 cm. Storage</u> (7.1)	9.0	10.7	12.1	12.1	7.8	2.4	0	0	0	1.2	2.5	3.7	
Surplus	0	0	0	0	0	0	0	0	0	0	0	0	0
Deficit	0	0	0	0	0	0	7.6	6.7	1.2	0	0	0	15.5
<u>25.0 cm. Storage</u> (7.1)	9.0	10.7	12.1	12.1	7.8	2.4	0	0	0	1.2	2.5	3.7	
Surplus	0	0	0	0	0	0	0	0	0	0	0	0	0
Deficit	0	0	0	0	0	0	7.6	6.7	1.2	0	0	0	15.5

* Circled numbers indicate surplus during freezing months to be carried over to next year

** P.E. (Deep Cold Lakes) - PPT. = P.E. - (S.C. + D - S)
26.0 = 44.9 - 3.4 - 22.6 + 7.1
26.0 = 26.0

** P.E. + ½D (Shallow Warm Lakes) - PPT. = P.E. + ½D + S - (S.C. + D + ½D)
26.0 = 44.9 + 11.3 + 7.1 - 3.4 - 22.6 - 11.3
26.0 = 26.-

** Data from 5.0 cm. Storage (average for basin)

Table 5-7: Water Balance Calculations for the Baker Creek Basin 1973-1976

Year	(cm.) Precipitation	=	(cm.) (P. E.	-	(cm) D)	+	(cm.) S	±	(cm.) S. C.
1973	32.9	=	(48.2	-	20.7)	+	6.2	-	0.8
1974	40.4	=	(37.8	-	7.4)	+	4.8	+	5.3
1975	24.1	=	(44.5	-	23.3)	+	9.2	-	6.3
1976	26.0	=	(44.9	-	20.1)	+	4.7	-	3.4

Table 5-8: Comparison of Calculated Yearly Surplus with Measured Runoff from the Baker Creek Basin

		hectares/meters
1971	Wight's Equation	1048.18
	Present Calculation	315.09
	Recorded Streamflow of Baker Creek	181.30
1972	Wight's Equation	1425.24
	Present Calculation	529.85
	Recorded Streamflow of Baker Creek	283.22
1973	Present Calculation	593.50
	Recorded Streamflow of Baker Creek	374.14
1974	Present Calculation	453.83
	Recorded Streamflow of Baker Creek	997.81
1975	Present Calculation	913.75
	Recorded Streamflow of Baker Creek	1083.14
1976	Present Calculation	444.62
	Recorded Streamflow of Baker Creek	570.57
6 Year Total (1971-1976)		
	Recorded Streamflow of Baker Creek	3490.18
	Present Calculation	3250.64
	Difference	239.54

accuracy of either their calculations or their choice of average moisture storages for the basin. Table 5-7 includes both the four years of the present study and the two previous years of Wight's study. This table demonstrates the only practical check on the value of this thesis as a more accurate method of calculating water surplus in the Thornthwaite water balance equation.

For the two survey years of Wight's (1973) study, 1971 and 1972, the present author determined the water balance of Baker Creek Basin according to the variability of storage categories within the basin u[illegible] for this thesis. In comparison with Wight's values thes[illegible]ew calculations are shown to be considerably closer to the measured stream discharge of Baker Creek for those particular years. Of the four years used in the present study, the 1975 and 1976 figures of calculated surplus are remarkably close to the Baker Creek discharges for these years, while the 1973 and 1974 computed surplus values are noticeably different. The differences in correlation can have several explanations. The fact that of the six years for which water balances were calculated, half of the surpluses were above the measured discharge for Baker Creek and half were below makes difficult the isolation of an error common to all. In fact, the probable explanation is that a combination of errors contributed to the differences.

When the six-year total of calculated surpluses is compared with the six-year total of measured discharges from

Baker Creek, however, the two figures are remarkably close (Fig. 5-7). The difference represents only a six percent error. It is believed that a longer study period, perhaps ten to twenty years, would provide an even closer correlation.

POSSIBLE SOURCES OF ERROR

As mentioned previously, the measurement of stream discharge from Baker Creek has been suspect in some years due to icing conditions in the winter and spring. A portion of the discharge may never have been registered on the gauge because it was diverted around an ice blockage. If this represented a sizeable amount of flow the lack of a close relationship between measured discharge and calculated surplus in some years might notreflect error in computation of the latter.

The precipitation data collected at the Yellowknife Airport may contain an element of error due to the mechanics of catching the rain or snow. Also, a more realistic value for the Baker Creek basin might have been obtained if precipitation and temperature data from Yellowknife Hydro, located northeast of the study area, had been averaged with the Yellowknife Airport material. This was not done due to the rather sketchy information available from this station for some years.

Another source of error might be that the nine smaller areas within the basin were not as representative of the entire study area as it was thought. This is a difficult relationship to establish without intensive interpretation of patterns for the whole of the basin. There are very few clear-cut divisions between surficial cover types on the land surface. One type grades into the next and vegetation associated with one type can often be found growing in another. Interpretation and division of surficial cover categories, and subsequently moisture storage groups, in this portion of the Shield is at best frustrating and often requires compromises to be made. It is believed, however, that the nine areas chosen as being representative were very close to being so.

The problem with the 1.3 cm. storage category has been mentioned above. It is probable that this particular category is more widespread within the study area than was found in this study (Laycock, personal communication). The fact that the smooth bare rock areas which represent that storage category rarely occur in areas big enough to map separately on the air photos, results in their being included within other surrounding categories as indicated earlier in this chapter. This would affect the total calculated surplus.

The error might lie in the Thornthwaite equations for P.E. and water balance themselves. They were not designed for use in the subarctic areas of the world above 50°N. latitude. As presented in Chapter Three, there is evidence to suggest that the 50°N. correction factor for daylight and season is not adequate for northern areas. The presence of nonvascular plants associated with large areas of organic terrain within the subarctic may alter the P.E. calculation.

Evaporation from these areas is low due to the non-transpiring nature of lichens and mosses and their excellent insulation properties which tend to keep the subsurface cool. On rock areas these plants can effectively trap potential runoff and the response with each shower is striking.

Despite these many possible error sources, the results of the present study indicate that division of the Baker Creek Basin into water storage categories and calculation of the water balance according to these categories provides a much closer correlation between measured yearly runoff and computed surplus than can be obtained using single storage values. Although there is room for improvement in the technique and parameter measurements, the process is believed to have been successful, and we now have a better basis for undertaking additional studies and making additional refinements in our procedures.

CHAPTER SIX

SUMMARY, CONCLUSIONS, AND SUGGESTIONS FOR FURTHER RESEARCH

SUMMARY

The Baker Creek basin, a small subarctic watershed on the Canadian Shield just north of Yellowknife, N.W.T., was chosen for a study of soil moisture storage - vegetative cover relationships in an attempt to more closely define the surplus component and other water balance parameters of the Thornthwaite water balance equation. Field work, consisting of the implementation of a series of transects within the basin, was carried out during the summer of 1973. Data were collected on the vegetation, soil, depth to the permafrost table, geomorphology and surficial geology.

Nine smaller areas of approximately 3900 square meters each were chosen as being representative of the basin. They included areas of different bedrock types and varying percentages of muskeg, lakes and predominantly bare rock surfaces. These nine areas were delineated on air photographs at a scale of 1:12,000. From observation and mapping in the field, patterns of vegetation and soil and site relationships were established and these were interpreted on the air photos as surface cover categories. Each of these cover types was assigned a soil moisture storage value and the nine intensive study areas were mapped according to moisture storage categories.

An attempt was made to identify the cover types on successively smaller-scale images. Air photos of the Baker Creek Basin at a scale of 1:31,680 were found to provide adequate detail for interpretation of the broader patterns, although differentiation of some vegetation species was difficult. For a surficial cover interpretation on air photos at this scale some of the categories used on the 1:12,000 scale photos would have to be combined. The LANDSAT image proved to be of very limited use for this type of study. Its scale of 1:1,000,000 was too small for cover differentiation to be made. Even when expanded to a scale of 1:250,000 it appears to be of marginal value. However, with density slicing and other interpretative techniques more might be accomplished with LANDSAT data, but only after key work has been done in a number of representative areas.

Percentages of each storage type in all nine of the study areas were calculated and averaged, and these means were applied to the Baker Creek Basin as a whole. The water balances for the basin, according to the Thornthwaite method, were calculated for the years 1973-1976. These data in conjunction with the computed basin storage values were then used to calculate the water balance equations for the respective years. The surplus components in the equations were compared to measured runoff of Baker Creek as a rough check on the viability of using representative soil moisture storage categories to compute surplus. The results were mixed. For the first two years in the study the correlation was not great. This could be due to one or more of a number of possible sources of error, some of which were not associated with the work of the present study. The last two years, 1975 and 1976, proved to be periods when computed surplus and measured streamflow were very similar in value. The reasons for these differences in results are not fully understood.

Water balances for the two previous years, 1971 and 1972, were calculated using the basin averages implemented in this study. As this was the time period of a previous study in the Baker Creek Basin (Wight, 1972), it proved an opportunity to compare the estimated basin soil moisture storage values used in that study with the calculated values found in the present work. In this comparison, the calculated values came considerably closer to measured stream flow from Baker Creek during the same years than did the previously estimated figures. It is anticipated that in most years the calculated values would be better but more field observations of storage values and relationships are needed.

CONCLUSIONS

In the field the Curtis Transect Method was employed because it was thought to be the one most suited for this type of study. The Braun-Blanquet Table Method, although perhaps more exacting in its vegetation collection and analysis techniques, seemed to be too subjective in the actual location of plots along a given transect. For this reason it was not used. In practice, however, it was found that subjectivity in locating representative sample areas on the transects was very desirable. The purpose of using transects was to identify specific vegetational areas for reference later during interpretation of the air photos. Quite often the sample vegetation noted as a specific stop along the transect was noticeably non-representative of the surrounding area which would be observable on the air photos. The needs of a particular study should be the deciding factor when choosing a vegetation sampling methodology.

The surficial cover categories chosenfor interpretation of the study area might need some revision. The Baker Creek Basin is a difficult area in which to consistently identify vegetation/site patterns on aerial photographs. Site characteristics and species distribution are generally considered to be highly correlated in most areas. However, in the basin, for example, jack pine can be found growing on organic terrain and black spruce on the upland bare rock sites. In many cases there are wet and dry areas, organic and bare rock sites, heavily and sparsely vegetated regions all within a very small area. When interpreted and mapped on an air photo, these areas cannot be adequately differentiated and must be placed in a single category. It has already been noted that smooth bare bedrock areas occur frequently throughout the basin, but normally only in sites too small to map on the photos. Thus they are placed in adjacent categories and don't widely register on the photo map of surficial cover types. Several changes in cover type categories could be made to facilitate a more accurate representation of the actual situation.

The Baker Creek Basin extends from approximately 2 to 28 kilometers north of Yellowknife and the airport weather station from which data on temperature and precipitation was taken. The proximity of Great Slave Lake to adjacent land areas, including the Yellowknife airport, has an influence on their local weather conditions. Use of this weather station exclusively as being representative of the entire study area is probably misleading and contributes to the problem of acquiring a realistic water balance. Precipitation and temperature data from the Yellowknife Hydro station, located northeast of the basin, incomplete as it is, should be averaged whenever possible with the airport information. Data from instrument stations within the basin have been used in some related studies, however, and the variations in precipitation and temperature data have been found to be slight.

Interpretation of surficial cover for the basin was found to be a relatively easy and accurate procedure using air photos at a scale of 1:12,000. Of the standard photo scales available for much of Canada, those of 1:15,840 and 1:31,680 would be the most favorable for this type of interpretation. The latter scale was examined in this study as part of a multistage sampling procedure. It was found to be sufficient for differentiation of most categories although without previous definition on the larger-scale photos the task would have been more difficult. A 1:1,000,000 scale LANDSAT image was examined manually in the hope that identification of even gross patterns of surficial cover within the study area might be accomplished. Unfortunately it was found to be of too small a scale to be of much use for this study. Perhaps, in the near future, interpretation techniques will be developed to allow LANDSAT images to be of use in studies such as this one.

The black and white infrared photographs, at a scale of 1:12,000, proved to be excellent as a backup for the panchromatic photographs. Separation of similar-appearing species on the pan photographs, such as jack pine and birch/aspen, was an easy procedure on the near IR prints. This was due to the differences in IR wavelength reflectively between pine needles and deciduous leaves. Near IR photographs should not be used exclusively, however, as certain features such as relief differentiation are not easily discerable.

The most important conclusion made in the present study is that the thesis originally put forward was a moderate success. Interpretation of the Baker Creek Basin as to surficial cover types and subsequent division into soil moisture storage categories and averaging for the basin as a whole provided a much closer correlation between calculated surplus and recorded streamflow measurements of Baker Creek than did mere estimation employing a single storage category for the basin (see Figure 5-8). The procedure can be improved and the basin can be mapped in more detail in order to increase the accuracy of the application, but the technique itself has been proven to be worthwhile.

Any attempt to calculate the water balance of an area, especially in the subarctic, employing the Thornthwaite water balance equation should include this method. Results obtained from this study indicate that a more realistic moisture storage value for the entire drainage basin can be achieved in thismanner. The more accurate the moisture storage parameter is, the closer the water balance equation for the basin will be to a true balance.

SUGGESTIONS FOR FURTHER RESEARCH

Future researchers in the Baker Creek Basin concerned with the clarification of the Thornthwaite water balance equation should be aware of problems encountered in this study. There are so many possible sources of error in measurements and calculations that only by continued research will a degree of accuracy be reached sufficient to make the application of the Thornthwaite equation or any other water balance study approach an unqualified success.

The exact boundary of the Baker Creek Basin may need redefinition. It is extremely difficult to perfectly delineate the watershed divide in an area such as this. The relief is not great and the presence of large tracts of muskeg, characterized by slow seepage of water from one lake to another, make demarcation of the divide uncertain in some areas.

A study should be made to determine a more representative climate of the basin. Small automatic recording devices could be installed at various points within the study area and checked at regular intervals. The basin is not so large as to make monthly visits unreasonable. The effects of Great Slave Lake on local weather conditions and their areal extent away from the lake could be documented in this way. Advection within the basin is only speculation at this time. It is thought that Great Slave Lake acts as a cold air sink during the summer months and cool winds blowing out onto the heated land surface could markedly affect the evapotranspiration of a portion of the Baker Creek Basin. Also, the possible effects of mineral processing plants and previous timber extraction for lumber and fuel in close proximity to, and partially within, the Baker Creek Basin should be explored.

More detailed and widespread evapotranspiration studies than those carried out by Wight in 1972, should be implemented, especially in the moss and lichen areas. A major problem in estimation of P.E. values within the basin could be due to over-estimation in these areas. The fate of water slowly percolating through the muskegs between lakes deep within the basin should be examined. How quickly does it move, how much is evaporated in transit and how much is incorporated as permanent storage are only some of the questions which need to be answered.

A lake study within the basin would be most valuable. Lake temperatures should be monitored to examine the relationship between the several lake categories and their evaporation regimes. Also the role of lakes as collecting areas for the runoff from surrounding regions should be studied more closely (see Kakela, 1969).

Research in soil moisture would be extremely valuable in eliminating some of the guesswork in assigning storage values to different surficial cover types. The values used in the present study were educated guesses based on other studies but were estimates never-the-less. The monitoring of soil water depth and change over time during a period of several years would be useful.

The study area is in an area of discontinuous permafrost. Literature on permafrost occurrence in such areas is extensive. Still, the permafrost relationships with surficial cover types should be examined in more detail than was done in this thesis. Presence of permafrost in areas other than those discovered would have an important effect in reducing the evapotranspiration from those areas.

A closer monitoring of the streamflow gauge on Baker Creek, especially in the winter when icing is a distinct possibility, would contribute to the clarification of a most important aspect in the water balance equation. Perhaps several gauges could be used and an average taken to better record the streamflow.

A large contribution to the use of the Thornthwaite equation would be more research into latitude and seasonal daylight conversion factors which extend above 50°N. This would increase the applicability of the Thornthwaite equation immensely and help to elucidate one of the biggest components of the equation. Also more information is needed concerning the proportion of solar radiation in this region that is expended in melting snow and ice and raising soil temperatures in the spring.

Finally, the entire Baker Creek Basin should be mapped in detail as to surficial cover and soil moisture storage. This study provides a framework within which further research can more accurately determine the water surplus factor for the basin. When this is done a major step will have been taken to clarify the Thornthwaite water balance equation for subarctic regions in general and the Baker Creek Basin in particular.

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APPENDIX A

FORMULAS

APPENDIX A

Dalton's Law

$E=C\ (ew - ea)$

C = coefficient depending on various uncounted factors affecting evaporation

ew = mean vapor pressure at water surface temperature in inches of Hg

ea = mean vapor pressure of saturated air at temperature of dew point in inches of Hg

(from Chow, 1964, p. 11-2)

Meyer's Evaporation Equation

$E=C\ (ew - ea)\chi \qquad \chi = 1 + 0.1w$

C = 15 (inches) for small shallow water

C = 11 (inches) for large deep water

ew = maximum vapor pressure, in Hg, for monthly mean air temperature at nearby stations for small bodies of shallow water, or water temperature for large bodies of deep water

ea = actual vapor pressure of air based on monthly mean air temperature and RH at nearby stations for small bodies of shallow water or based on information about 30 feet above water surface for large bodies of deep water

w = monthly mean wind velocity, in mph, at about 30 feet above ground

(from Chow, 1964, p. 11-2)

APPENDIX B

SAMPLE VEGETATION SURVEY SHEET

APPENDIX C

TAXONOMY OF VEGETATION ALONG TRANSECTS IN THE STUDY AREA

APPENDIX C.

TAXONOMY OF VEGETATION ENCOUNTERED ON TRANSECTS

Alnus crispa	(Mountain alder)
Alnus rugosa	(Speckled alder)
Betula glandulosa	(Dwarf birch)
Betula occidentalis	(Water birch)
Betula papyrifera	(White birch)
Juniperus communis	(Common juniper)
Juniperus horizontalis	(Creeping juniper)
Larix laricina	(Larch)
Picea glauca	(White spruce)
Picea mariana	(Black spruce)
Pinus banksiana	(Jack pine)
Populus tremuloides	(Aspen)
Salix spp.	(Willow)
Andromeda polifolia	(Bog rosemary)
Arctostaphylos rubra	(Arctic bearberry)
Arctostaphylos uva-ursi	(Bearberry)
Carex spp.	(Sedges)
Chamaedaphne calyculata	(Leatherleaf)
Cladonia rangifera	(Lichen)
Cornus stolonifera	(Red-osier dogwood)
Cryptogramma crispa var. acrostichoides	(Parsley fern)
Drypoteris fragrans	(Fragrant fern)
Empetrum nigrum	(Crowberry)
Epilobium augustifolium	(Fireweed)

Epilobium latifolium	(Broadleaved fireweed)
Equisteum arvense	(Common horsetail)
Equisetum scirpoides	(Dwarf scouring-rush)
Equisetum silvaticum	(Woodland horsetail)
Erigeron acris subsp. politus	
Eriophorum augustifolium	(Cotton-Grass)
Fragaria glauca	(Wild Stawberry)
Geocaulon lividum	(Northern comandra)
Hordeum jabatum	(Foxtail barley)
Juncan spp.	(Rush)
Ledum groenlandicum	(Labrador tea)
Linnaea borealis americana	(Twinflower)
Menyanthes trifoliata	(Buckbean)
Myrica gale	(Bayberry)
Parnassia palustris	(Grass-of-parnassus)
Potentilla fruiticosa	(Shrubby cinquefoil)
Potentilla palustris	(March cinquefoil)
Pyrola asarifolia	(Pink wintergreen)
Rhododendron lapponicum	(Lapland rhododendron)
Rubus chamaemorus	(Coudberry)
Rubus pubescens	(Dewberry)
Rosa acicularis	(Prickly rose)
Ribes hudsonianum	(Northern black currant)
Ribes oxyalanthoides	(Northern gooseberry)
Sagittaria cuneata	(Arum-leaved arrowhead)
Saxifragia bronchialis	(Common saxifrage)

Scheuchzeria palustrus subsp. americna	(Fern)
Solidago decumbens	(Mountain goldenrod)
Sphagnum spp.	(Moss)
Triglochin maritima	(Seaside arrow-grass)
Typha latifolia	(Cattaic)
Utricularia cornuta	(Horn-bladderwort)
Vaccinium vitis-idea var. minus	(Bog cranberry)
Viburnum edule	(Low bush-cranberry)

Arctostaphylos rubra																	
Arctostaphylos uva-ursi					X								X			X	
Betula glandulosa									X								
Carex spp.																	
Chamaedaphne calyculata									X	X							
Cornus stolonifera																	
Cryptogramma crispa var. acrostichoides																	
Dryopteris fragrans																	
Empetrum nigrum																	
Epilobium augustifolium			X	X	X		X	X			X			X	X		
Epilobium latifolium																	
Equisetum arvense																	
Equisetum scirpoides																	
Equisetum silvaticum																	X
Erigeron acris subsp. politus								X									
Eriophorum augustifolium																	
Fragaria glauca																	
Geocaulon lividum			X	X	X								X				
Grasses		X	X		X						X			X			
Hordeum jubatum																	
Juncus spp.																	
Juniperus communis																	
Juniperus horizontalis																	
Ledum groenlandicum		X	X	X				X		X	X	X	X				X
Lichen (yellow-green)	X		X	X	X									X	X	X	
Lichen (black)	X		X	X	X									X	X	X	
Lichen (grey)	X		X	X	X									X	X	X	
Lichen (cladonia)	X	X	X	X	X	X								X	X	X	
Linnaea borealis americana												X					
Menyanthes trifoliata																	
Moss	X	X	X	X	X	X	X			X		X		X		X	X
Myrica gale								X									
Parnassia palustris																	
Potentilla fruiticosa								X	X								
Potentilla palustre																	
Pyrola asarifolia											X						
Rhododendron lapponicum																	