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THE UNIVERSITY OF ALBERTA

THE MAPPING OF SNOW PATTERNS ON THE COOKING LAKE MORAINE WITH LANDSAT I IMAGERY

by

© SCOTT GEORGE WITTER

A THESIS

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

DEPARTMENT OF GEOGRAPHY

EDMONTON, ALBERTA

FALL 1976

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 ..The Mapping of Snow Patterns on the Cooking Lake Moraine With LANDSAT I Imagery..........

submitted by ..Scott George Witter..........

in partial fulfilment of the requirements for the degree of

Master of ..Science..........

Arleigh H. Laycock
Supervisor

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....

Date Oct 6, 1976...

ABSTRACT

Improvement of water supply and water quality in the Cooking Lake Moraine near Edmonton is the key to more intensive recreational use and other uses of the area. One of the ways of improving both might be found in better snow management. To accomplish this an improved method for estimating regional and local patterns of snowfall is needed so that snowmelt runoff can be estimated.

There are three main parts in the study. The first is a review of the landform, vegetative cover, meteorological data, and other factors that might affect snowfall and snow drifting patterns. The second involves the use of LANDSAT I imagery and ground truthing in various ways to map snowfall and snow drifting patterns on the moraine.[1] The third part contains an analysis of these patterns using Thornthwaite techniques in determining local and regional water balance patterns.

Snow depth and density studies were conducted at 12 sites with a Mt. Rose snow sampler. These sites were identified on photographic plates.

Based on the information obtained from the snow surveys, Thornthwaite water balance calculations, and LANDSAT I imagery it was possible to estimate runoff potential. Calculations of potential snowmelt runoff were made for several areas on the moraine.

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[1] LANDSAT I imagery was discussed under five subheadings: Scale 1:1,000,000 LANDSAT I Imagery, Scale 1:250,000 LANDSAT I Imagery, Density Sliced LANDSAT I Imagery, Tri-Color Projected LANDSAT I Imagery and Water Balance Relationships and LANDSAT I Imagery.

The procedures employed in this thesis, with the modifications suggested, should be useful in future investigations of snow distribution patterns. With more in-depth information about these patterns it may be possible to manage snowmelt runoff for both water supply and water quality in the moraine and in other areas with similar problems and opportunities.

ACKNOWLEDGEMENTS

The author wishes to express his gratitude to Dr. Arleigh Laycock, his major professor, for his valuable guidance and support throughout this study. His sense of professionalism and personal integrity are deeply admired. The comments of Dr. Steve Pawluk, Department of Soil Science, and Dr. Keith Hage, of Meteorology, both members of the thesis committee, are sincerely appreciated.

The cooperation of the Alberta Remote Sensing Centre and the Federal Forestry Laboratory in making vital equipment for this study available is appreciated. My thanks are expressed to these organizations and to Cal Bricker, Ken Simpson and Cam Kirby who helped to make my use of this equipment more effective.

There are also several individuals who although not directly involved with the study did influence the author greatly. Appreciation is extended to Dr. Ronald Weinkauf, Faculty of Geography, South Dakota State University, for pressing the author toward professional development and to Victor Myers, Director of the Remote Sensing Institute, Brookings, South Dakota, for helping the author to develop valuable skills. Dr. Larry Anderson is remembered for his contribution to the learning experience in Edmonton both as a friend and as an instructor.

In addition, a special acknowledgement is extended to Michael Hallock for his time, deeply appreciated assistance and friendship during this study. Finally, appreciation is expressed to Brenda Witter for her help and enthusiasm which allowed the author to overcome all obstacles.

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Chapter I

INTRODUCTION

> One of the most dynamic geophysical features of Planet Earth is the ever-changing snow-cover. No other widespread soil material on the earth's surface is deposited--and is removed--so quickly (Meier, 1973, p. 1).

The purpose of this study was to develop a more accurate means of estimating regional patterns of snowmelt runoff using remote sensing techniques. The area selected for study was the Cooking Lake Moraine twenty-five miles east and south-east of Edmonton (Plate 1). The area is a hummocky dead-ice moraine with widespread sloughs, minor depressions and deep forest soils.

There are major water quantity and quality problems relative to recreational facility development and to other uses of the Cooking Lake Moraine. Restoration of the lakes on the moraine to levels and qualities experienced in a relatively wet period early in this century is a widely supported objective. A pipeline from the North Saskatchewan River (near Devon) to Miquelon Lakes and a cascading system to other lakes was one of the proposed solutions to the water quantity problems (EPEC, 1970). Pipelines could be built and maintained at a substantial cost to the public. A less expensive alternative might be found in better management of regional snowmelt runoff each spring and in use of regional or nearby surpluses.

Legend for Plate 1

A December 5, 1974 1:1,000,000 LANDSAT I

Image of the Edmonton Area

Miles 0 5

Kilometres 0 5

Plate 1

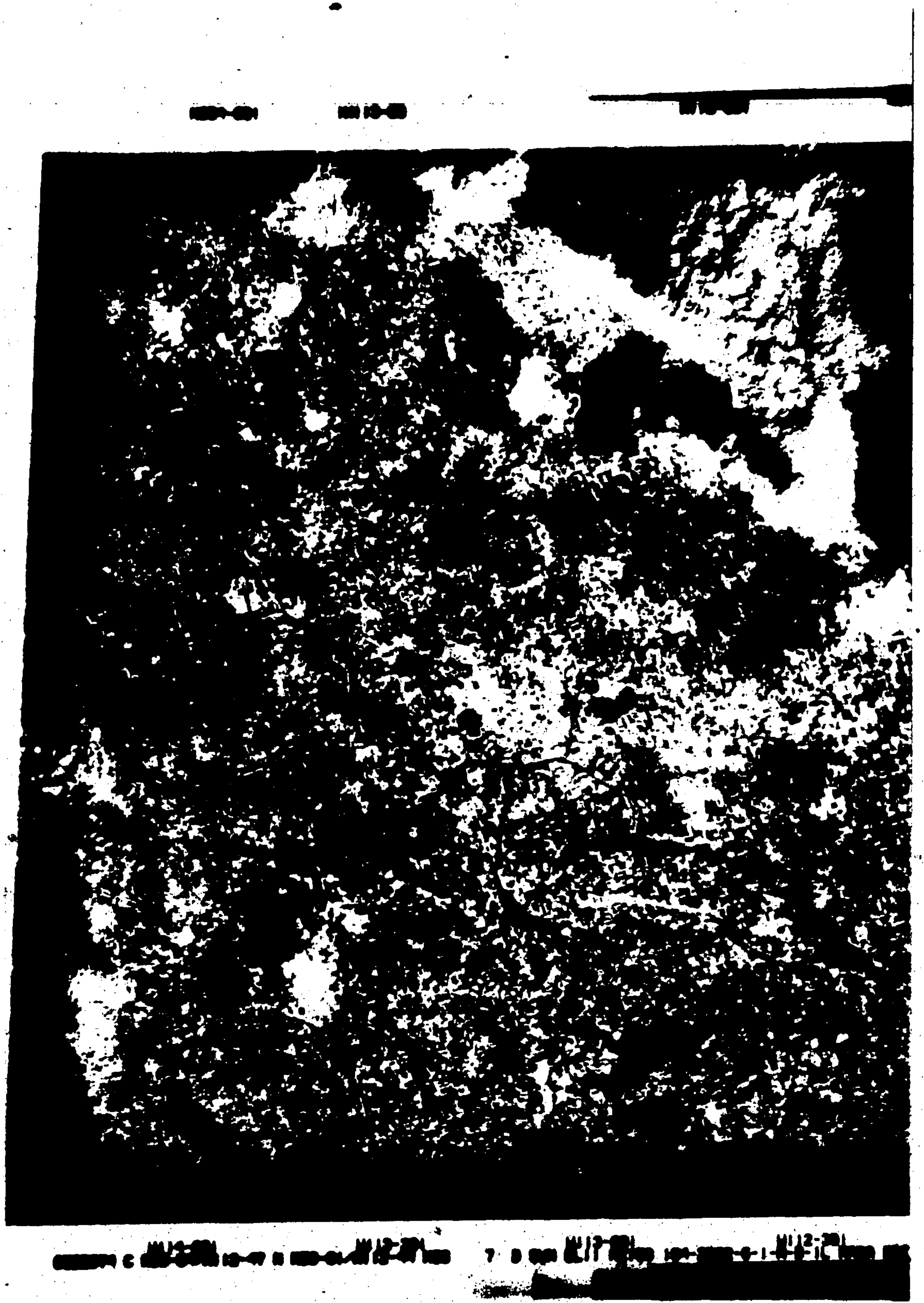


Plate 1

Source EROS Data Center

Scale [illegible]

The objectives for this study were:

1. To establish what variations in winter snowfall are present in the Cooking Lake Moraine area;
2. To develop a procedure using LANDSAT I imagery for determining snow concentration and distribution patterns;
3. To investigate the relationship between LANDSAT I images' tonal variations and snow concentration and distribution patterns;
4. To experiment with various enhancement devices to maximize discrimination of snow cover variations;
5. To compare regional snow moisture recharge capacities and snow water content levels required to produce runoff;
6. To investigate the relationship of snow concentration and distribution patterns to soil moisture storage capacities so that runoff potential might be estimated.

Interpretations from the LANDSAT I imagery were made with two major assumptions in mind. The first assumption was that snow concentration and distribution patterns would not vary appreciably from January 10, 1975 to April 10, 1975. This was a necessary assumption because the April 10, 1975 LANDSAT I imagery could not be obtained (Refer to Chapter V for details). The second assumption was that meteorological data for the Edmonton International Airport combined with 1975 winter snow depth and water content measurements taken with a Mt. Rose snow sampler would be representative of the major patterns in the Cooking Lake Moraine.

The bases for water quality and quantity studies for the

Cooking Lake Moraine developed out of public concern for lake improvement. Historically the Cooking Lake Moraine has experienced rather large fluctuations in water quality and quantity. In some instances man has played a major role in these fluctuations. The following chapter is a review of studies elsewhere that might serve as bases for the analysis of these problems.

Chapter II

REVIEW OF LITERATURE

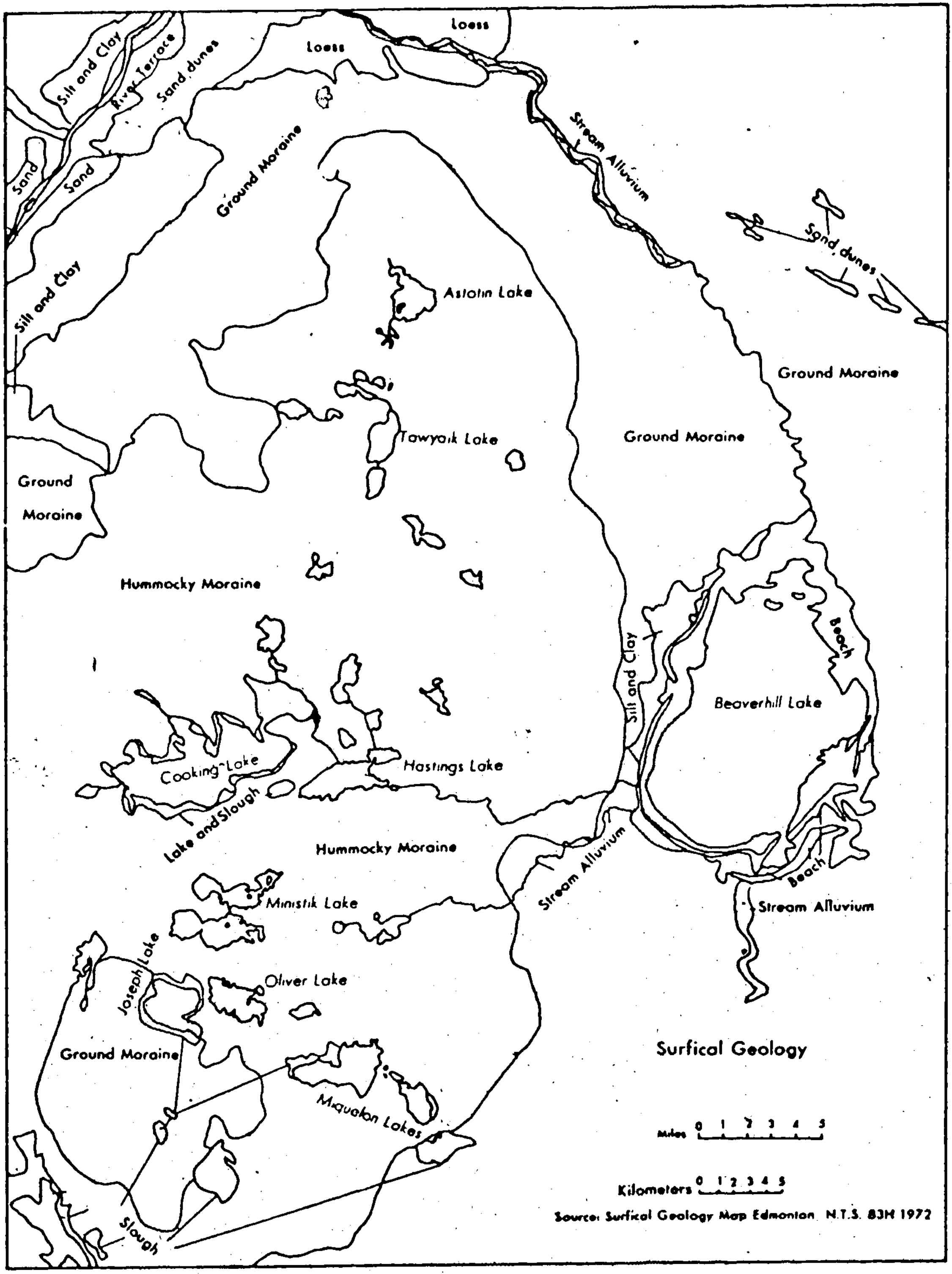
This chapter is a review of the literature pertaining to the Cooking Lake Moraine, and an explanation of the enhancement techniques used to show snow concentration and distribution patterns with LANDSAT I imagery. The chapter is subdivided into four parts: Geological History, Settlement, Lake Levels, and LANDSAT I Imagery and Snow Drifting.

Geological History

"During the Pleistocene epoch, a continental ice sheet originating on the Precambrian Shield in Keewatin Territory advanced from the northeast and covered the region at least twice" (Bayrock, 1962, marginal notes on Surficial Geology map 83H). The second advance and recession, in late Wisonsin time, formed most of the local topographic features of the Cooking Lake Moraine. The Cooking Lake Moraine is a "hummocky moraine: . . . till composed of mixed clay, silt and sand, with pebbles and boulders; lenses of sand, gravel and local bedrock; generally more than 40 feet thick; topography undulating to gently rolling" (Bayrock, 1962, marginal notes on Surfical Geology map 83H, Figure 1). The area to the south-west of Joseph Lake, is a "ground moraine: . . . till composed of mixed clay, silt and sand, with pebbles and boulders, variable in thickness, but generally less than 40 feet, topography level to undulating" (Bayrock, 1962, marginal notes on Surficial Geology map 83H, Figure 1). Most of the Edmonton district surficial materials are formed on a bedrock surface sculptured in poorly consolidated materials, which comprise the Edmonton Formation of late Cretaceous age (Carlson, 1967, p. 5). An erosional remnant of this material served as a base for the Cooking Lake Moraine and provided much of the regional relief. The district was comprised of three main formations: the Edmonton, the Bearpaw, and the Pale and Variegated (Figure II). Carlson (1969) provided an in-depth analysis of the bedrock topography in "Bedrock Topography and Surficial Aquifers of the Edmonton District, Alberta". Since glaciation there have been very few topographical changes on the moraine. The relatively dry climate combined with the lack of a major river has helped to keep erosion and deposition to a minimum. Minor filling, though, has occurred with vegetation, in most of the sloughs.

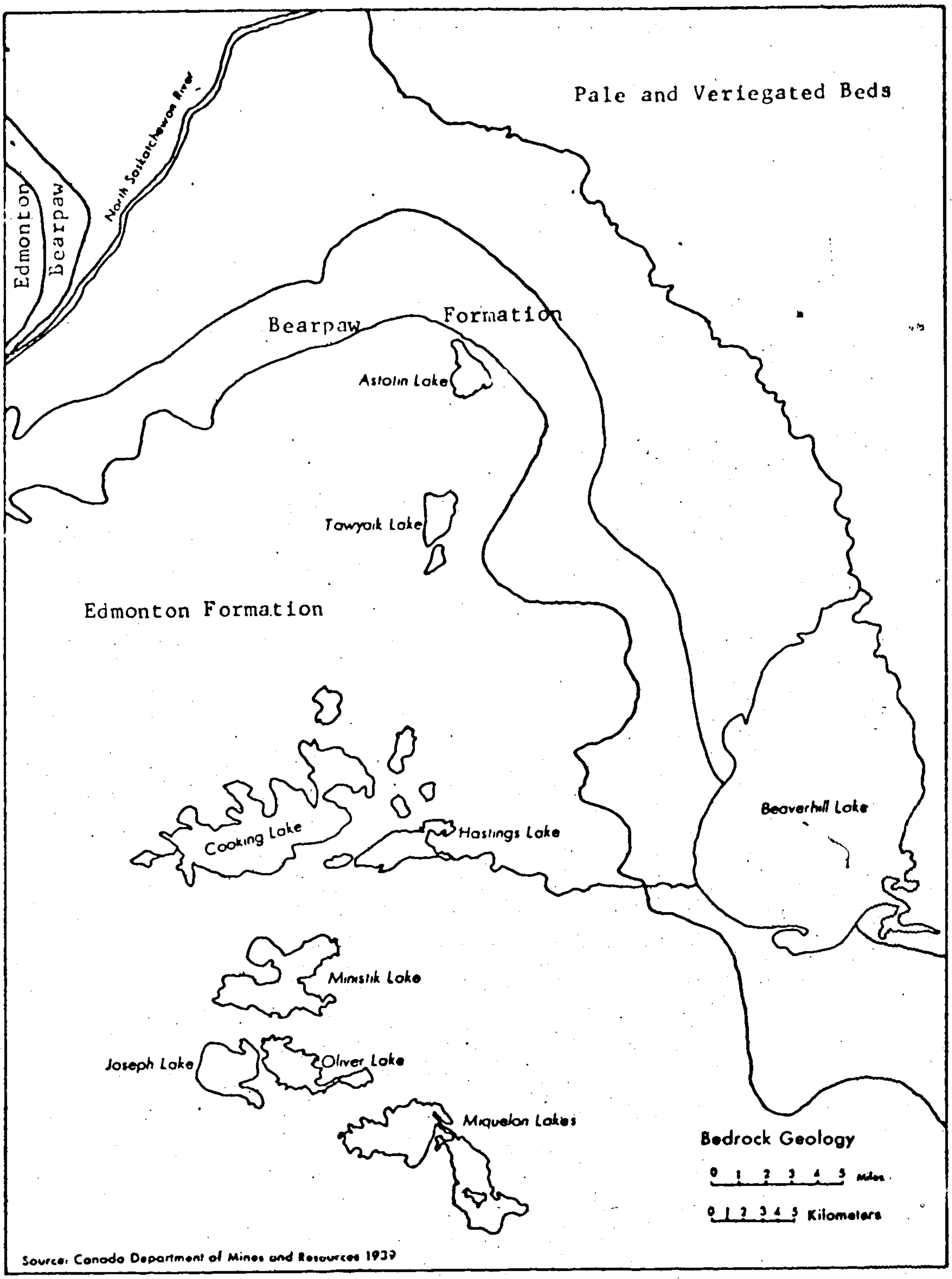
Cooking Lake loam is the predominant soil of the area (Figure III). This loam and other soils such as Uncas loam, Falun loam, Angus Ridge loam, Camrose loam, and others are all present on the Cooking Lake moraine. For an in-depth study of these soils refer to the Soil Survey of Edmonton Sheet (83H) 1962, by Bowser, Kjearsgarrd, Peters, and Wells; Grey Wooded Soils and Their Management by the University of Alberta, Faculty of Agriculture; and Canadian Soil Science by Atkinson.

Figure I



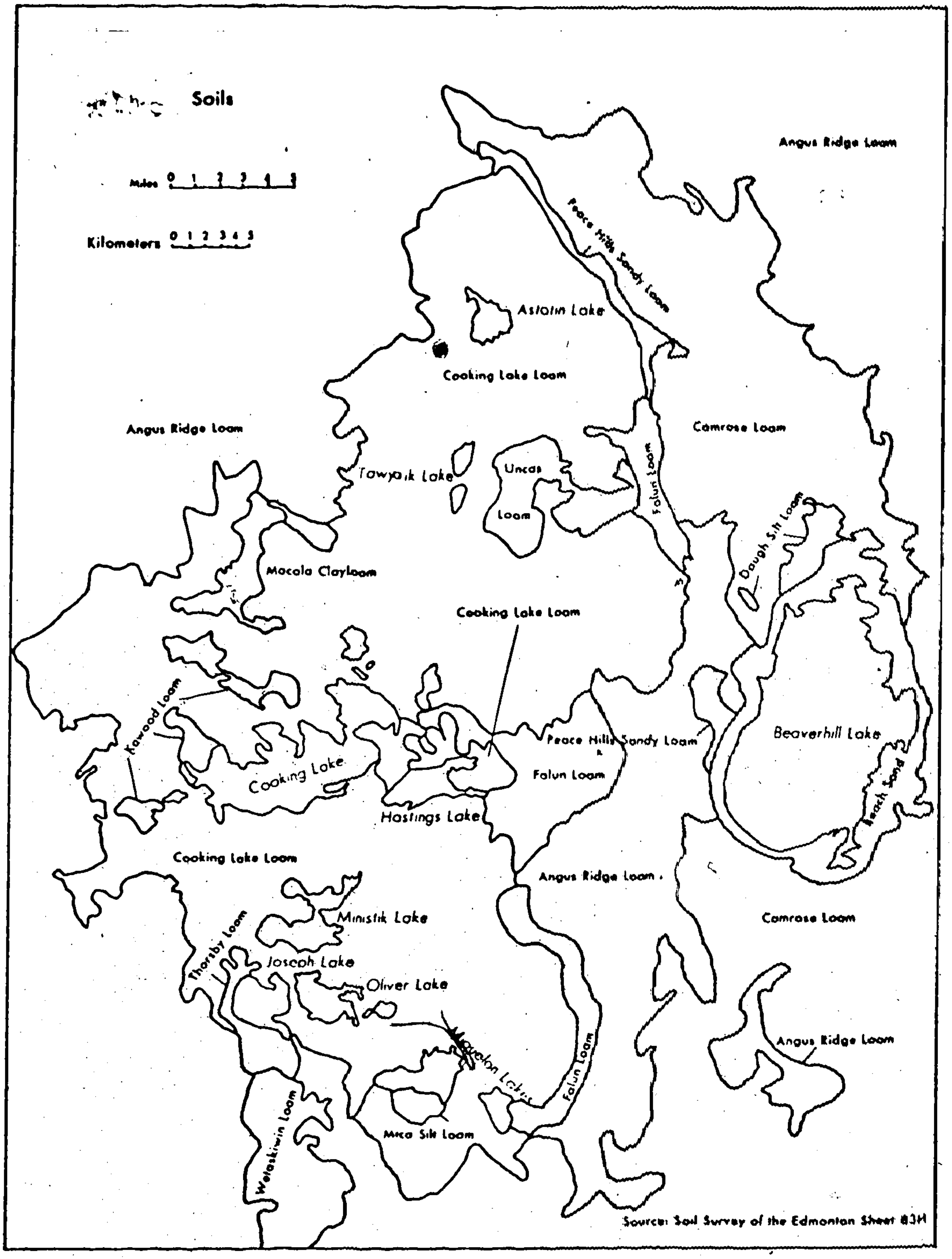
Source: Surfical Geology Map Edmonton N.T.S. 83H 1972

Figure II



Source: Canada Department of Mines and Resources 1939

Figure III



Source: Soil Survey of the Edmonton Sheet 83H

Settlement

"About 18 miles east of Edmonton lies a hilly area which some people call the Cooking Lake Moraine, while others use the old Indian name Beaver Hills (Amisk Wachee)" (Nyland, 1969, p. 22). It was assumed that the origin of the name "Beaver Hills" came from the Beaver Indians who inhabited the area. About 1780, the Blackfeet Indians passed into the Beaver Hills region during their migration from the south eastern prairies, and later the Crees invaded and forced the Blackfeet Indians from the Beaver Hills. There was an abundance of game--bison, moose, elk, deer, ducks, geese, and swans--on the Cooking Lake Moraine. Those rich hunting grounds led to a number of conflicts among the various tribes living in the area.

By 1895, the Cooking Lake Moraine was sparsely inhabited by white settlers. They cleared the land and burned the trees. Some of the fires were blown out of control, destroying large stands of natural forest. The Edmonton Bulletin described the destruction on May 9, 1895.

> The worst of the matter is that many settlers look upon this wholesale destruction of timber as something commendable and to the advantage of the country in making more land available for settlement. Even in those parts of the country that are open, only a very small percentage of the land is actually cultivated, so that there is no necessity for destroying the timber wholesale. (Nyland, 1969, p. 22)

According to Nyland the rain had put the fire out in August of the same year. In October of 1895, the fire was reignited and the flames crossed the North Saskatchewan River, burning on northward; leaving only small stands of trees. Some of the settlers had a more constructive idea for the natural surroundings. The first tree replanting conservation practices originated in 1892; by 1898 the first ranger station on the moraine was established and during 1910, the first tree nursery in Alberta was established on the shores of Cooking Lake (Nyland, 1969)

Lake Levels

"In 1865 both Beaverhill Lake and the lakes in the moraine were dry, but heavy rains in 1875 restored the water levels" (Environment Conservation Authority, 1971, p. 2). Appendix A, indicates the progression of lake level fluctuations as calculated by Laycock in an article entitled "Lake Level Fluctuation and Climatic Variation in Central Alberta" (1973). The years 1883 and 1888 were the only years prior to 1900 which showed a surplus and a positive lake level change. There are conflicts in the literature concerning lake level fluctuations from 1904-1930. Research by Acres West Limited indicated that the lakes were in satisfactory condition for most uses until the 1930's when water levels declined steadily and the lake quality began to deteriorate (Acres Western Limited, 1971). The surplus and deficiency patterns presented by Laycock, Appendix A, showed that from 1900 to 1904, there was a major rise in lake levels. Also, surpluses in 1907, 1914, 1917, 1920, 1925, and 1927 combined with a negative or very minor lake level change during the remaining nineteen years (1900-1930) indicated that neither a stationary pattern nor inadequate lake levels existed for most recreational activities.

Stanley Associates Engineering Limited in a report entitled "Water Inventory and Demand Draft Report", (1974) agreed with Acres Western Limited, that the lakes were in good condition before 1930.

It was apparent from reviewing EPEC's and Stanley Associate's lake level graphs that the lakes on the Cooking Lake Moraine have been fluctuating continuously. Both EPEC and Stanley Associates used these graphs to indicate a continual recession in lake levels, even though data used to construct these graphs were very limited. For example most of the data for Cooking Lake were estimated from interviews with local residents. For Ministik Lakes less than two years of data were available thus rendering any conclusions made from these graphs to describe lake patterns in the 1930's meaningless.

For Miquelon Lake, negative lake level fluctuations have occurred as a direct result of man's activities.

> No mention of a noticeable drop in lake levels was made until 1925. A settler had slightly deepened the outlet of the lake, but the big blow did not come until 1927 when a water shortage in the Camrose town reservoir was temporarily solved by digging a canal through the height of land south of Miquelon Lake to divert water into Stony Creek. There appears to have been no permission given for this diversion. The move was, to say the least, ill advised (Nyland, 1970, p. 22).

In reality the small drainage basin of the Miquelon Lakes suffered several dry years (approximately 10) and thus was unable to withstand the drainage draft put on it by the ditch into the Camrose Creek Basin. "When in 1928 the lake level dropped lower than the control weir, the canal was dug deeper with the help of heavy machinery until on the height of the land the canal was close to 20 feet deep" (Nyland, 1970, p. 22). In 1971, Nyland went on to say, that Calgary Power had dug a ditch which drained Miquelon Lakes 16 feet (Nyland, 1971, Public Hearings). Calgary Power could not be blamed for the entire 16 foot drop in lake levels, particularly when lake levels dropped well below the ditch during the next few years.

Deforestation caused by fires and land clearing has had an effect on land use on the Cooking Lake Moraine. In many areas the "parkland" was changed into grain fields and pasture land. The effects of deforestation on water retention capacities have been debated.

> Deforestation and topographical changes associated with land cultivation and the advent of modern civilization in the watershed and surrounding areas has resulted in the deterioration of water retention capabilities of the watershed, consequently ground water storage and water tables in the watershed have been falling (Zuzak, 1971, Public Hearings, p. 7).

Zuzak also accepted Nyland's explanations about falling lake levels. Nyland named land clearing operations and slough drainage projects in the watershed as having adverse effects on runoff. "These previously timbered lands used to provide a reliable source of water for the springs in the lake, which now flow only intermittently" (Nyland, 1970, p. 25). In the author's opinion, deforestation would add to lake levels due to a decrease in soil moisture storage utilization by plants. Drops in yearly precipitation patterns, in this case, appear to have had a greater effect on lake levels than did deforestation.

> It has been suggested that the clearing and burning of forest cover in the Cooking Lake basin has resulted in lower flow into the lake. In principle, such clearing and burning would result in a reduced soil moisture consumption and thus in yield increases, particularly in a sub-humid region such as this. In practice, the extensive burning before 1900 probably contributed to the very heavy yields of the wet years that followed because of the reduction in consumptive use (Laycock, 1973, p. 89).

Similar variations in thought (non professional versus professional) typified much of the discussion in the literature available about the Cooking Lake Moraine.

Major interest in the water quality and quantity problems of the Cooking Lake Moraine resulted in a series of studies beginning in the late 1960's. In 1969, the Conservation and Utilization Committee of the Alberta Department of the Environment in cooperation with the Cooking Lake Area Study Committee established a conservation area. In the fall of the same year Nyland presented a description of the Moraine's settlement, fires, forestry, recreation, precipitation, and water levels in an article entitled "The Dying Watershed". The article provided a detailed review of the history of the Cooking Lake Moraine, but lacked reference to in-depth water studies which would be required for the type of conclusions which were drawn.

> The watershed can be restored, then the beaches will come to life again and the fish will return to be enjoyed by man and beast. Grazing areas can be placed under proper management and possibly support more cattle than is now the case. Those soils most suitable to trees can be replanted to the benefit of wildlife, for recreation and to help restore the balance of nature. Both the people of the city and the rural residents can only benefit by such a scheme (Nyland, 1969, p. 38).

During the remainder of 1969 and 1970 a number of reports were published concerning the Cooking Lake Moraine. Many of the publications dealing with the Cooking Lake Moraine were repetitive and would add little to this review.

Environmental Planning and Engineering Consultants (EPEC) of Edmonton, Alberta produced the first consultant's report on June 10, 1971, entitled "Economic Analysis of the Cooking-Hastings Lakes".

The report was developed at the request of the Water Resources Division, Department of Agriculture, Province of Alberta.

> More specifically the study was to incorporate the investigation of three areas. Firstly, a verification of the authenticity of a petition calling for "Action to Reclaim the Beaverhill Watershed" presented to the Environmental Conservation Authority in the fall of 1970. This was a requirement in order to be able to determine the validity of the petitioner's alleged concern respecting Cooking and Hasting Lakes. Secondly, an investigation as to the possibilities of improving the conditions of the lakes through internal water management and/or the importation of water from sources outside the Cooking-Hastings watershed. This necessitated an examination of possible schemes and their ramifications. Thirdly, an economic analysis identifying probable costs of possible schemes and identifying benefits that could accrue in various sectors such as recreation as a result of improvement to the existing conditions of the lakes (EPEC, 1971, p. 1-1a).

During the fall of 1970, a total of 598 people signed a petition calling for "Action to Reclaim the Beaverhill Watershed" (EPEC, 1971, p. 5). Only 284 signatures were available and of those only 222 had legible names and addresses. A questionaire was sent to 25 individuals on the list: 24 people completed the questionaire. The results of this questionaire were presented to EPEC by Bailey, Director of the Water Resources Division, (Appendix A page vii of the EPEC report). Unfortunately or fortunately depending on how the results were to be used it was found that twenty of those petitioned owned property in the Cooking Lake Moraine. Most property owners would enjoy an opportunity to increase their property values. The prices were increasing and will undoubtedly continue to grow as development occurs (Table 1). In all instances the mean increase in purchase price was 36.2 percent and the properties were resold in an average of 13.5 months.

Table 1

PRICE INCREASES FOR SELECTED PROPERTIES IN STRATHCONA COUNTY

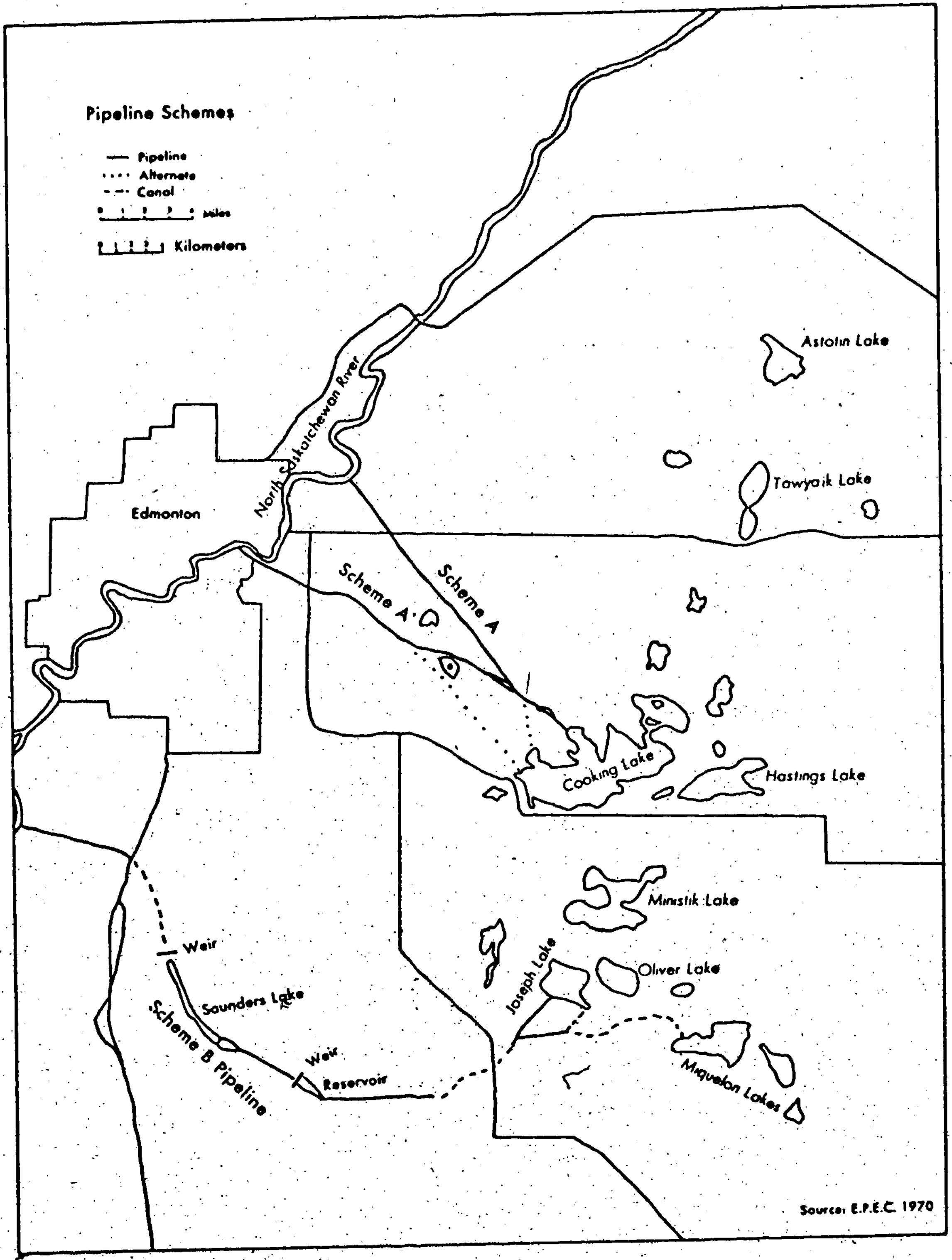
Location (Tp./Range)	Size (Acres)	Purchase Price ($)	Selling Price ($)	Holding Period (Months)	Percentage Increase Over Purchase Price
51/20	161	8,700	16,000	38	84
51/21	161	12,000	18,000	38	50
51/21	161	8,350	10,000	23	17
51/21	161	2,500	3,668	1	47
51/21	161	11,912	13,700	6	15
51/21	166	10,000	16,000	19	60
51/21	601	67,000	87,500	14	31
51/22	40	30,000	35,000	3	17
51/22	6	5,500	7,500	1	36
52/22	3	4,400	6,500	3	48
52/22	38	11,000	12,000	2	9
53/22	20	10,000	10,800	8	8
53/21	20	6,000	6,800	2	13
54/20	159	5,500	9,500	29	73
54/20	161	3,700	5,000	15	35

Source: Acres Western Limited, 1971 "Alternative Land Use Evaluation Cooking Lake and Hastings Lake Area".

In many instances EPEC seemed to lack adequate hydrological information. "Water balance relationships are much better established and the effects of the watershed management are much better known professionally, than is suggested in the EPEC report" (Laycock, 1971, Public Hearings, p. 79).

Hydrological matters were not the only subjects in the EPEC report to receive criticism. "We are of the opinion that the economic analysis of Cooking and Hastings Lakes prepared by EPEC Consulting Ltd. should not be the bases for the decision on whether or not to invest in restoring the water levels of these lakes" (Lefrancois, 1971, Public Hearings, p. 46). The report was narrowly multiple-purpose with consideration of recreation, cottage development, residential development, commercial development, and waterfowl needs. EPEC's strategy, which aimed for multiple means, but did not achieve them for raising lake levels, was represented by three pipeline schemes (A, A', and B) for pumping water from the North Saskatchewan River to various points on the Cooking Lake Moraine (Figure IV). In 1971, the direct costs were estimated to be $4,128,840 for scheme A, $4,408,680 for scheme A', and $7,971,160 for scheme B. If a choice of one of three pipeline schemes had been made in 1971, it appeared from a review of the Public Hearings that scheme B would have been favored. If this decision had been made it would have been based almost totally on estimations rather than fact. Mayon Dent of Edmonton stated, "In our opinion, the recreational benefits would be dramatically increased by using scheme B over scheme A" (Mayor Dent, 1971, Public Hearings,

Figure IV



Source: E.P.E.C. 1970

p. 13). The Fish and Game Department endorsed scheme B (Chymko, 1971, Public Hearings). "Tentatively however, I would opt for No. 6 in the list that I have, or plan "B" in the EPEC report" (Laycock, 1971, Public Hearings, p. 83). The place of intake for scheme B near Devon would result in fewer pollutants being present than for schemes A or A'. "The problem of high bacteria counts in the North Saskatchewan River downstream of Edmonton is well known, and it has been the subject of much discussion already at these Hearings" (Simpson, 1971, Public Hearings, p. 94).

Four years later Gallup (1975), after conducting intensive water quality studies, stated that in raising the level of water on the Cooking Lake Moraine the only effect would be to create large sloughs out of small ones (Gallup, 1975, Cooking Lake Management Committee Meeting). In the same year Underwood, McLellan and Associates stated, "That while the level of Cooking Lake may be raised, giving more area for boating, the water quality won't be changed much" (Edmonton Journal, 1975)

Laycock, in 1971, and in 1973, suggested internal modification of lake levels using drainage of one of the larger lakes such as Joseph Lake and of local depressions as a means of restoring Cooking Lake and Hastings Lake. Laycock indicated that the cost for this type of internal management would be approximately one tenth of that of the pipeline schemes. In a 1973 article, several other alternatives were suggested by Laycock, one of these was to pump water from adjoining basins, such as Little and Big Hay Lakes, in the spring into the Cooking

Lake Basin and using Looking Back Lake and other water bodies as storage reservoirs to extend pumping seasons.

In light of Gallup's and Underwood, McLellan and Associate's statements, spending approximately $8 million for massive pumping from the North Saskatchewan River did not appear to be the best alternative. Also, if construction cost increases parallel many of the increases for the Corp of Engineers projects in the United States, or dredging operations on the St. Lawrence River, the costs may double or triple before completion of the project.

The second consultant's report was presented to the Cooking Lake Area Study Management Committee on October 1, 1974, by Stanley Associates Engineering Ltd. The report was entitled "Water Inventory and Demand--Draft Report". The Stanley Associates' Report came closer to developing a multiple purpose and multiple means approach to the water quality and quantity problems which the Cooking Lake Moraine now endures. The Stanley Associates study included research, but there are many instances where they employed research as a tool without adequate thought. "A detailed analysis was carried out on Hastings, Cooking, Ministik, and Miquelon Lakes to determine the correlation, if any, between rainfall and lake levels for 1972" (Stanley Associates Engineering Ltd., 1974, p. 40). Three years earlier at the Public Hearings, Kellerhals said that five years of hydrological data are needed before conclusions could be drawn (Kellerhals, 1971, Public Hearings). The Stanley Associates report was, in many instances, based on only one year's data. Two internal drainage schemes were presented by the Stanley

Associates, the draining of sloughs and other small pockets of water and the draining of one of the lakes in the moraine. Their conclusions were, "In view of the relatively large water volume deficit calculated for the moraine it is probable that such a scheme would only provide a small percentage of the volume of water required to just stabilize the lakes at their present level, and have a high cost benefit ratio" (Stanley Associates Engineering Ltd., 1974, p. 103). In some years this may be true, but in years of above average precipitation, such as 1974, large volumes of snowmelt runoff would be available for internal management schemes.

The cost of internal water management would be small compared to piping water from the North Saskatchewan River. In most years stablization of lake levels (for Cooking and Hastings Lakes) could be obtained by internal management of snowmelt runoff and by draining some sloughs and small lakes.

The purpose of the report was centered around the Dodds Thermal Plant.

> It has not been possible to carry out the in-depth study we originally envisaged. This was due to two reasons. Firstly, time constraints were imposed on the study by the need to investigate the possibility of a multi-purpose pipeline being constructed to serve the needs of the proposed Dodds Thermal Plant and the Cooking Lake Moraine. The time constraints [were] being imposed by the need for Calgary Power to have a decision on such a scheme by March 1, 1975. Secondly, paucity of data has precluded in-depth analysis of the situation with respect to the hydrology of the Cooking Lake Moraine (Stanley Associates, 1974, p. 2).

Scheme B from the original EPEC report had been altered to include the Dodds Thermal Plant. "One gets the impression that both may have been influenced by a prior knowledge of government desires to have a strong case for a pipeline through the area to serve thermal power development to the east" (Laycock, 1974, p. 10).

At a meeting of the Study Management Committee, October 11, 1974, Laycock, the co-ordinator of the University of Alberta's Water Resource Center Lake Area Study Program, presented objections pointing out the inadequacies in the report. Deeprose, the Chairman of the meeting, suggested that Laycock be contacted concerning elaboration of points raised at the meeting. He was contacted once, a week later, concerning groundwater aspects of the report. Laycock then prepared a paper highlighting certain aspects of the report and presented it to Stanley Associates. "Our Study Program group was not satisfied with this degree of contact, at least partly because we had supplied some of the background research data (almost unacknowledged) which we believed had been ill-used in the interpretations and conclusions given in the draft report" (Laycock, 1974, p. 1).

If lake levels were to be raised, the cheapest, most efficient method should be employed. In the author's opinion better management of snowmelt runoff and the sacrificing of one or more of the lesser used lakes would provide a viable solution in most years. If more water was needed the Little Hay Lake drain flow to the south of the Cooking Lake Moraine, could be used in the spring of each year. This could be complemented with flow from the Clearwater Creek and the Irvine Creek Basin from the west, and the Katchemut Creek Basin from the east, which could be pumped to various points on the moraine. Thus the purpose of this thesis was to develop a more accurate means of estimating regional patterns of snowmelt runoff using remote sensing on and around the Cooking Lake Moraine. LANDSAT I imagery proved to be an efficient tool from which snowmelt runoff could be estimated.

LANDSAT I Imagery and Snow Drifting

"Snow cover is the primary source of Canadian water supplies" (McKay and Findlay, 1971, p. 17). Snowmelt and spring rains are substantial sources of runoff (Laycock, 1971, Public Hearings, p. 80). The amount of snowmelt runoff, in most years, determines much of lake level fluctuations on the Cooking Lake Moraine. Obviously there are other factors affecting lake level fluctuations, such as summer rains and evaporation, but in average and above average snowfall years snowmelt runoff causes the greatest lake level fluctuation.

To properly manage this resource, there is a need for continual synoptic data on snow distribution patterns. "Continuous monitoring of the highly variable snowcover is possible only from satellites" (Meier, 1973, p. 1). Research by Wendler and Carlson (1974) supported the contention that LANDSAT I imagery could be used successfully to monitor snowmelt.

The major complication with LANDSAT I imagery was cloud cover. Yet, there are a number of images available for the fall and winter periods of each year except 1974, when only two cloud free images were available for the Cooking Lake Moraine, one in November of 1973 and one in April of 1974.

A number of snow surveys have been conducted using remote sensing techniques. Meiers (1973) evaluated LANDSAT I imagery for mapping and detection of changes in snow cover on land and on glaciers (Northern Cascades in Washington). Meiers found that under favorable conditions the mapping procedure used was reliable to within four percent of the snow covered area. Meiers (1973) monitored drainage basins by using the Stanford Research Institute console to electronically superimpose basin outlines on imagery and by using video density slicing to measure areas. A zoom transfer scope was also used to transfer information from 1:250,000 prints to standard topographical maps.

Barnes (1973) evaluated the applications of LANDSAT I imagery for mapping snow cover in mountainous regions of the western United States (Salt River Project in Arizona, 1973). Barnes found that band 5 (.6 to .7 um) was the most useful band for detecting and mapping mountain snow cover (Barnes, 1973). Barnes also found that the near infrared band (7) proved to be useful in detecting areas of melting snow.

The hydrologic characteristics of snow covered terrain with thermal infrared imagery (Near Cape Discovery, Ellesmere Island) were investigated by Poulin (1973). "The energy that penetrates the snow over land is either absorbed or reflected at the snow/soil interface, while at a snow/ice interface a significant portion of energy continues to be transmitted into and through the ice" (Poulin, 1973, p. 5). Several graphs were presented showing the thermal conductivity of snow compared to sea ice, fresh ice, frozen silt and clay, and frozen sandy silt to add significance to his previous statement. Poulin indicated that a satellite would be the preferred vehicle for obtaining thermal imagery, but with present systems the noise level would cause large temperature differentials.

The majority of the articles published on remote sensing and snow surveys deal with the mountain environment; consequently many of the investigators found problems with slope angles, cloud cover, snow depth, and accessibility. A complete List of publications with references to the use of remote sensing for snow surveying was provided by the Canada Centre for Remote Sensing (Appendix B).

Based on the review of literature, several remote sensing systems were found to be superior for snow surveys. A radar system and a microwave radiometer system (antenna systems) produced the most useful images and printouts available for snow surveys. These systems could be used to display the general snow cover and could be adjusted to penetrate the same snow cover to calculate snow depth (water content measurements would have to be made in the field). A thermal infrared scanner (optical system) could be used to provide detailed information about varying degrees of snow ripeness and water content. Computer printouts from LANDSAT magnetic tapes provided a digitized format of the study area. The "Imager 100" sorts digitized data and is capable of identifying the spectral signatures of a target, and of sorting the digital data to discriminate and provide an image prediction, through correlation analysis, for the occurrence of a particular target.

The remote sensing systems listed represent some of the finest presently available, in capabilities for a snow survey and also some of the most expensive to use. The microwave radiometer, radar, and thermal infrared systems are presently used only on aircraft platforms, making continual coverage very expensive and time consuming. The LANDSAT magnetic tapes provide continual coverage, but the user must have access to a computer (comparable to an IBM 360) and in most cases a computer technician, both of which are expensive. An Imager 100 system would cost as much as one million dollars. The only such system in Canada, is located at the Canada Centre for Remote Sensing in Ottawa.

For these reasons it was impossible to incorporate any of those systems into the study. Consequently, available equipment had to be used (a density slicer and a color additive viewer).

A major difficulty in mapping snow patterns from satellite imagery was snow drifting. This was especially true on the Cooking Lake Moraine. In its initial distribution, snowfall is more uniform than rainfall (McKay and Findlay, 1971, Western Snow Conference). "However, because it is easily moved by the wind, snow usually accumulates on the ground in a highly heterogenous manner, and it is, therefore, difficult to obtain representative measurements" (McKay and Findlay, 1971, Western Snow Conference, p. 18).

Physical features play an important role in snow concentration and distribution patterns on the Cooking Lake Moraine. Plate 2 is a photo of an open, flat, windswept section of Hastings Lake (Mt. Rose snow sampler indicating 11 inches or 27.5 cm of snow). On the south side of Joseph Lake, trees provided a natural snow fence (56 inches or 130 cm of snow, Plate 3). During the winter of 1974-75 drifting

Plate 2

Windswept Area of Hastings Lake

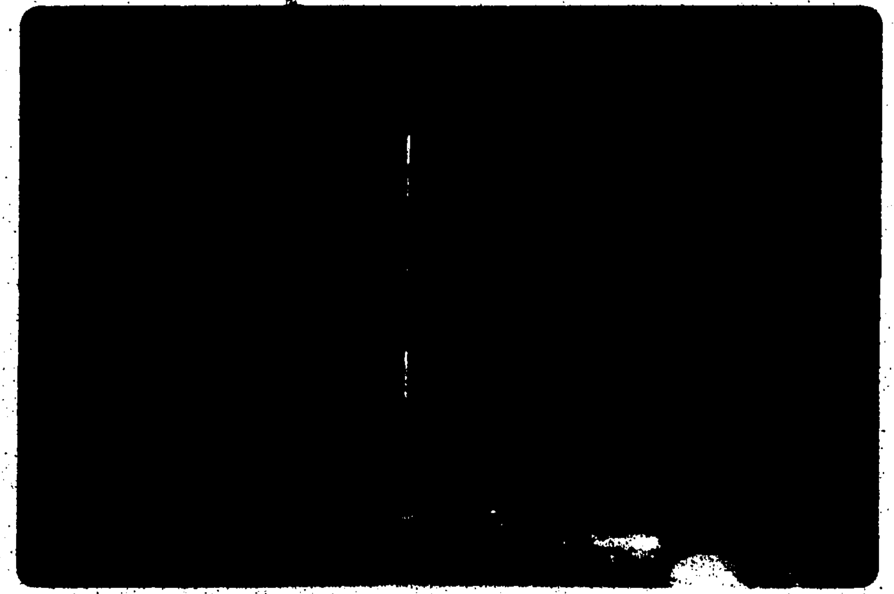


Plate 3

Snow Drifting Patterns on the South

Side of Joseph Lake

within and behind the natural snow fences was the bases for much of the spring runoff.

The snow pack tended to be fairly uniform in relationship to topographic and vegetation variation on the Cooking Moraine (author's field work during 1974-75). The amounts varied from north to south on the moraine, but the snow tended to be constant in heterogeneous zones. "The close relationship existing between snow cover depth and density and vegetation on the local scale persists even in regional patterns" (McKay and Findlay, 1971, Western Snow Conference, p. 19). McKay and Findlay further stated, "It is interesting to note that the standard deviations of the mean course value for each vegetation zone are small, considering the relatively few data used" (McKay and Findlay, 1971, Western Snow Conference, p. 19). If this is true, as it appears to be, it would mean a higher percentage level of predictability for snowmelt runoff on and around the Cooking Lake Moraine.

The majority of the Cooking Lake Moraine is covered by a thick growth of poplars.

> Areas predominantly in aspen generally denote dry, well-drained sites. These may or may not be groundwater recharge areas. However, any snow accumulated in these areas has a high infiltration opportunity. Even under rather intense cultivation to remove this vegetation, the surface runoff from these areas is slight. If all were managed as recharge areas, the probability of improved ground water regime would be high" (Swanson and Stevenson, 1971, Western Snow Conference, p. 67).

Swanson and Stevensons' report pertained to the eastern slopes of Alberta, a more humid region than the Cooking Lake Moraine. Yet, their suggestion to develop recharge areas to improve the groundwater regime could play a large role in an internal water management scheme for the Cooking Lake Moraine, if depth of rooting was changed by changes in vegetative cover.

Before an internal water management scheme could be developed for the Cooking Lake Moraine there are several important factors in need of consideration: Firstly, regional and local variations in annual precipitation patterns must be outlined using existing information services; secondly, background data on the effects of major storm tracks, topographical variations, and wind direction should be analyzed as to their effects on precipitation patterns. Chapter III provides a description of these factors as they appeared to relate to the Cooking Lake Moraine.

Chapter III

REGIONAL AND LOCAL VARIATIONS IN TOTAL PRECIPITATION

The emphasis in this chapter was placed on regional and local variations in total annual precipitation patterns. Maps, tables, and LANDSAT I imagery were used to identify the patterns as they exist on and around the Cooking Lake Moraine.

The meteorological record for the Edmonton area is a moderately long one but it is for stations near, not within the moraine. A meteorological station was developed at Fort Edmonton, and observations began on July 11, 1880 (Environment Canada, 1974). The station was moved to several different locations and finally closed in 1942. After that time the meteorological data was obtained from the Edmonton Industrial Airport Station. The Edmonton Industrial Airport is on level ground surrounded by the city of Edmonton (Environment Canada, 1974).

Laycock summed up the meteorological data for the Edmonton station in the following;

> Let us review the 90-year record for Edmonton from 1883 to 1972. We find that the average water balance for areas with four inches storage (again an average value) is 17.6" Ppt. = (21.0" P.E. - 4.6" D) + 1.2" S. +/-0" St. Change (Laycock, 1973, pp. 88).

Laycock used Thornthwaite's water balance equation in this long term average water balance for the Edmonton station. With

Thornthwaite's water balance equation it was possible to calculate a balance among incoming precipitation, potential evapotranspiration, water deficit, water surplus, and soil moisture storage changes (Thornthwaite, 1955).

A brief definition of the variables:

Precipitation = drizzle, rain, dew, snow, glaze, and frost, which falls to or forms upon the earths surface.

Potential Evapotranspiration = the total amount of water which might be transpired and evaporated by the vegetation with the energy supply available if moisture isn't limiting.

Deficit = the difference between potential evapotranspiration and the amount of moisture that is actually available for evapotranspiration.

Surplus = the amount of incoming moisture in excess of demand when soil moisture storage is fully recharged to root depth. This includes both surface and groundwater flow.

Storage Change = plus or minus changes in soil moisture storage in the budget period. Changes in snow detention storage may be included.

This formula was used to show water balance relationships for three soil moisture storage capacities (Table 8) on the Cooking Lake Moraine. The assigned soil moisture storage capacities used were: 4 inch (10 cm) representing small grain crops and closely grazed pasture land, 6 inch (15 cm) representing mixed scrub forest and wooded pasture and the 8 inch (20 cm) representing mixed closed forest cover. The number of soil moisture storage capacity divisions will vary from one area to the next. For example, a 1/2 inch (1.3 cm) storage capacity may be used for intensively developed urban areas and 2 inches (5 cm) storage capacity for suburbs, where larger areas are devoted to lawns. A 10 inch (25 cm) capacity would be appropriate for more mature forest cover. Almost all of the area under study can be classified using the 3 intermediate classes noted, because the urban areas are too small to be separately identified and dense, mature forest growth is present only in a few small grov-s. Refer to Thornthwaite, Laycock and Verma for factors involved in formulating soil moisture storage capacities for various soil complexes.

To better envision climatic variations on the Cooking Lake Moraine it was beneficial to review the yearly water balance equations based on Thornthwaite procedures (1955, 1957) for five surrounding stations (Plate 4, Tables 2, 3, 4, 5, and 6)(metric conversions Appendix D). The stations were the Edmonton International Airport, the Edmonton Industrial Airport, Edmonton Namao, Camrose, and Vegreville CDA. The average soil moisture storage capacities, for the areas surrounding the stations were assumed to be four inches so that climatic differences might be stressed in comparison. The yearly water balance tables presented were computed for the four inch (10 cm) storage level. The records for the Elk Island Park station dated from 1967 to 1975; but no year had a complete twelve month record. The data for the Ministik Lake station were also incomplete. Water balance tables for the Elk Island Park station were thus omitted.

Because regional oomparisons cannot be made on the bases of one station, there was little need to consider the meteorological data for the Edmonton station before 1950, except to show long term variations (Chapter II, Climatic Variations for the 90-year record). Several conclusions were reached based on analysis of the water balance equation tables for the five stations. The most apparent variation

Legend For Plate 4

A July 14, 1974 1:1,000,000 LANDSAT I

Image of the Study Area

Miles 0 5

Kilometres 0 5

Plate 4


N054-001
W113-001
W112-001
W114-001
W113-301
W113-00
14JUL74 C N53-04/W112-40 N N53-02/W112-38 MSS 5 D SUN EL52 AZ137 34 0054 G 1 N-D-2L NASA ERTS E

Plate 4

Source EROS Data Center

Scale 1:1,000,000

Table 2

Water Balance for Edmonton International Airport 1962-1974

(Thornthwaite procedures using four inches storage)*

	Precipitation	=	(P.E - D) + Surplus	±Storage Change
1962	21.4"	=	(21.2" - .3") + 2.4"	-1.9
1963	16.6	=	(21.8 - 5.9) + .6	+ .1
1964	17.6	=	(19.9 - 3.6) + 0	+1.3
1965	22.3	=	(19.5 - .6) + 4.3	- .9
1966	16.3	=	(18.8 - 1.7) + .4	-1.2
1967	13.2	=	(19.8 - 7.7) + .3	+ .8
1968	13.8	=	(18.1 - 3.6) + 0	- .7
1969	18.2	=	(19.4 - 3.6) + 0	+2.4
1970	17.5	=	(20.2 - 3.8) + 1.9	+ .2
1971	16.2	=	(20.4 - 5.7) + 2.0	- .5
1972	22.0	=	(18.4 - 0) + 2.4	+1.2
1973	23.0	=	(20.1 - 0) + 2.0	+ .9
1974	18.7	=	(20.1 - 2.5) + 4.7	-3.6
Average	18.2	=	(19.8 - 3) + 1.6	- .2

* See Appendices for metric conversions.

Source: Atmospheric Environment Service Monthly Records.

Table 3

Water Balance for Edmonton Industrial Airport 1950-1974

(Thornthwaite procedures using four inches storage)*

	Precipitation	=	(P.E. - D) + Surplus	±Storage
1950	12.9	=	(20.5 - 7.5) + 0	- .1
1951	20.4	=	(19.5 - 2.2) + 1.5	+ 1.9
1952	16.4	=	(23.3 - 6.2) + 1.7	- 2.4
1953	25.5	=	(22.5 - 0) + 2.1	+ .9
1954	19.9	=	(19.9 - 0) + .7	- .7
1955	20.1	=	(22.9 - 5.8) + 1.2	+ 1.8
1956	20.1	=	(22.5 - 3.4) + 2.5	+ 1.5
1957	13.1	=	(22.3 -10) + 0	+ .8
1958	17.2	=	(24.3 - 7.2) + .8	- .7
1959	17.6	=	(21.0 - 3.7) + 0	+ .3
1960	19.6	=	(22.6 - 2.4) + 0	- .6
1961	12.4	=	(23.5 -10) + 0	- 1.1
1962	18.4	=	(22.2 - 4.6) + 1.0	- .2
1963	13.4	=	(23.7 - 9.9) + .2	- .6
1964	16.1	=	(22.8 - 8.0) + 0	+ 1.3
1965	21.4	=	(21.7 - 4.2) + 4.8	- .9
1966	15.5	=	(21.8 - 6.1) + 0	- .2
1967	15.4	=	(22.7 - 9.0) + .7	+ .7
1968	13.4	=	(22.2 - 7.9) + 0	- .9
1969	18.9	=	(22.7 - 5.1) + 0	+ 1.3
1970	18.5	=	(24.1 - 5.6) + .4	- .4
1971	15.8	=	(23.7 - 8.8) + .6	+ .3
1972	20.3	=	(21.5 - 2.8) + 2.5	- .9
1973	21.9	=	(21.8 - .9) + 0	+ 1.2
1974	20.8	=	(21.2 - 1.4) + 2.5	- 1.5
Average	17.8	=	(22.3 - 5.3) + .9	- .1

Source: Atmospheric Environment Service Monthly Records.
* See Appendices for Metric Conversions.

Table 4

Water Balance for Edmonton Namao 1957-1974

(Thornthwaite procedures using four inches storage)*

	Precipitation	=	(P.E. - D) + Surplus	±Storage Change
1957	14.0	=	(21.5 -10) + 0	+ 2.5
1958	17.9	=	(22.1 - 7.2) + 2.5	+ .5
1959	18.1	=	(18.6 - 1.4) + 1.3	- .4
1960	18.9	=	(21.2 - 1.7) + .8	- 1.4
1961	17.6	=	(21.7 - 5.3) + 1	+ .2
1962	16.9	=	(21.5 - 6.6) + 3.2	- 1.2
1963	11.5	=	(22.2 -11) + .6	- .3
1964	15.9	=	(22.1 - 7.7) + 0	+ 1.5
1965	21.1	=	(20.7 - 3.9) + 5.4	- 1.1
1966	15.2	=	(19.6 - 4.6) + .5	- .3
1967	14.0	=	(20.9 - 8.9) + .5	+ 1.5
1968	14.4	=	(19.9 - 5.2) + .4	- .7
1969	17.9	=	(20.8 - 4.7) + .1	+ 1.7
1970	17.5	=	(21.3 - 4.5) + 1.6	- .9
1971	15.9	=	(21.8 - 7.4) + 1.2	+ .3
1972	20.2	=	(19.8 - 2.0) + 3.1	- .7
1973	22.6	=	(21.8 - .6) + 0	+ 1.4
1974	21.8	=	(20.8 - 1.0) + 3.8	- 1.8
Average	17.3	=	(21.0 - 5.2) + 1.4	+ .1

Source: Atmospheric Environment Service Monthly Records.
* See Appendices for Metric Conversions.

Table 5

Water Balance for Camrose 1951-1974

(Thornthwaite procedures using four inches storage)*

	Precipitation	=	(P.E. - D) + Surplus	±Storage Change
1951	16.9	=	(19.9 - 3.9) + .9	+ .3
1952	13.5	=	(21.8 - 7.1) + 0	+ 1.2
1953	18.6	=	(20.2 - 2.7) + 0	+ 1.1
1954	22.0	=	(18.4 - 0) + 3.4	+ .2
1955	16.2	=	(20.7 - 5.2) + .2	+ .5
1956	16.7	=	(20.4 - 3.8) + .6	- .5
1957	15.1	=	(21.1 - 5.8) + 0	- .2
1958	11.4	=	(21.4 -10) + 0	+ 0
1959	16.5	=	(20.0 - 5.5) + 0	+ 2
1960	--		--	--
1961	--		--	--
1962	--		--	--
1963	--		--	--
1964	--		--	--
1965	--		--	--
1966	18.2	=	(20.6 - 3.0) + 0	+ .6
1967	13.4	=	(21.3 - 9.5) + .7	+ .9
1968	13.6	=	(20.2 - 5.6) + 0	- 1
1969	18.1	=	(21.6 - 5.9) + .2	+ 2.2
1970	16.9	=	(22.4 - 6.8) + 2.5	- 1.2
1971	14.3	=	(21.5 - 8.2) + 1.4	- .4
1972	20.6	=	(20.9 - 3.2) + 3.1	- .2
1973	28.9	=	(20.3 - 0) + 5.3	+ 3.3
1974	20.1	=	(20.1 - 3.8) + 7.7	- 3.9
Average	17.3	=	(20.7 - 5) + 1.4	+ .2

Source: Atmospheric Environment Service Monthly Records.

* See Appendices for Metric Conversion.

Table 6

Water Balance for Vegreville CDA 1964-1974

(Thornthwaite procedures using four-inches storage)*

	Precipitation	=	(P.E. - D) + Surplus	±Storage Change
1964	13.8	=	(20.1 - 8.1) + 0	+ 1.9
1965	18.5	=	(20.1 - 1.9) + .8	- .5
1966	11.2	=	(20.4 - 8.9) + 0	- .4
1967	11.8	=	(20.2 - 9.1) + 0	+ .7
1968	14.2	=	(18.9 - 4.5) + 0	- .2
1969	13.4	=	(21.4 - 8.5) + 0	- .5
1970	15.1	=	(20.6 - 5.9) + 0	+ .4
1971	14.5	=	(20.8 - 6.0) + 0	- .3
1972	15.7	=	(19.2 - 3.9) + .6	- .2
1973	21.5	=	(20.7 - .9) + 0	+ 1.7
1974	15.[illegible]	=	(19.9 - 3.7) + 1.9	- 2.5
Average	15.0	=	(20.2 - 5.6) + .3	+ .1

Sources: Atmospheric Environment Service Monthly Records.

* See Appendices for Metric Conversions.

occurred at the Vegreville CDA station. Comparisons show that the Vegreville CDA station trailed the other stations in total precipitation by 2.3 to 3.2 inches (5.8 to 8 cm). Further comparisons showed that the Vegreville CDA station had the second largest deficit (-5.6 inches or 14 cm).

The largest average annual precipitation was received at the Edmonton International Airport (18.5 inches or 45.5 cm). The Edmonton International Airport station differed from the Vegreville CDA station in the total average deficit (3 inches or 7.5 cm smaller), surplus (1.5 inches or 3.8 cm larger), and storage change (.4 inches or 1 cm larger).

Part of the variation in total annual precipitation was caused by the location of the station, and by the type of gauging equipment used. The Edmonton International Airport, Edmonton Industrial Airport, and Edmonton Namao stations are first order stations (since 1960) with nipher snow gauges. The Camrose and Vegreville CDA stations are second order stations and snow content is estimated to be one inch of water to ten inches of snow (2.5 cm to 25 cm). This could account for larger or smaller amounts of regional snowfall on and around the Cooking Lake Moraine than was indicated by average calculations for the surrounding stations.

To compare meteorological data since 1961, for the five stations, it would be necessary to use the ten to one ratios for the snow data at the three airport stations. Due to the amounts recorded using a nipher gauge and the ten to one ratio, the actual precipitation was probably greater than was indicated using the two gauging techniques.

The Edmonton Industrial Airport station is located on level ground and is subject to a heat island effect by the city of Edmonton. This is indicated by the average potential evaporation calculations for the station (22.3 inches or 55.8 cm) which are higher than for any of the other stations. It was then assumed that variations in total precipitation would occur on the Cooking Lake Moraine.

Three factors which may create variations in snowfall patterns on and around the Cooking Lake Moraine are: the paths of the major storms, topography, and wind direction. The first two factors, storms and topography, directly affect the amount of snowfall. The third factor, wind direction, tends to alter the distribution patterns of the snow by drifting it.

Storms

In July of 1964, Kozub, of the Department of Transport Meteorological Branch published a report entitled "Heavy Snowfalls at Edmonton". In this report Kozub classified 41 snow storms which occurred between 1944 and 1963 (Table 7). Kozub found that the majority of the storms fell into two categories: Surface Type I (12 storms) and Surface Type III (19 storms). The Surface Type I storms were characterized by low-pressure areas near or on the British Columbia coast-line, which had been stationary or had moved in slowly from the Pacific Ocean (Figure V). The centers of this type of storm

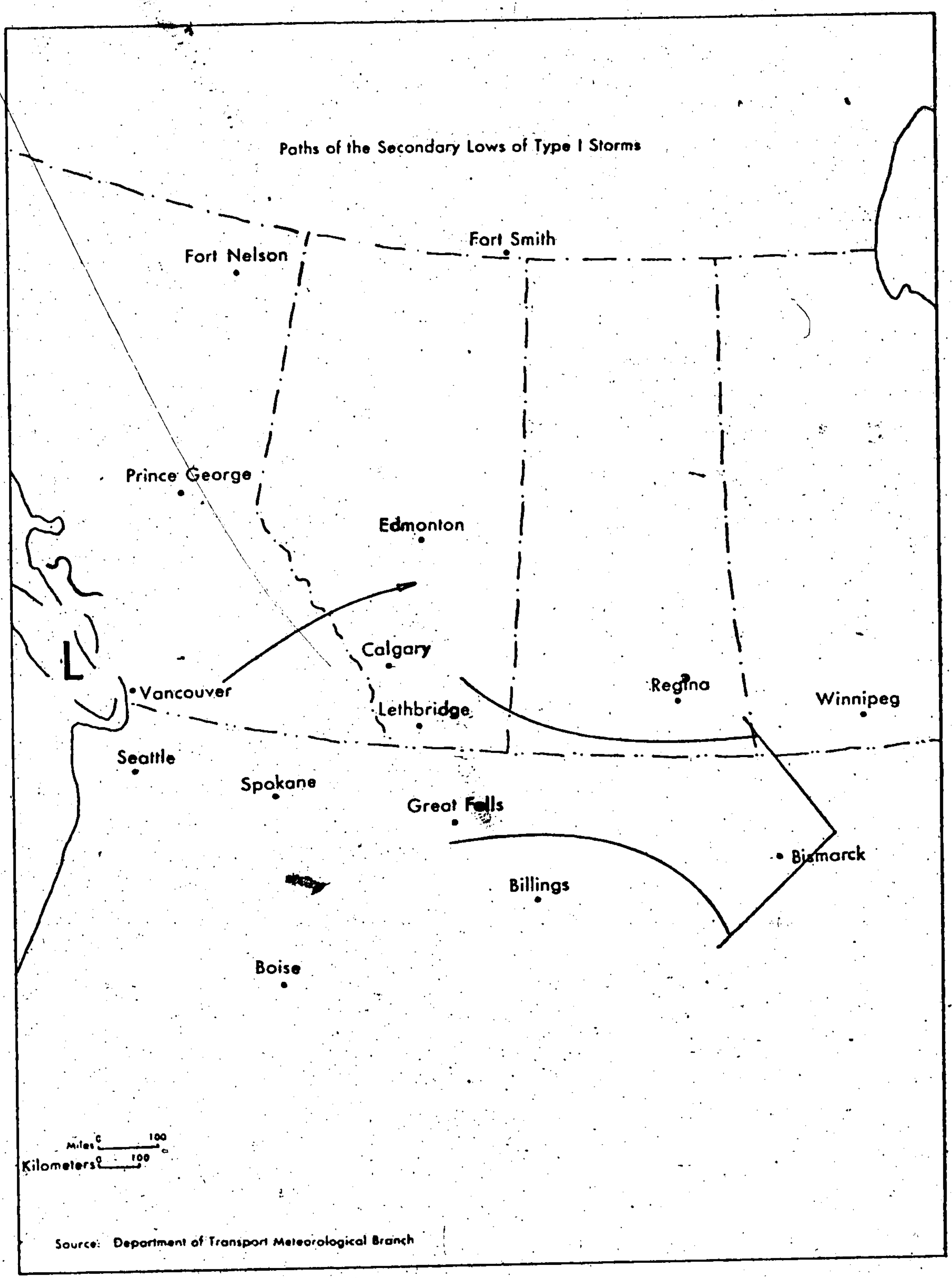
Table 7

Number of Snowstorms of Various Ranges,
In Inches, By Months at Edmonton, Alberta,
In the Winters 1944-45 to 1962-63 *

Range	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Total
2.0" - 2.9" 5.0cm - 7.3	9	6	3	2					2	2	5	8	37
3.0" - 3.9 7.5cm - 9.8	9	6	3	3					1	2	5	2	31
4.0" - 4.9 10cm -12.3	2	2	2	3	2					3	3	4	21
5.0" - 5.9 12.5cm-14.8	3	4									1	3	11
6.0" - 6.9 15cm -17.3	2	1		1						2			6
7.0" - 7.9 17.5cm-19.8	1	2										1	4
8.0" - 8.9 20cm -22.3	1		1							1			3
9.0" - 9.9 22.5cm-24.8		1	1	1									3
10.0" -10.9 25cm -27.3													
11.0" -11.9 27.5[illegible]-29.8												1	1
12.0" -12.9 30.0cm-32.3													
13.0" -13.9 32.5cm-34.8													
14.0" -14.9 35.0cm-37.3													
15.0" -15.9 37.5cm-39.8													
16.0" -16.9 40.0cm-42.3													
[illegible]" -17.9 42.5cm-44.8				1									1
18.0" -18.9 45.0cm-47.3				1									1
TOTAL	27	22	10	12	2				3	10	14	19	119

Source: Kozub "Heavy Snowfalls at Edmonton", 1964.
* See Appendices for Metric Conversions.

Figure V

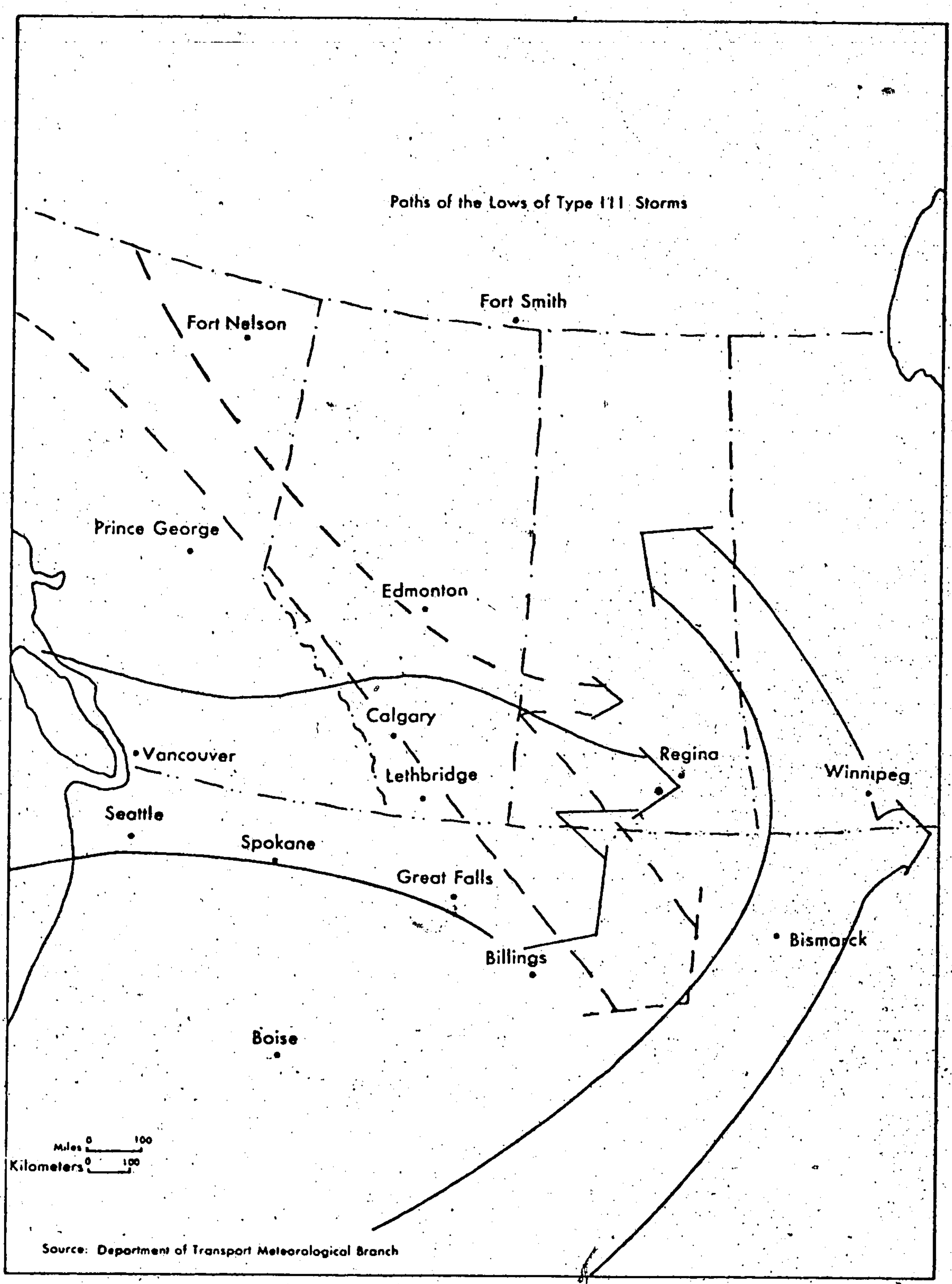


Paths of the Secondary Lows of Type I Storms

Source: Department of Transport Meteorological Branch tended to pass slightly south of Alberta. The Surface Type III storms were characterized by the movement of a low or a trough through Alberta at the surface (Figure VI) indicated by the arrow starting at Vancouver. With the major snow storms, 31 out of 41, following these patterns it was apparent that these storms had a random effect on precipitation on and around the Cooking Lake Moraine. Kozub's study is only one of several dealing with precipitation patterns for the Edmonton area. Refer to Longley, Whistance-Smith, Schrom, the Atlas of Climatic Maps, and Erxleben, and Potter for more in depth research pertaining to regional precipitation variations. It was impossible to depict any significant regional precipitation variations, for the Cooking Lake Moraine, from their research. Thus, the purpose of this study was to develop a more accurate means of estimating regional patterns of snowmelt runoff using remote sensing techniques.

Effects of summer storms appeared to play a smaller role in precipitation variations on and around the Cooking Lake Moraine. Burrows, in a study entitled "Heavy Rainfalls at Edmonton", analyzed 60 storms occuring in a period extending from April 21 - September 30, (1950 to 1965). "Surface, 850-mb, 700-mb, and 500-mb charts were carefully examined for each of the 60 storms of 0.75 inches or more, starting about 24 hours before commencement of rain at Edmonton" (Burrows, 1966, p. 5). Burrows found that an average of four storms a year with greater than .75 inches (1.9 cm) occurred during the summer season. Kozub limited the snowfalls he investigated to those depositing at least one inch on the ground (Kozub, 1964). Storms

Figure VI



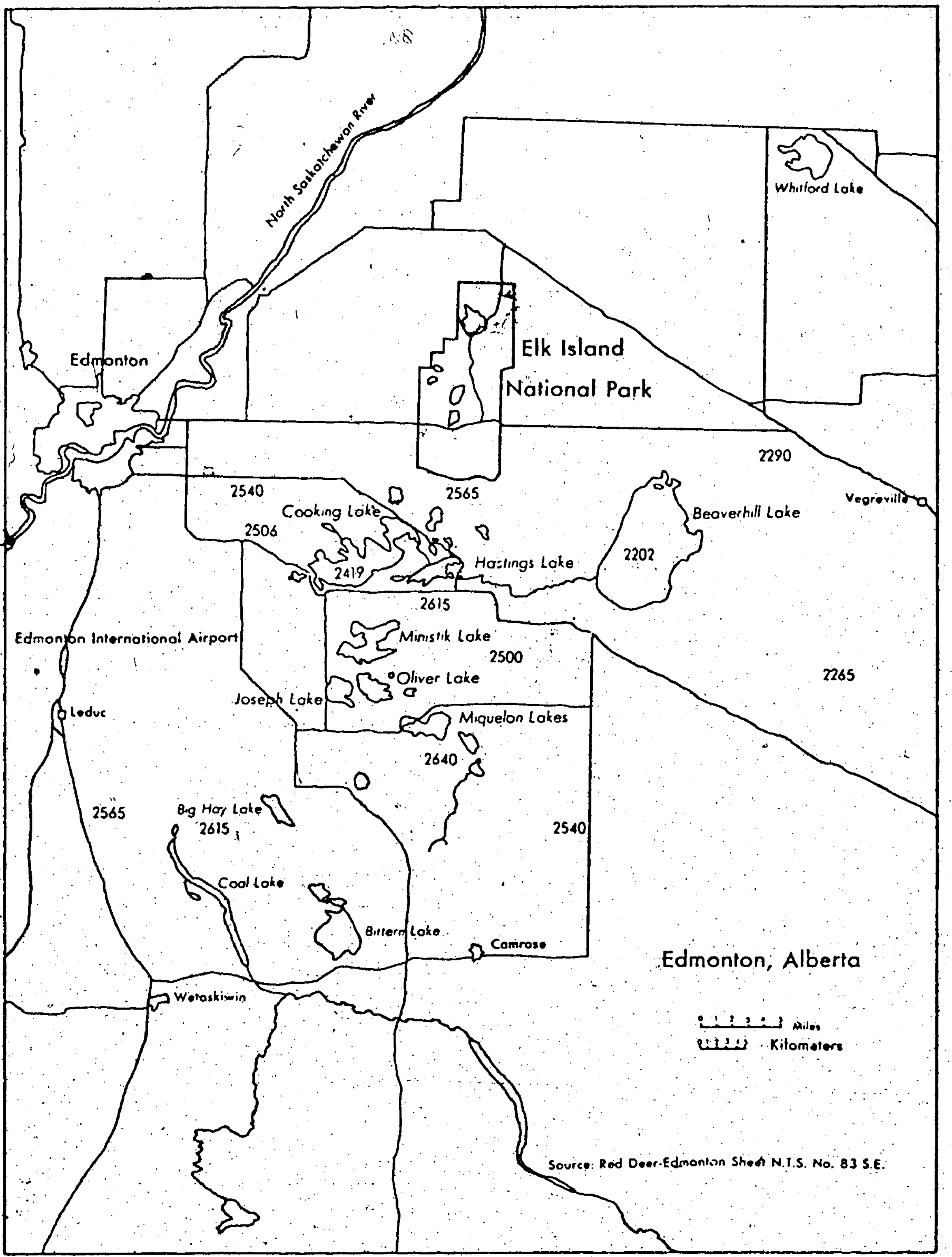
Source: Department of Transport Meteorological Branch originating in the west produced the most frequent heavy rain storms, while heavy rain storms from the north occurred very seldom (Burrows, 1966). Similar patterns were present in the major snow storm tracks. Burrows also found that the storms producing the most complete rain cover over a large area, developed from a cold low in the southwestern United States. Kozub did not indicate one type of storm which produced more complete snow cover than other storms. Refer to the previously indicated sources and to Reinalt and Longley for a more complete background.

Topography

Topography probably plays a smaller role in regional precipitation patterns on the Cooking Lake Moraine than storm tracks. Topography it appears, does play an important role in larger regional patterns.

The Edmonton Industrial Airport lies 2200 feet above sea level, and the Vegreville CDA station is approximately 2084 feet above sea level, a very small variation. Hastings Lake, directly between the two stations, is 2418 feet above sea level, directly in the middle of the Cooking Lake Moraine (Figure VII). The Moraine peaks at approximately 2600 feet, 20 miles (32 kilometres) to the south. Total precipitation patterns from the west to the east side of the Cooking Lake Moraine are probably affected by topographic variations. This may be partially illustrated by comparing the Vegreville CDA station's total annual precipitation record with the other four station's records. Other factors which affect regional variations in precipitation patterns are

Figure VII



Source: Red Deer-Edmonton Sheet N.T.S. No. 83 S.E.

discussed in articles by Laycock and Longley. A method, which may be used to indicate the effects of regional variations in snow depth and water content patterns, on the Cooking Lake Moraine and surrounding area is presented in Chapter IV.

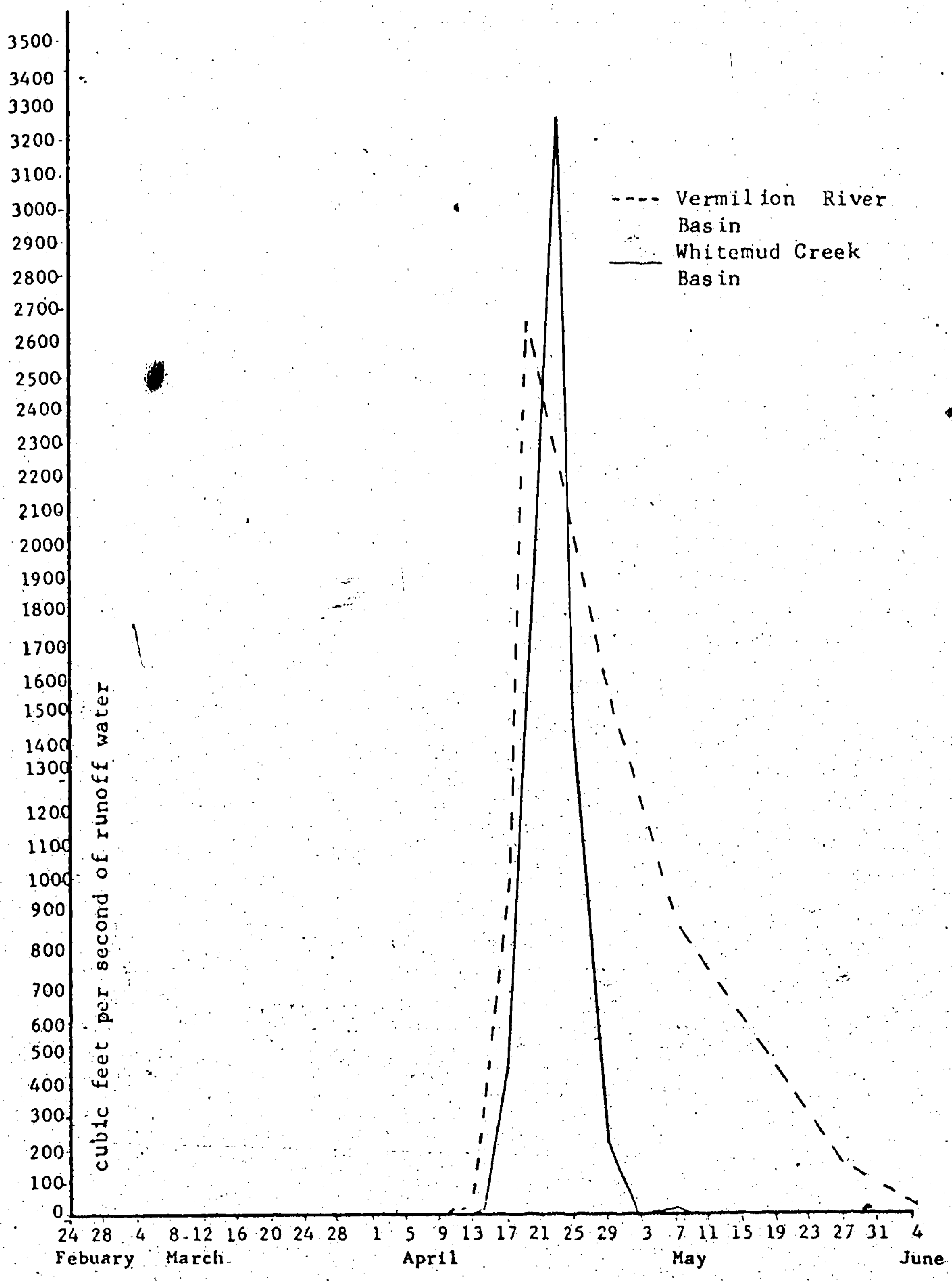
Topographical variations play an important role in the duration of snowmelt runoff. The daily discharge data illustrate this, in hydrograph form, and they [illegible]lustrate the significance of snowmelt runoff as compared to [illegible] for the Whitemud Creek near Edmonton, and the Vermil[illegible] Vegreville (Figure VIII).

The Whitemud Creek [illegible] encompasses 142 square miles (367,8 square kilometres) of bevelled till plain with lacustrine deposits in the north. The Vermilion River Basin (376 square miles or 973.8 square kilometres) is composed of much the same type of deposits with many more broad shallow depressions.

It is apparent from the hydrograph that the Whitemud Creek has a much higher flow than that of the Vermilion River. The Whitemud Basin is a smaller system, which experienced a flashy runoff period after storage capacities had been recharged. The Vermilion River Basin experienced a similar peak flow, but due to the greater size of the basin and more depression storage the flow is extended over a longer period. The Cooking Lake Moraine (approximately 700 square miles or 1813 square kilometres) has approximately two or three times as much depression storage as the Vermilion River Basin (hummocky moraine versus a ground moraine). Heavy tree cover and lack of a major creek or river system to drain the moraine impedes snowmelt runoff.

Figure VIII

Hydrograph for the Whitemud Creek and the Vermilion River Basins



It is possible to estimate the snowmelt runoff period as beginning a week later and continuing as much as a week longer than in either of the two smaller basins. Most of the snowmelt on the Cooking Lake Moraine, after soil moisture storage capacities are recharged, is left to be evaporated from ponds and land surfaces.

Wind

The third factor which probably affects variations in total precipitation is wind direction. The prevailing monthly wind directions for January-April 1975, at the Edmonton International Airport, were: January West North West, February South, March East South East, and April South East (Environment Canada, 1975).

Predominant winds, to some extent, do affect the localized snowfall concentration and distribution patterns on the Cooking Lake Moraine by inducing drifting. Although, the majority of the drifting probably takes place from more localized winds. These winds are probably altered by topography and vegetative cover, thus causing a variety of snow drift patterns to occur on the moraine. This can be shown by reviewing a density sliced LANDSAT I Image. Density slicing accentuates pattern differentiation patterns on the Cooking Lake Moraine (Plate 5).

Major as well as minor drifting patterns can be detected on Plate 5. Note the following: the light gold areas, predominantly along the east-southeast borders of the lakes, represent areas of major build-up; the light blue on the lakes have shallow wind swept

Legend For Plate 5

Localized Drifting Patterns Indicated on a Density Sliced Band 5 LANDSAT I Image of the Cooking Lake Moraine.

1 - cloud cover (blue)

2 - minor snow build-ups (gold)

3 - dense tree cover (black)

4 - major snow build-ups (bright gold)

5 - major snow build-ups at the forests edge (green)

6 - very dense tree cover (red)

Miles 0 5

Kilometres 0 5

Plate 5

Plate 5

snow cover; the medium gold density levels are minor build-ups of drifted snow; the black and red areas indicate thick tree cover (red the thickest); and the green, which borders much of the black areas, shows major snow build-ups on the edge of and in the first few yards of the forest cover. All of the above snowfall concentration and distribution patterns are discussed in Chapter IV.

Chapter IV

MAPPING OF SNOW CONCENTRATION AND DISTRIBUTION PATTERNS WITH LANDSAT I IMAGERY

Four methods of mapping snow patterns with LANDSAT I imagery are discussed in this chapter. The first method involved the use of a black and white (scale of 1:1,000,000) band 7, LANDSAT I print combined with Levels I and II of Andersons' Land Use Classification System. The remaining three methods involved the use of Andersons' Level II categories, Thornthwaites' soil moisture storage levels, and a zoom transfer scope. The enhancement techniques used were: enlargement, density slicing, and tri-color projection. These procedures and conclusions based upon their use are discussed under five subheadings:

Scale 1:1,000,000 LANDSAT I Imagery
Scale 1:250,000 LANDSAT I Imagery
Density Sliced LANDSAT I Imagery
Tri-Color Projected LANDSAT I Imagery
Water Balance Relationships and LANDSAT I Imagery

The April 10, 1975, LANDSAT I imagery was not available, therefore, April 10, 1975, snow depth and water content data were used in conjunction with January 10, 1975, imagery. The reasons for this substitution are discussed in Chapter V under the subheading "Problems

Encountered During the Study".

Scale 1:1,000,000 LANDSAT I Imagery

The standard form for LANDSAT I Imagery is black and white positive prints at a scale of approximately 1:1,000,000. In this study black and white positive transparencies at an approximate scale of 1:1,000,000 were used for interpretation purposes. For illustrative purposes LANDSAT I Imagery, such as Plate 6, were presented in the form of black and white prints which were made from the positive transparencies at same scale. The dark areas surrounding the lakes represent heavy deciduous tree cover on Plate 6. Lake boundaries were easily mapped, except on the west side of Beaverhill Lake and the southwest side of Joseph Lake. In both instances the lake surfaces blended in with the surrounding snowcovered farm land. Tonal variations in the snow cover were almost non-existent at this scale. Light cloud cover was also apparent southwest of Cooking Lake.

The land use patterns outlined on the first overlay (#1) were classified with Andersons' Level I Classification System (Anderson, 1973). Only three categories were used, 02 - Agricultural land, 04 - Forest Land, and 05 - water (Appendix F). The boundaries for the three categories were drawn without supplemental information (maps and low level photography), as Anderson suggested. Only general land use patterns for the Cooking Lake Moraine could be identified using these categories. Conceivably, Anderson's Level I Categories 03 -

Legend For Overlay 1

Anderson's Level I Land Use Classification

02 Agricultural Land

04 Forest Land

05 Water

Legend For Overlay 2

Anderson's Level II Land Use Classification

01 Cropland and Pasture

02 Lakes

03 Mixed Forest Land

Legend For Plate 6

Andersons' Level I and Level II Land Use Classification
on a January 10, 1975 LANDSAT I Image.
Scale 1:1,000,000

Miles 0 5

Kilometres 0 5

Plate 6

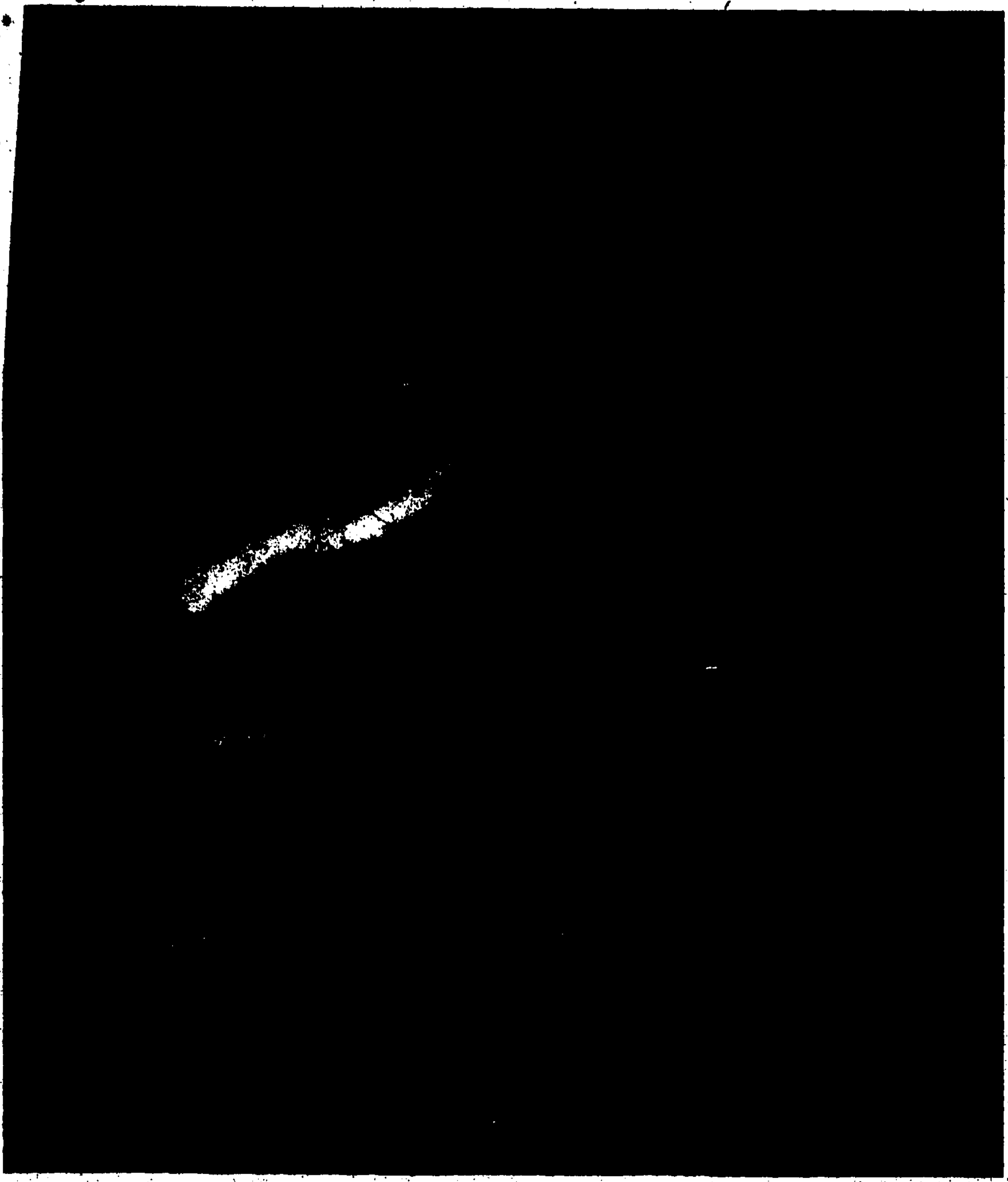
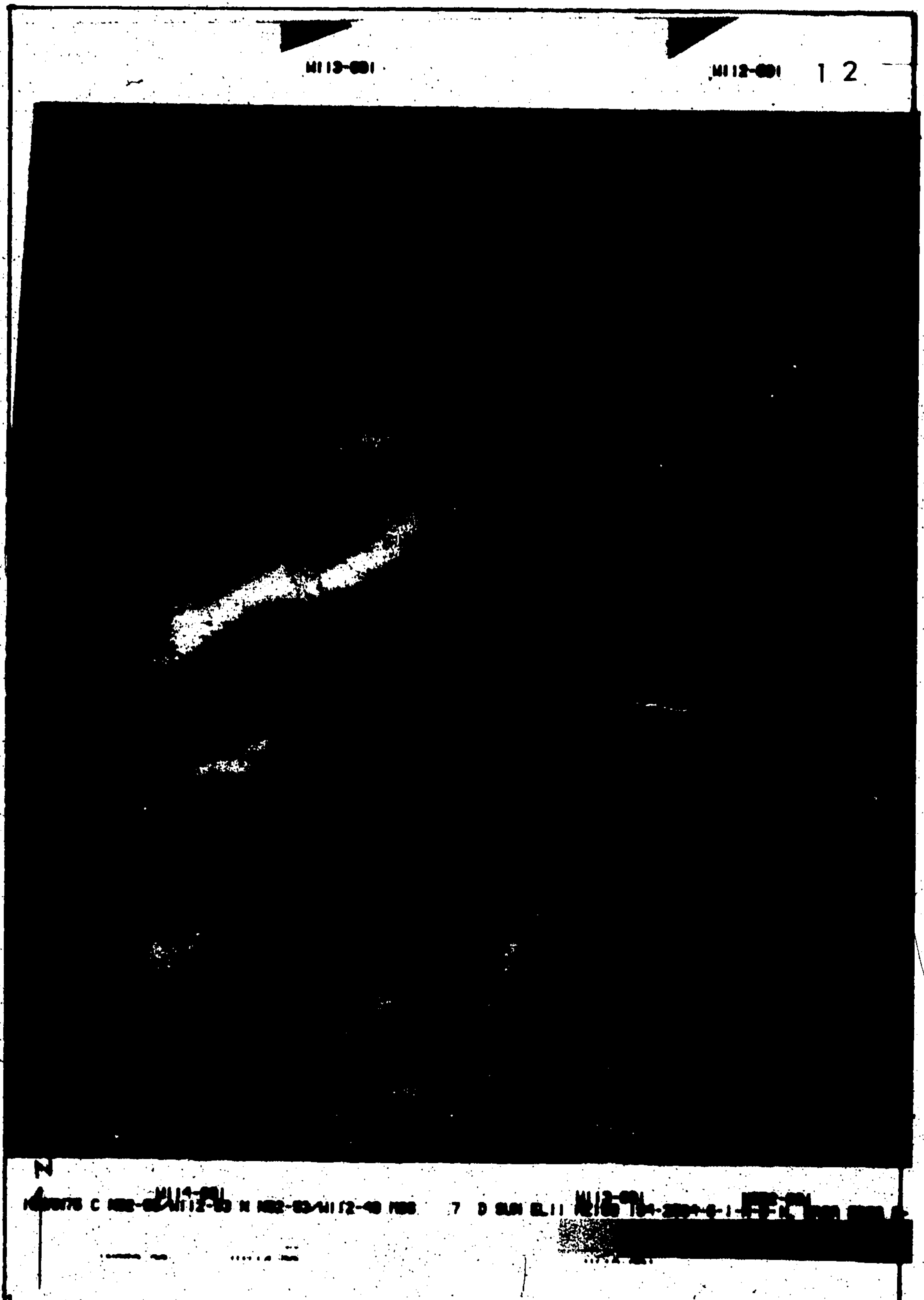


Plate 6



Source EROS Data Center

Scale 1:1,000,000

Rangeland and 06 - Barren Land might have been used. These categories were not readily adaptable to the Cooking Lake Moraine for two reasons; firstly, there were only small scattered areas which represented the categories; and secondly, the sub-categories for each of the Level I categories were more representative of land use variations at lower latitudes.

It was impossible to estimate runoff potential with Level I categories. It was possible, though, to make runoff potential estimates by combining actual ground measurements with classification based on Anderson's Level II categories by associating soil moisture storage capacities with each category. The divisions used were: Agricultural land 02 - 01 = 4 inch (10 cm) capacity, Forest Land 04 - 03 (mixed scrub forest with small ponds and sloughs) = 6 inch (15 cm) capacity, Forest Land 04 - 03 (mixed mature stands with dense crown cover) = 8 inch (20 cm) capacity, and Water 05 - 02 = total lake area. Once the soil moisture storage capacities and land use relationships had been estimated the next step was to calculate the total area encompassed by each storage capacity in the study area. The study area represents the section of the image that was density sliced for intensive study. The next step was to relate snow depth and water content data (taken with a Mt. Rose snow sampler) to each soil moisture storage level. This can be done for larger areas than the one represented by the study area, but once the area exceeds two square inches (12 square cm) distortion on the image occurs. This is not a serious factor when the image is used only for land use classification purpose. If relationships, though, are to be drawn between these images and density sliced images, to determine which areas are encompassed by each density level, serious errors in area percentages could occur. For discussion of image distortion refer to Photogrammetric Engineering and Remote Sensing, May edition 1975, for an article by Wong.

Using this procedure, combined with Thornthwaite water balance tables it was possible to estimate runoff potential. These data were omitted from the discussion because more accurate calculations were obtained using a larger scaled image. This is discussed under the next subheading "Scale 1:250,000 LANDSAT I Imagery".

Scale 1:250,000 LANDSAT I Imagery

The January 10, 1975 LANDSAT I image was enlarged four times (sixteen times in area), from approximately 1:1,000,000 to 1:250,000, to enhance the tonal variations in the study area. This was necessary to decrease error in area percentage calculations for each soil moisture storage capacity. At this scale the resolution was still good with only minor scan lines appearing on Cooking and Hastings Lakes (Plate 7).

The enlargement was made from the same black and white positive transparency (approximate scale 1:1,000,000) as the print described in the previous section. It was necessary first to make a negative of the transparency so that a positive print could then be made.

In this instance the sharper boundary distinctions made it

Legend For Plate 7

Andersons' Level II Land Use Classification

January 10, 1975 LANDSAT I Image

Scale 1:250,000

01 Cropland and Pasture

02 Lakes

03 Mixed Forest Land

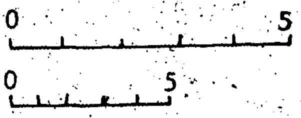
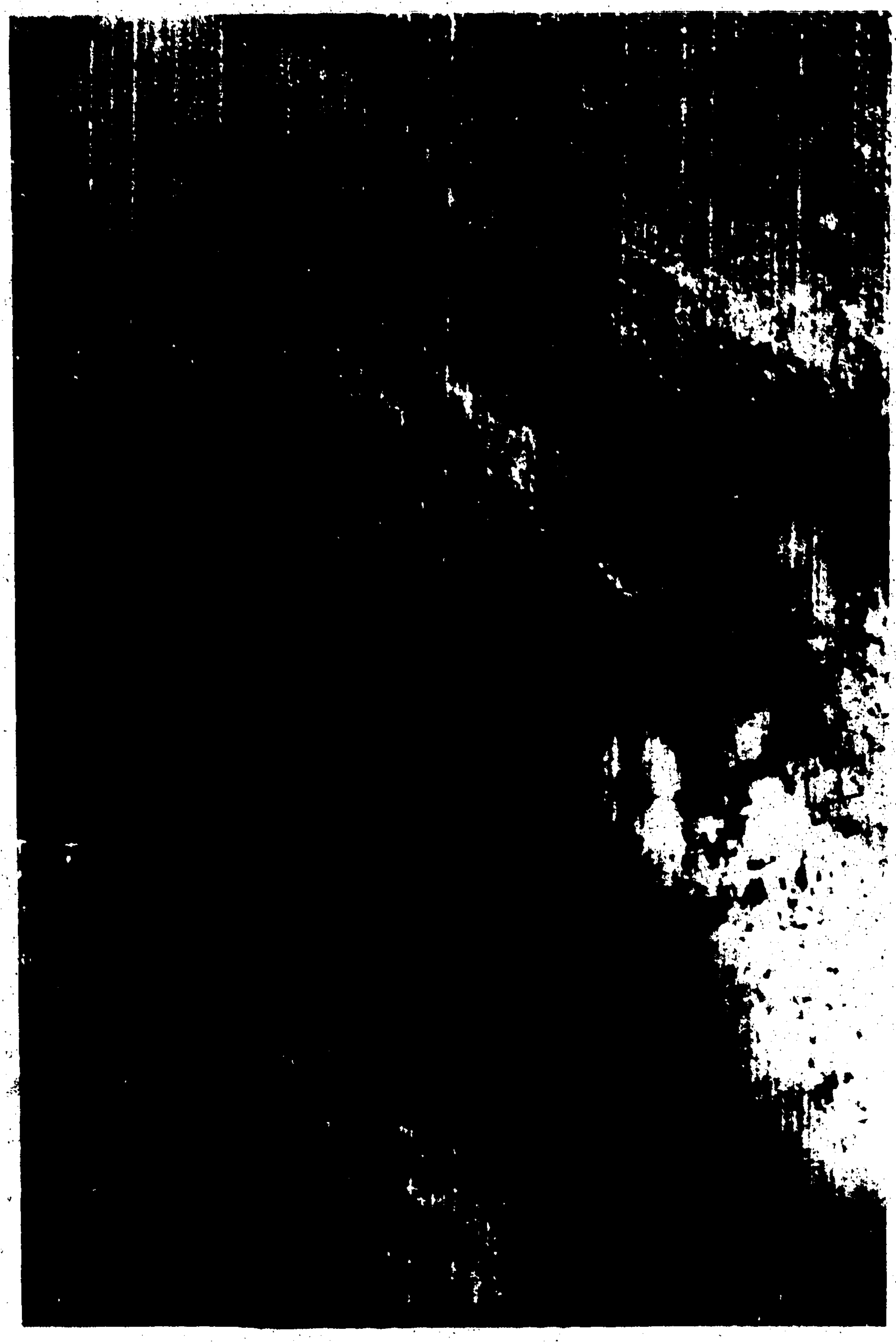
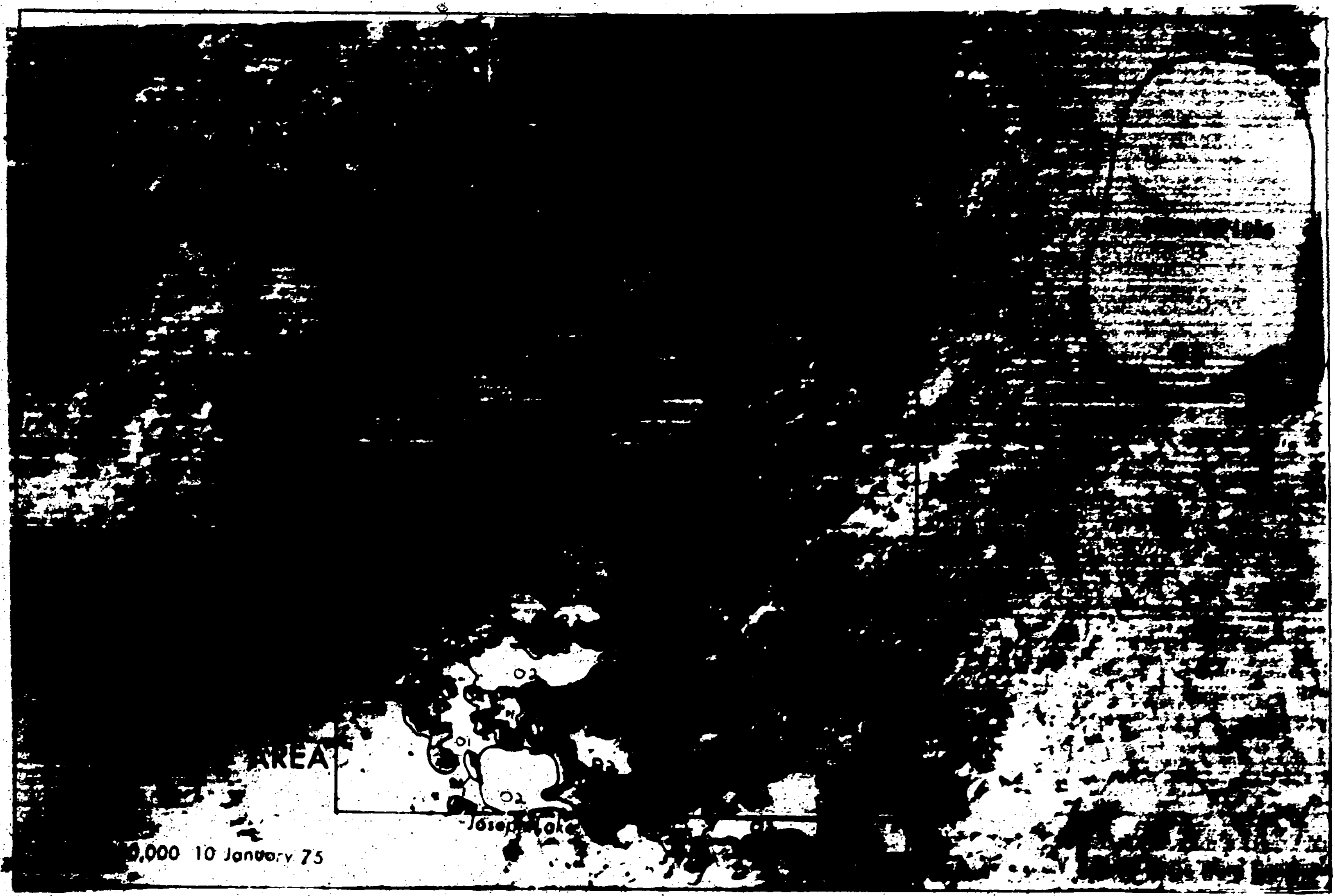


Plate 7




02
01
02
AREA
Joseph Lake
,000 10 January 75

possible to determine finer boundary distinctions for each soil moisture storage capacity. Anderson's Level II categories were again used to relate soil moisture storage capacities to land use patterns. The divisions used were: Agricultural land (crop and pasture lands) 02-01 = 4 inch (10 cm) capacity, Forest land (mixed scrub forest with small ponds and sloughs) 04-03 = 6 inch (15 cm) capacity, Forest land (mixed mature stands with a dense crown cover) 04-03 = 8 inch (20 cm) capacity, and Water 05-02 = total lake area.

By using the procedures, for estimating runoff potential, outlined in the previous section, more reliable percentages were obtained with LANDSAT I imagery at an approximate scale of 1:250,000. Tables showing these results are presented and discussed under the subheading "Water Balance and LANDSAT I Imager" later in this chapter.

One major problem that enlargement alone could not overcome was detection of the lack of uniformity in the snow cover. Consequently, it was impossible to detect the extent of snow drifting patterns in the study area or to make allowances for the drifting patterns in the Thornthwaite water balance tables. A method for overcoming this obstacle is discussed under the next subheading "Density Sliced LANDSAT I Imagery".

Density Sliced LANDSAT I Imagery

The density slicer used in this study was a Spectral Data Corporation model with a 32 false color level capability. The density slicer is located at the Alberta Remote Sensing Centre, Edmonton, Alberta. The major advantages with the density slicer is opportunity to observe the image being split (step by step) into as many as 32 false color levels.

After testing several various false color combinations, of the 32 density levels, the settings used were: 1-16, 28, and 29. These settings gave the best correlation between the density levels and the actual snow patterns on the Cooking Lake Moraine. These settings were employed throughout the study on all bands of LANDSAT I imagery.

Where close inspection of standard LANDSAT I images did not show snow drifting patterns, density slicing did (Plates 8 and 9). For example the light blue area (#1) on Plate 8, band 5, represents snow which has drifted and has a high reflectivity (leaving a smooth, crystalized surface) in the visible portion of the electromagnetic spectrum. The high reflectivity was illustrated by the cloud cover, in the lower left hand corner of the photograph, being recorded at the same density level as the snow cover. In contrast, Plate 9, band 7, showed several density variations within the same clouded area. Some of the variation was caused by photographic processing, rather than actual surface variations. Refer to the legend of each Plate for a description of the false color density levels, which are listed numerically on each photograph.

To better envisage the density level variations the density slicer was adjusted to enlarge the section of the image representing the main study area (Plate 10 and 11). On Plate 10 for example, the various

Legend For Plate 8

Regional Snow Pattern Variations Using a
Density Sliced Band 5 LANDSAT I Image
of January 10, 1975

1 - Flat wind swept areas with shallow snow cover

2 - Cloud cover

3 - Areas where drifting is partially hampered by wind breaks

4 - Accumulated snow cover from drifting

5 - Forest edges and small openings where snow accumulated

6 - Inner dense forest cover

Miles 0 5

Kilometres 0 5

Plate 8

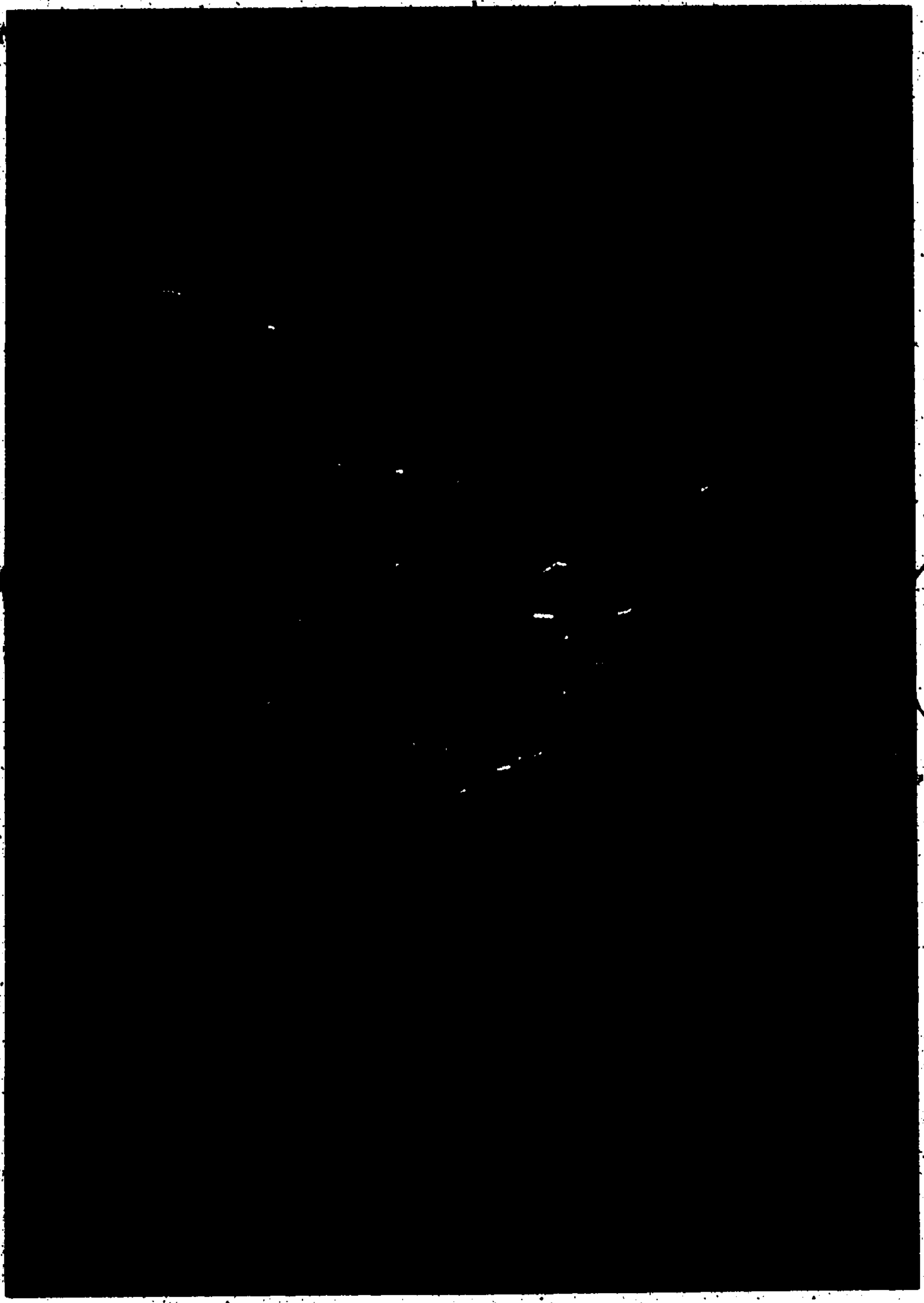
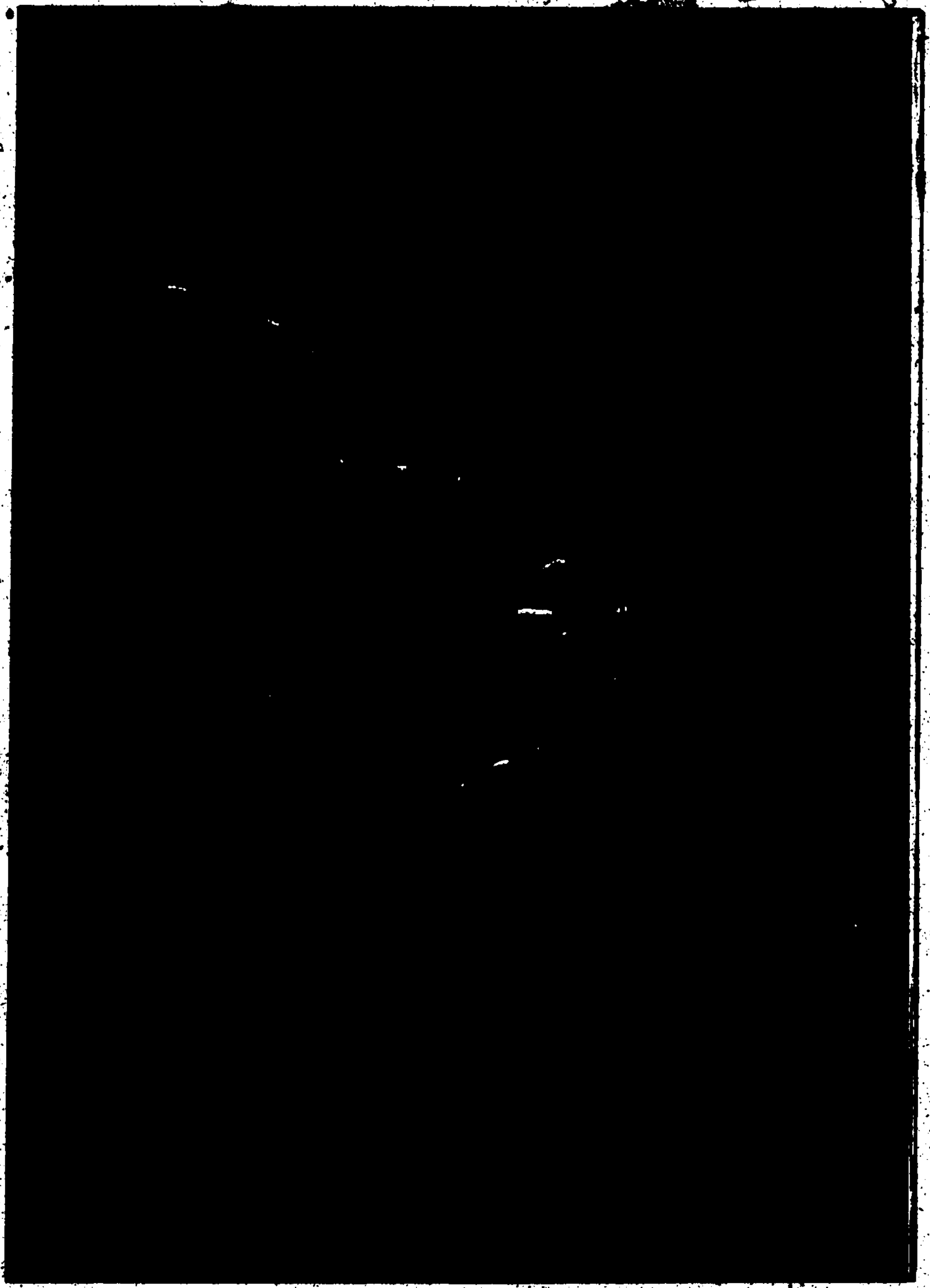


Plate 8



Legend for Plate 9

Regional Snow Pattern Variations Using a
Density Sliced Band 7 LANDSAT I Image
of January 10, 1975

1 - Flat wind swept areas with shallow snow cover
2 - Cloud cover
3 - Drifting development induced by wind breaks
4 - Accumulated snow cover from drifting
5 - Forest edges and small openings where snow has accumulated
6 - Inner forest cover
7 - Haze or cloud cover of sufficient density to impede reflectance

Miles 0 5

Kilometres 0 5

Plate 9

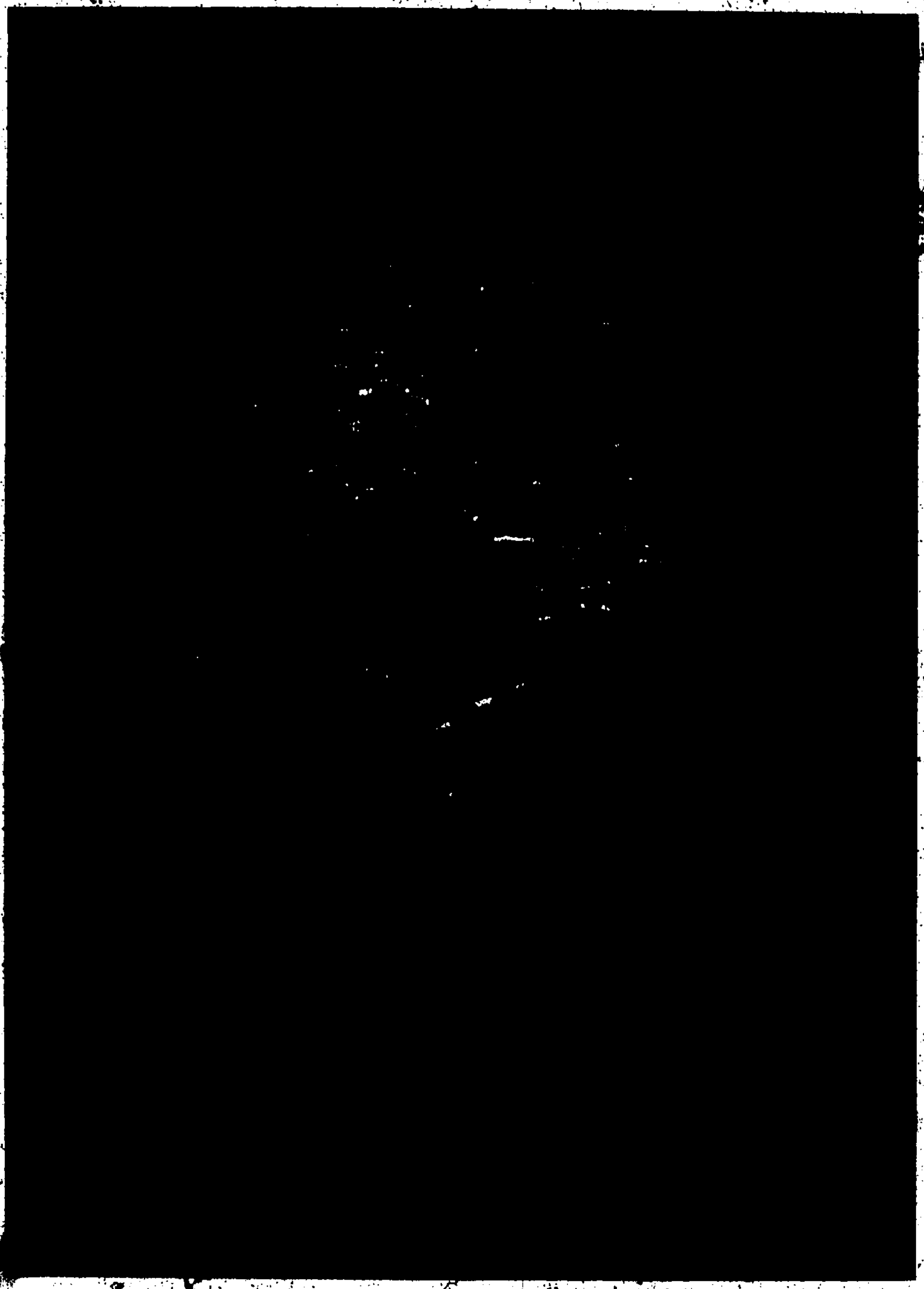
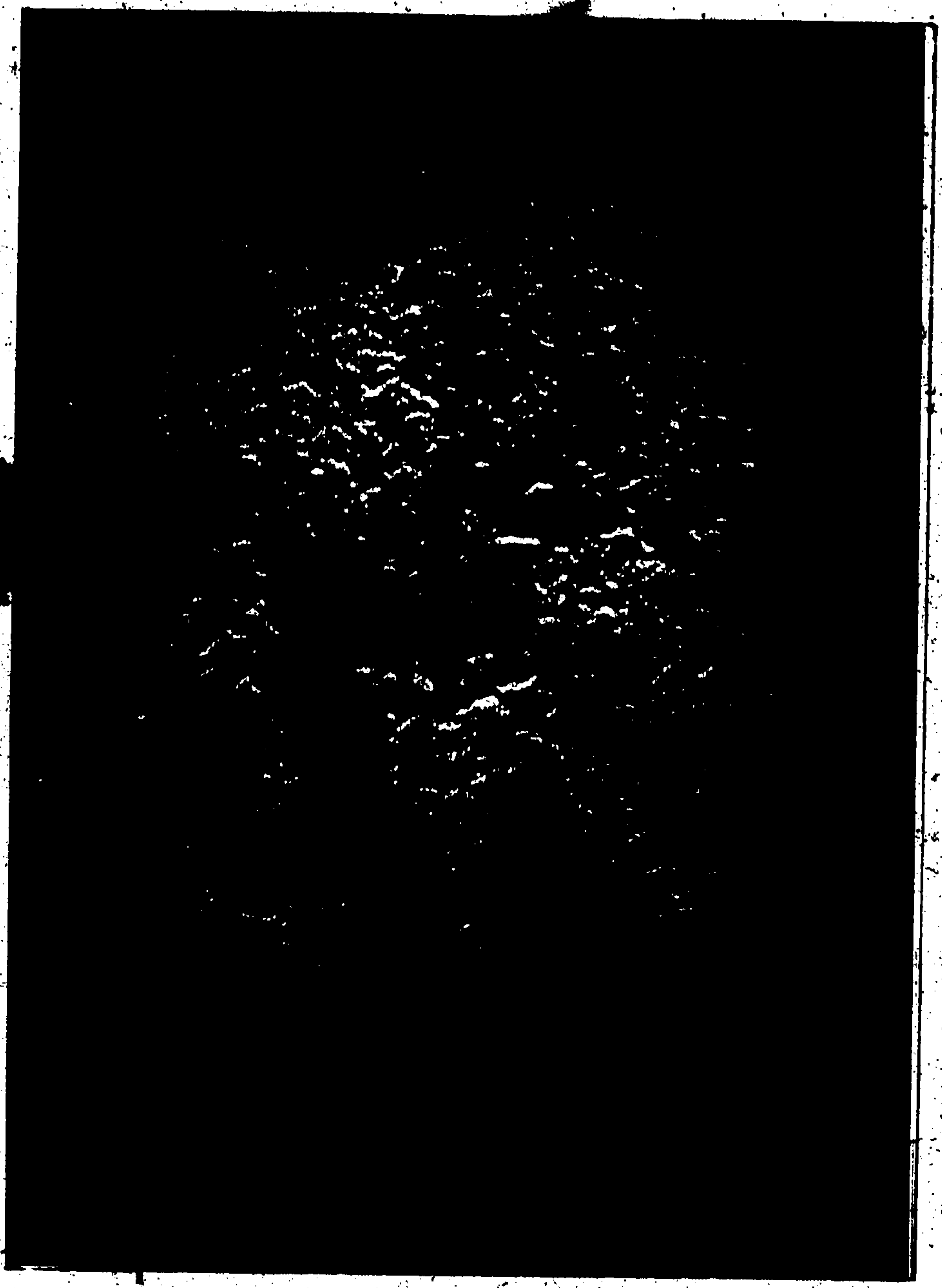


Plate [illegible]



Legend For Overlay 1

Soil Moisture Storage Capacity Levels

4 - Four inch soil moisture storage capacity

6 - Six inch soil moisture storage capacity

8 - Eight inch soil moisture storage capacity

(Based on text in subheading "Scale 1:250,000 LANDSAT I Imagery")

Legend For Plate 10

Localized Snow Pattern Variations Using a
Density Sliced Band [illegible] I Image
of January 10, 1975

1 - Flat wind swept areas with shallow snow cover

2 - Drifting partially hampered by wind breaks

3 - Forest edges and small openings where snow has accumulated

4 - Inner forest cover

5 - Fields where drifting was at a minimum due to wind breaks

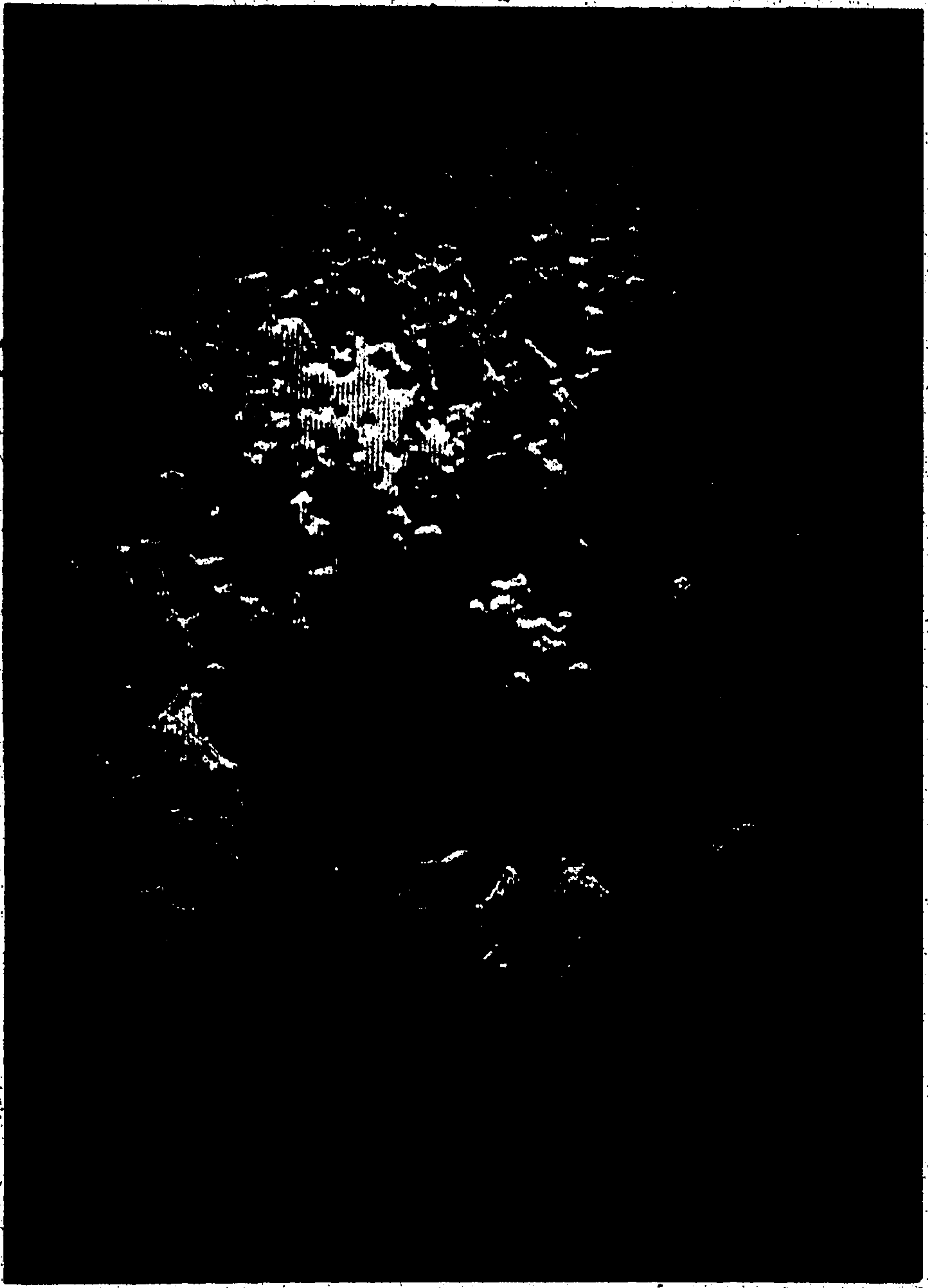
6 - Accumulated snow from drifting

7 - Haze or cloud cover existed of sufficient density to impede reflectance

Miles 0 ⊢⊢⊢⊢⊢⊣ 5

Kilometres 0 ⊢⊢⊢⊢⊢⊣ 5

Plate 10



12

Legend for Plate 11

Localized Snow Patterns Using a
Density Sliced Band 7 LANDSAT I Image
of January 10, 1975

1 - Flat wind swept areas with shallow snow cover
2 - Flat areas where drifting was hampered by wind breaks
3 - Forest edges and small openings where snow has accumulated
4 - Inner forest cover
5 - Fields where drifting was at a minimum due to lack of wind breaks
6 - Accumulated snow from drifting
7 - Haze or cloud cover of sufficient density to impede reflectance

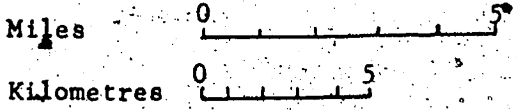


Plate 11

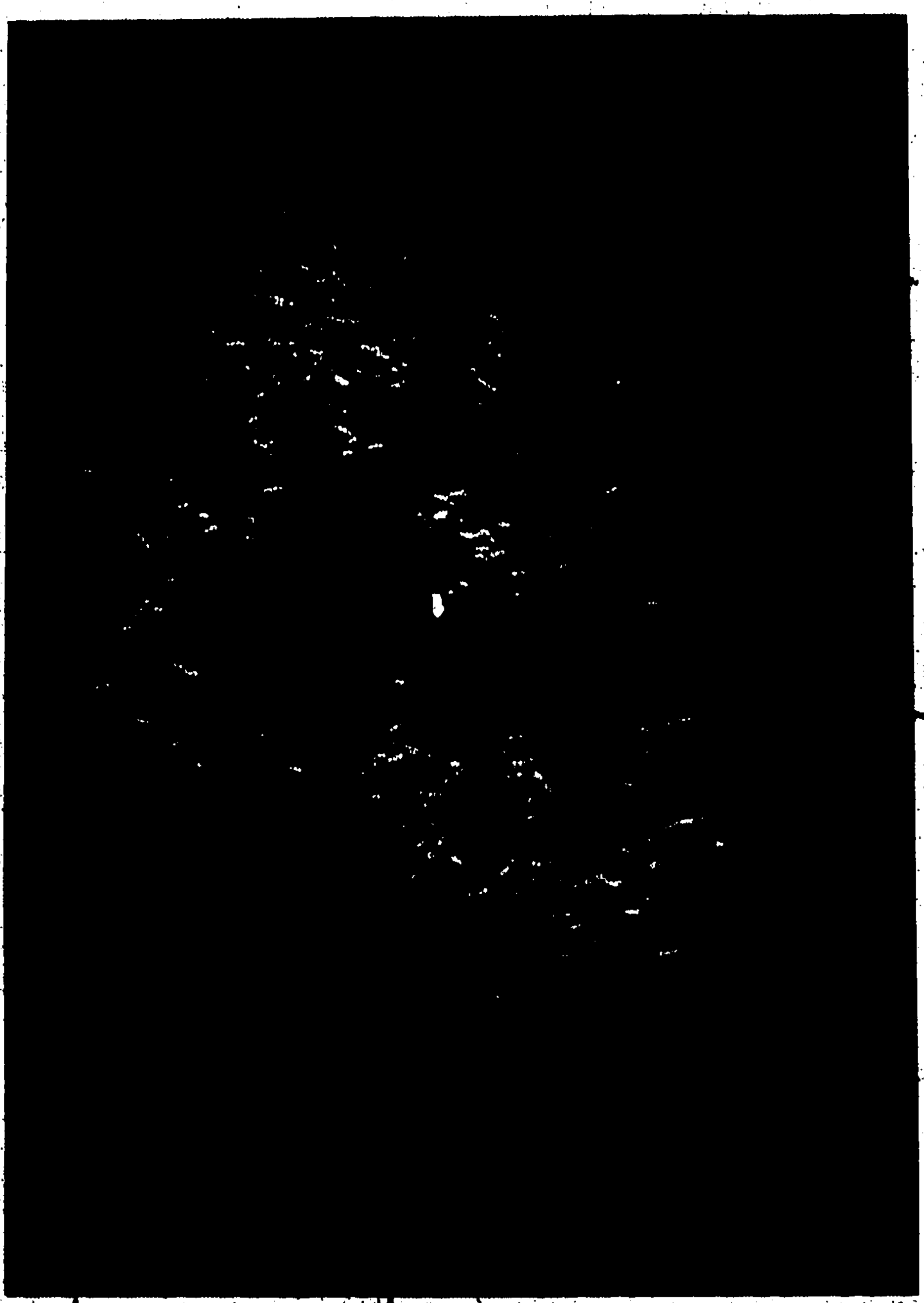


Plate 11

drifting patterns on Cooking Lake can be easily separated. The blue area represents shallow wind swept snow, while the medium gold and light gold colors represent areas where the snow has accumulated (light gold represents the largest accumulations). The separation of drifting patterns were not as evident on Plate 11 as they were on Plate 10. For example, density level variations were more distinct on Plate 10 (band 5), than they were on Plate 11 (band 7). This was especially true of the density levels on Cooking Lake. Further comparisons indicated that Plate 10, band 5, illustrated the best density distinctions, as they in turn related to the actual snow patterns observed during field work. One reason for the contrasts in Plate 10 and Plate 11 was the lack of open water or melting snow which would increase the tonal response in the near infrared (band 7). On January 10, 1975, the temperature was -24°F (-31°C) at the Edmonton International Airport, consequently, no melting was taking place. Dominant reflectance occurred in the visible portion of the spectrum (band 5). It should be noted that on January 9, 1975, the average wind speed was 15 miles per hour from the WNW at the Edmonton International Airport, causing fresh drifting in the study area.

The approximate lake boundaries and snow sampling sites were outlined on Plates 10 and 11. Distinction of exact lake boundaries and snow sampling site locations was not possible because of two complications; the first complication resulted from the curvature of the TV monitor from which the 35 mm photographs were taken. The second complication resulted from the overlapping of similar density levels on the photograph, which in some cases made separate distinction of boundaries impossible (for example, it would be difficult to distinguish a lake surface from a snow covered field if they were side by side).

Using actual field measurements taken with a Mt. Rose snow sampler on April 10, 1975, it was possible to relate these readings to the false color density levels, Plate 10 was used as an example.

The next step was to make an overlay from the January 10, 1975, black and white LANDSAT I positive transparency (band 5), which could be overlaid on Plate 10 (overlay 1). The overlay was constructed using a zoom transfer scope, which enabled the author to make the necessary boundary adjustments. The purpose of this overlay was to show the varying soil moisture capacities in relation to the seven density levels. A grid system was used to determine what areas were encompassed by each density level. The area distinctions were made to the nearest .6 of a square mile (1.6 square kilometres).

These percentage measurements were not made with the instrumentation available on the density slicer for two reasons: Firstly, the percentage readings represent the total area of that density being displayed on the TV monitor. The density levels cannot be broken down to show just the densities representing lake surfaces as opposed to those representing farm land. Secondly, distortion occur l along the borders of the image as it was displayed on the TV monitor. Distortion was caused by small cracks in the screening material, which allowed light to pass through and shadows to occur around the edges. Due to shadow interference on the sides of the photographs it was necessary to reduce the size of the study area from 350 square miles to

224 square miles (906.5 square kilometres to 580 square kilometres). The area is outlined and labeled "Study Area" on Plates VI and VII.

Because each band of LANDSAT I imagery depicts a different portion of the electromagnetic spectrum (.4 to 1.1 microns) slightly different tonal patterns appeared on each image. By overlaying and registering each band of imagery the complete tonal pattern for an area could be observed. A method of accomplishing this is discussed under the next subheading "Tri-Color Projected LANDSAT I Imagery".

Tri-Color Projected LANDSAT I Imagery

"The Additive Color Viewer provides a simple and effective means of analyzing and evaluating multispectral imagery" (I^2S, 1974, Data Sheet 9). The additive color viewer used in this study was a Spectral Data Corporation model (located at the Federal Forestry Building, Edmonton, Alberta). This was the only viewer available for use at the time this study was conducted. In the author's opinion the I^2S Corporation's additive color viewer is superior to the Spectral Data viewer in every aspect and would have contributed more to the study.

April 15, 1974, imagery in 70mm form, was used to illustrate a complication encountered with deep snow. The major complication was the lack of land use patterns that could be detected visually. Only band 4 and band 5 were available for the April 15, 1974 scene.

On Plate 12 band 4 was falsely colored green and band 5 was falsely colored red; both were set on maximum light intensity. The fuzziness at the right and bottom of the photographs was a direct result

Legend for Plate 12

Regional Snow and Land Use Pattern Variations Using
A Tri-Color Projected Image Combining Bands 4 and 5

Band 4 false colored green - maximum light intensity
Band 5 false colored red - maximum light intensity

Miles 0 5
Kilometres 0 5

Plate 12

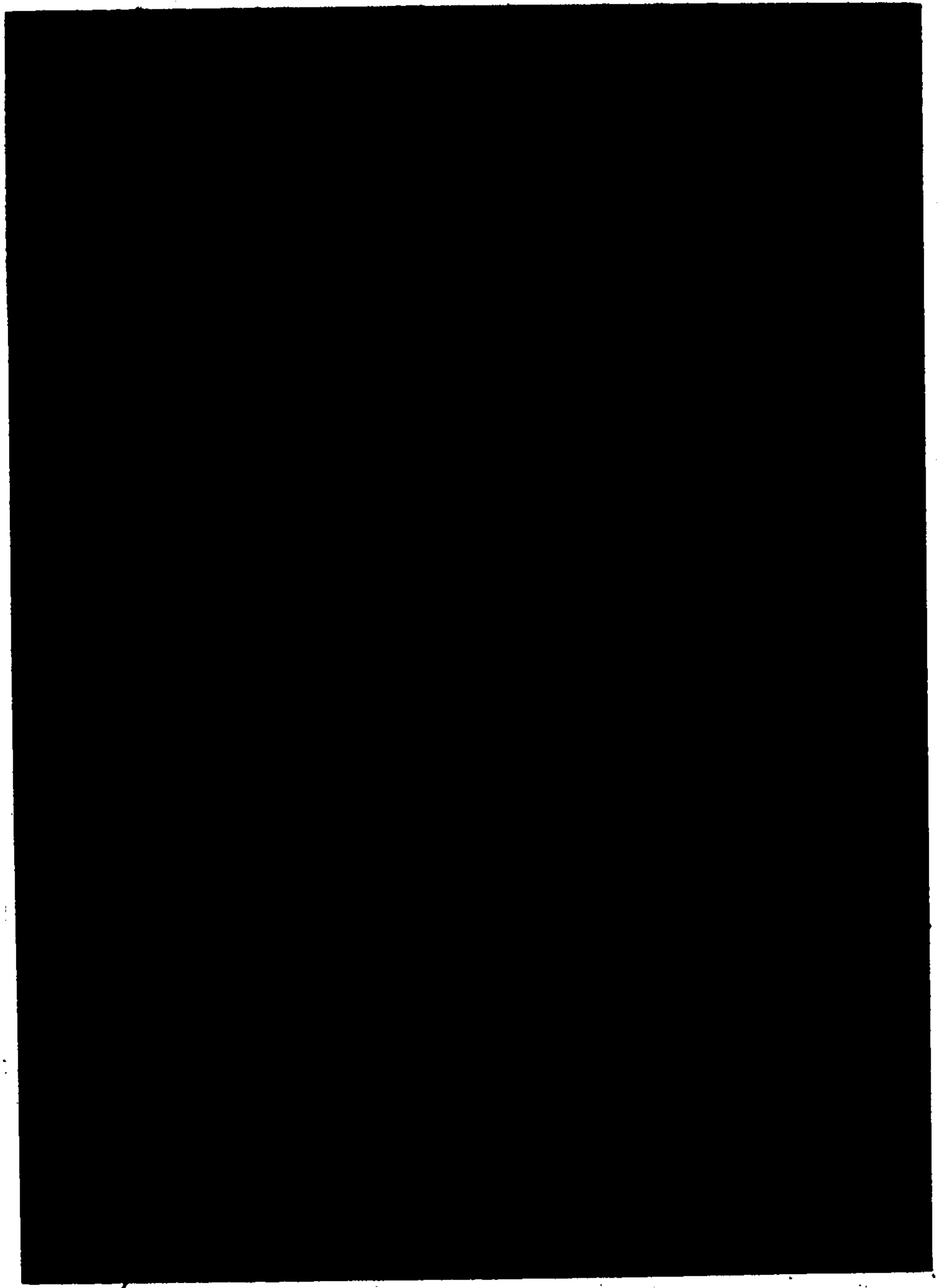
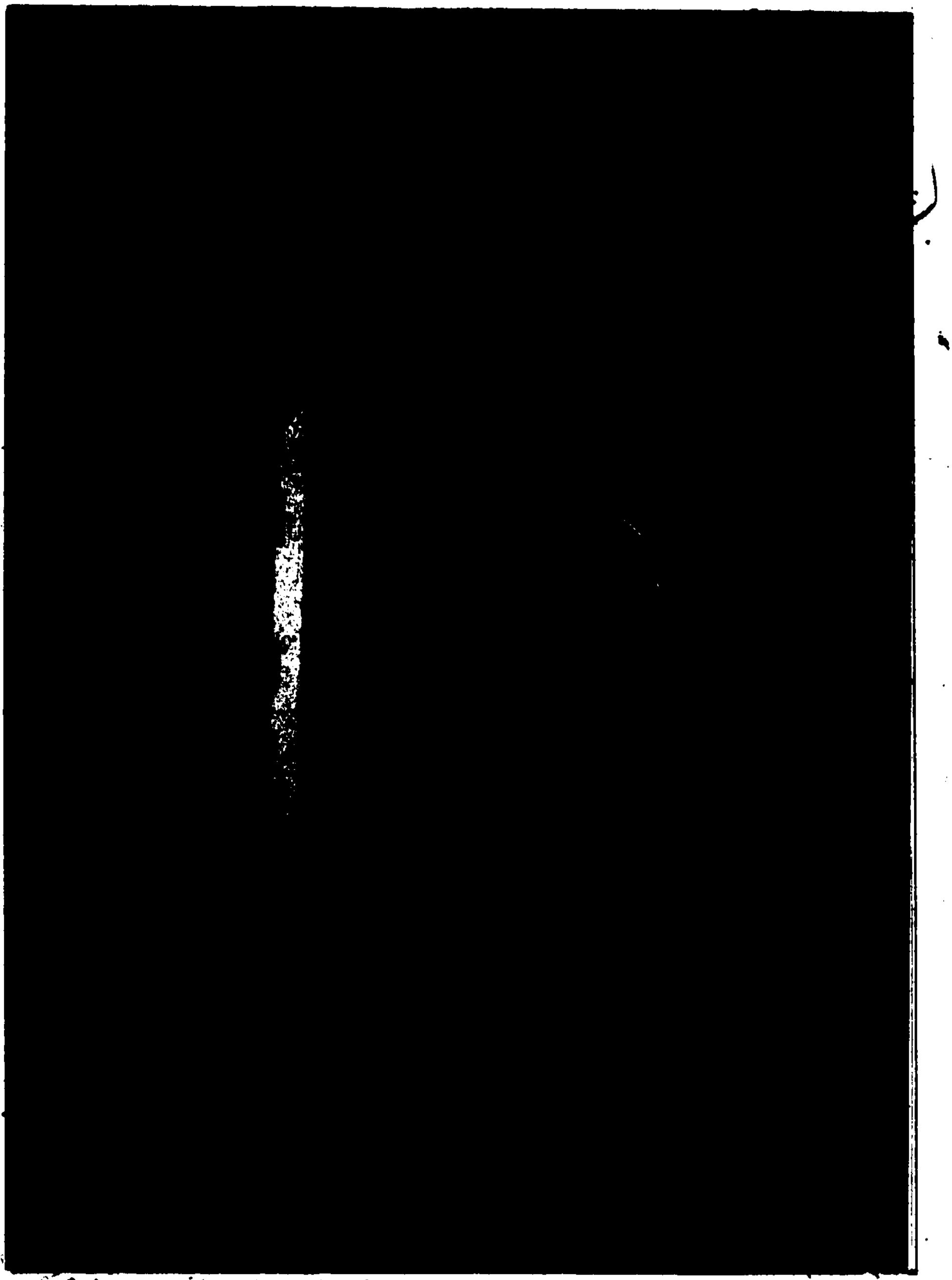


Plate 12



Legend for Plate 13

Regional Snow and Land Use Pattern Variations Using A Tri-Color Projected Image Combining Bands 4 and 5

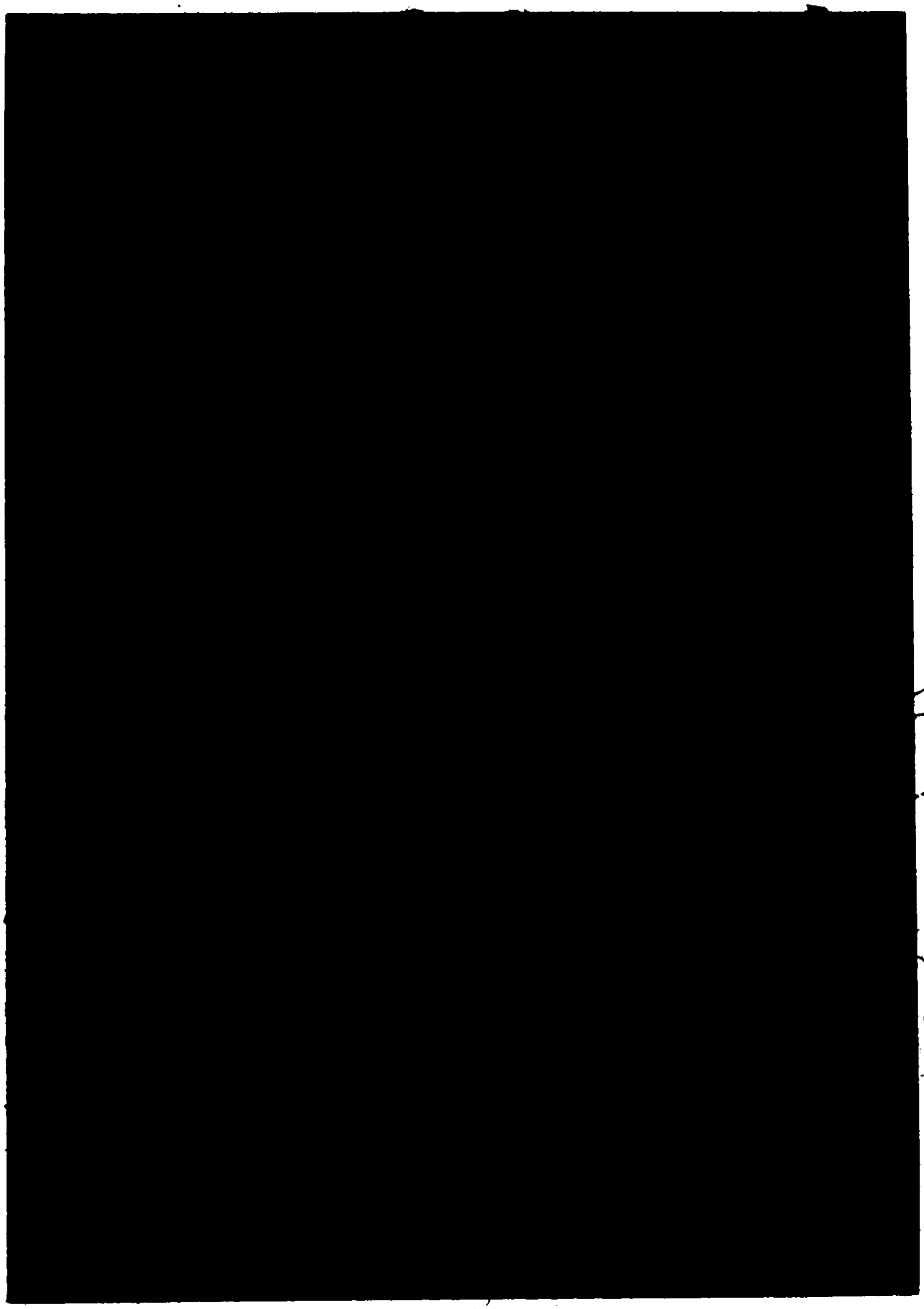
Band 4 false colored green - half light intensity

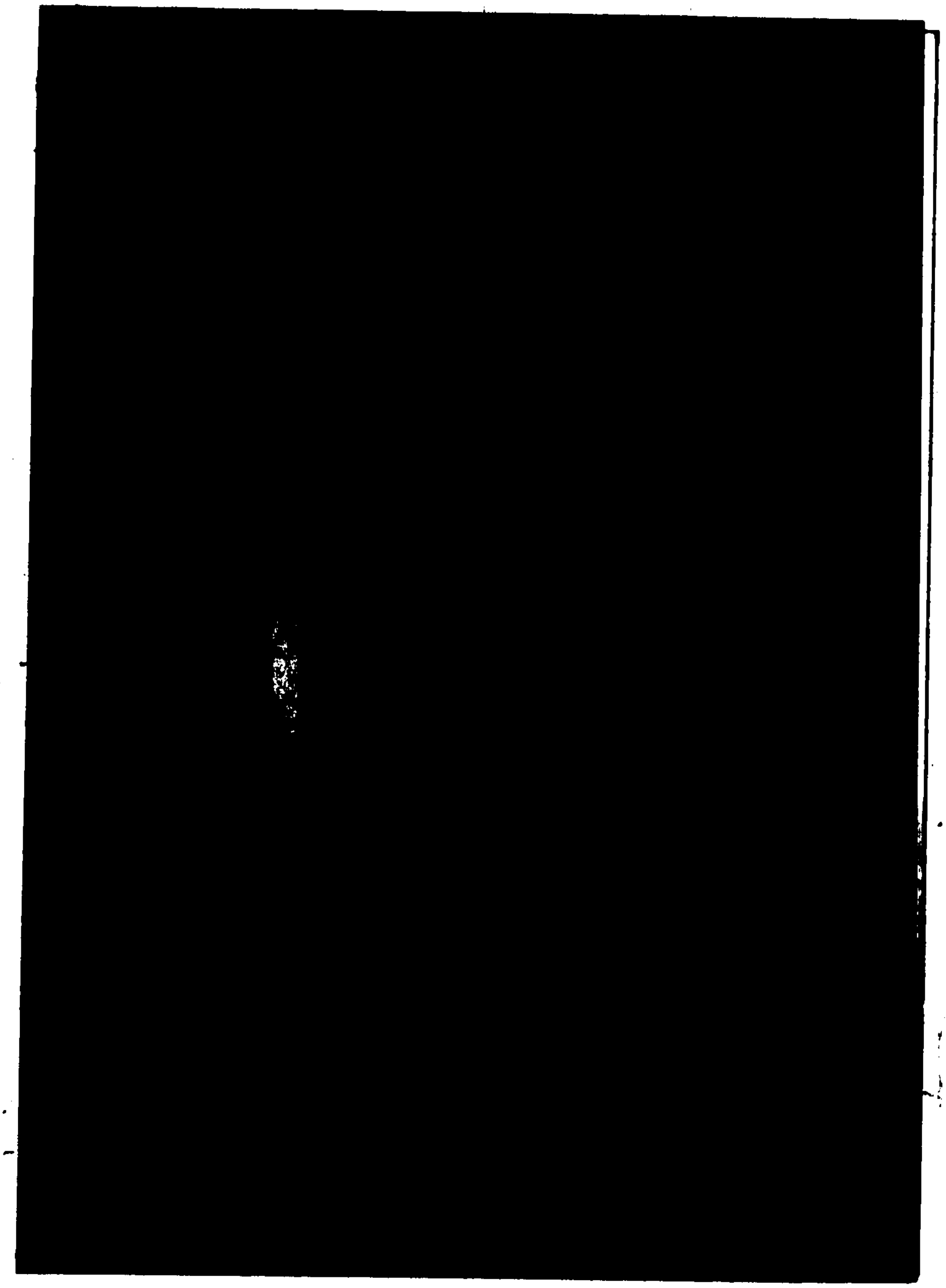
Band 5 false colored red - maximum light intensity

Miles 0 5

Kilometres 0 5

Plate 13





of a lack of fine adjustment instrumentation on the model of viewer used.

Urban and forest patterns were enhanced with these settings (outlined on Plate 12 and Plate 13), while lake boundaries and tonal boundaries for snow cover were almost non-existent in the study area, making it impossible to extract pertinent information concerning snow patterns with those settings. The author found that snow exceeding 30 inches tended to cause a washing out of tonal response in all forms of LANDSAT I imagery used except when enhanced by density slicing.

Plate 13 represents the same bands as before with a different filter scheme. Band 4 was filtered green and set on half light intensity, while band 5 was filtered blue and set on maximum light intensity. Tonal boundaries were improved over those in Plate 12 (note forest patterns) allowing more information about land use patterns to be extracted. Even so, the usefulness of Plate 12 and Plate 13 in this snow study was questionable.

The problem of deep snow camouflaging land use patterns could have been eliminated with an additive color viewer in which proper registry could be obtained. With proper registry, enlargements could have been obtained to increase the tonal variations in the land use patterns. Density slicing of all of the bands used in the tri-color projections and selecting the band which best depicts the desired variations would be the next step (Plate 14). (Note the reduction in the number of density patterns.) If drifting patterns are constant from one year to the next the blue area would represent the heaviest snow cover.

Legend for Plate 14

Regional Snow Pattern Variations Using
A Density Sliced Band 5 LANDSAT I Image
on April 5, 1975

1 - Deep accumulations of snow

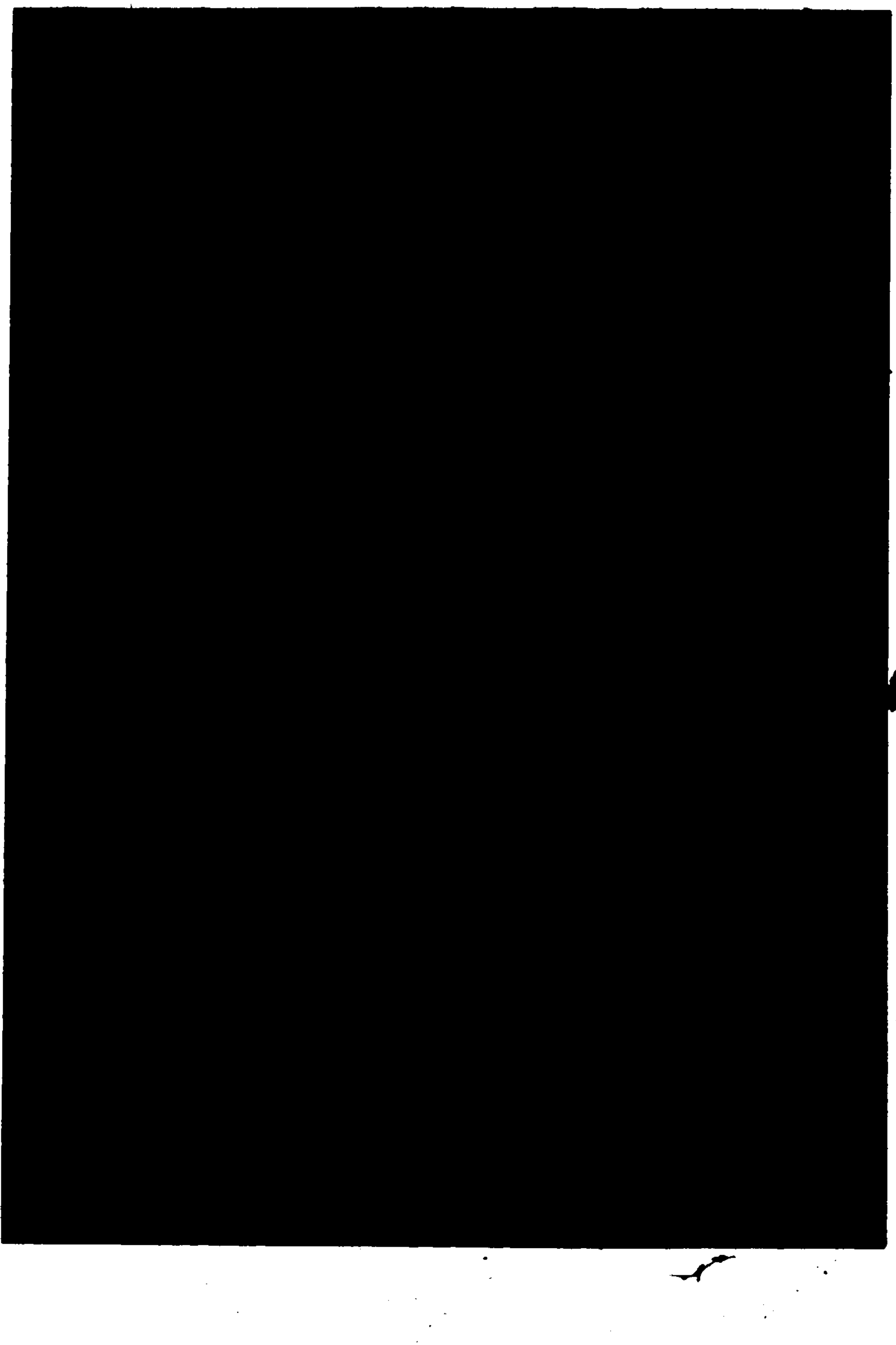
2 - Minor accumulations of snow

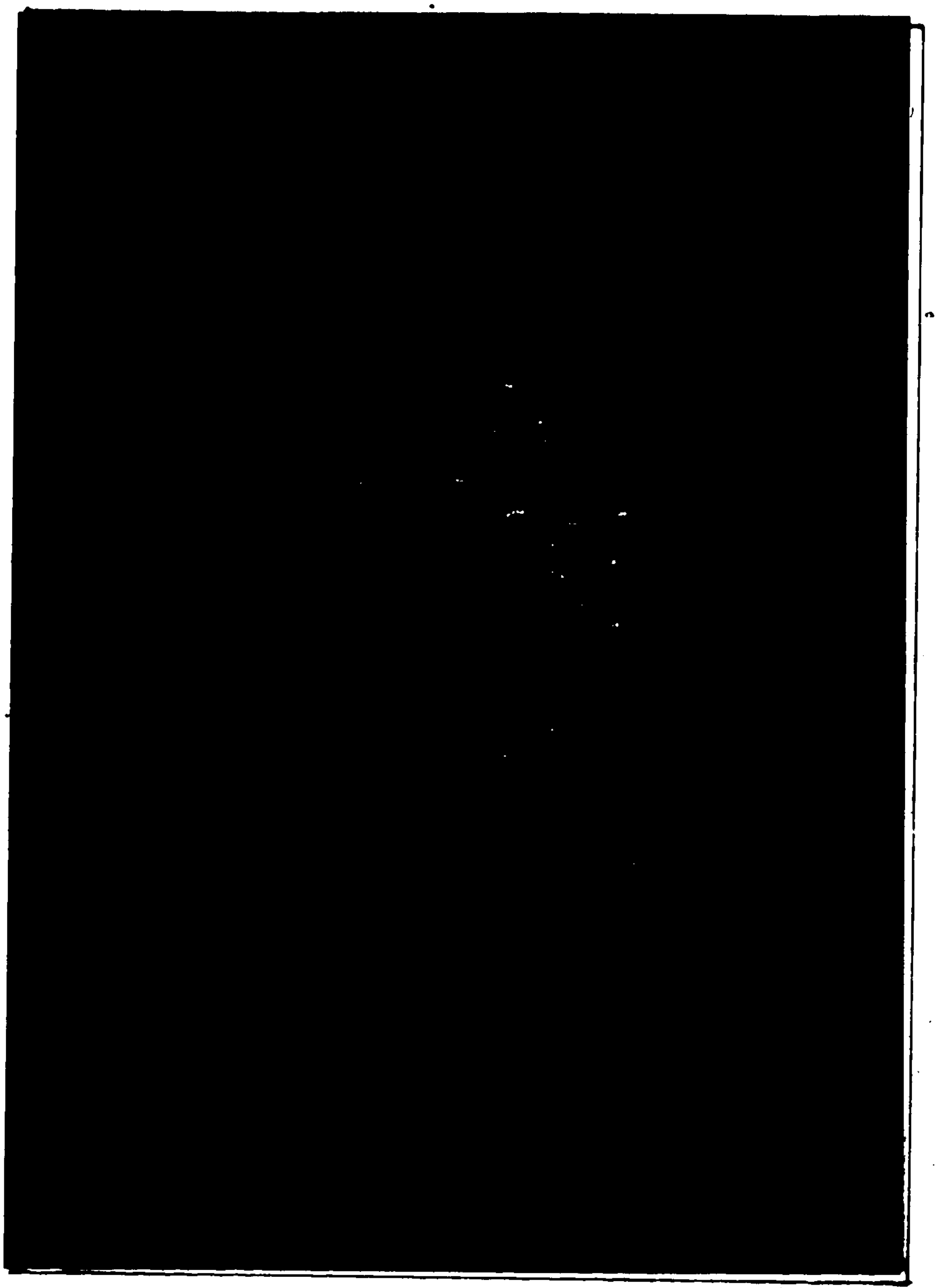
3 - Windswept snow

4 - Dense tree cover

Miles 0 5

Kilometres 0 5





Following the procedures outlined in the previous section, overlays for either land-use patterns or density levels which represented snow cover could have been made using the zoom transfer scope.

By using the viewer in this manner a more accurate relationship could be drawn among land use patterns, storage level patterns, and snow patterns. With the additive color viewer the user has the benefit of all the bands of one image laid one over another, producing better tonal distinctions.

Water Balance Relationships and LANDSAT I Imagery

Comparisons showing the applications of a LANDSAT I image in its standard form (black and white, 1:1,000,000 print) and an image enhanced through density slicing were used to determine water balance patterns on a section of the Cooking Lake Moraine. Black and white LANDSAT I imagery, in its standard form was the basis for all interpretations made in the study area.

Black and White LANDSAT I Imagery in Standard Form

Anderson's Level II Classification categories were used to relate land/use patterns to soil moisture storage capacities for the study area in the following manner: Agricultural land 01 = 4 inch (10 cm) capacities, Forest land 03 (mixed scrub forest with small ponds and sloughs) = 6 inch (15 cm) capacities, Forest land 03 (mixed mature stands with a dense crown cover) = 8 inch (20 cm) capacities, and 02 =

total lake area (Plate VI, overlay 1). Approximately four percent (an estimation based on fieldwork) of the study area would fall into the 2 inch (5 cm) soil moisture storage capacity. It was impossible to detect areas of 2 inch (5 cm) storage level large enough (greater than .3 of a square mile or .8 of a square kilometre, half cell size on the graph) for mapping from the imagery and consequently this category was omitted. Water balance tables (following Thornthwaite procedures) were prepared to establish surplus and deficiency patterns for each storage level (Table 9 or metric Table 9A). The potential soil moisture storage levels (with snowmelt) were below the 4 inch (10 cm), 6 inch (15 cm), and 8 inch (20 cm) storage capacity levels in April, 1975, where average snowfall was present. The dry summer and fall of 1974 caused a depletion of moisture levels in each storage category.

Storage level types and the total lake area in the 224 square milesor 360 square kilometres study area are shown in Table 10. These are related to snowmelt water content, the percentage area encompassed within each of the storage capacities, and the potential surplus of snowmelt waters. The snowmelt water content figures used were the means of the (Appendix D) readings obtained at each field site that pertained to the given soil moisture storage capacity. The potential snowmelt water surplus calculations, in acre feet, were the sums of the moisture available in each soil moisture storage type at the end of October (1974) and the snowmelt water available in each type area in April (1975) minus the storage capacity. The figure obtained represents the available surplus for each storage capacity. Finally the potential surpluses of

Table 9

Monthly Water Balance For Edmonton International Airport

June to December 1974

	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual
°F	58.2	59.2	44.9	47.7	44.0	26.9	21.3	
I	5.04	5.34	4.11	2.32	1.54			
UPE	.10	.11	.09	.06	.05			
PE	4.49	4.52	3.38	2.23	1.38			19.08
Ppt."	4.59	3.48	1.92	1.23	.17	.11	.84	18.65
S.C.	.10	-1.04	-1.46	-1.00	-1.21	.11	.84	
4.00St.4"	3.17	2.13	.67			.11	.95	
(.92)Surp.								5.08
Def.				.33	1.21			1.54
6.00St.6"	5.17	4.13	2.67	1.67	.46	.57	1.41	
(.92)Surp.								5.08
Def								
8.00St.8"	7.17	6.13	4.67	3.67	2.46	2.57	3.41	
(.92)Surp.								
Def								

Table 9A

Monthly Water Balance For Edmonton International Airport

January to June 1975

	Jan.	Feb.	Mar.	Apr.	May	June
°F	10.2	3.6	14.5	30.4	49.2	55.3
I					2.64	4.19
UPE					.07	.09
PE"					2.79	3.67
Ppt."	.48	.60	.67	1.17	2.06	4.04
S.C.	.48	.60	.67	1.17	-.73	.37
(.96) St. 4"	1.43	3.03	2.64	3.81	3.08	3.45
(.95) St. 6"	1.43	3.03	2.64	3.81	3.08	3.45
(3.41) St. 8"	3.89	4.49	5.16	6.33	5.60	5.97

Table 9B

Monthly Water Balance For Edmonton International Airport
June to December 1974

	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual
°C	14.5	15.1	12.	8.7	6.7	-2.8	-5.9	
I	128.02	135.64	104.39	58.93	39.12			
UPE	2.54	2.79	2.29	1.52	1.27			
PEcm	11.2	11.3	8.5	5.6	3.45			
Ppt.cm	11.5	8.7	4.8	3.1	.43	.28	-2.1	
S.C.	.25	-2.6	-3.7	-2.5	-3.0	.28	2.1	
10.00St.10cm	7.9	5.3	1.7			.28	2.4	
(2.3cm)Surp.								12.7
Def				.83	3.0			3.9
15cmSt.15cm	12.9	10.3	6.7	4.2	1.2	1.4	3.5	
(2.3cm)Surp.								12.7
Def								
20cmSt.20cm	17.9	15.3	11.7	9.2	6.2	6.4	8.5	
(2.3cm)Surp.								12.7
Def								

Table 9C

Monthly Water Balance For Edmonton International Airport
January to June 1975 (Metric)

	Jan.	Feb.	Mar.	Apr.	May	June
°C	-12.1	-15.8	-9.7	30.4	49.2	55.3
I						
UPE						
PEcm					6.97	9.17
Ppt. cm	1.2	1.5	1.7	2.9	5.15	10.1
S.C.	1.2	1.5	1.7	2.0	-1.82	-.93
(2.4) St. 10cm	3.6	5.1	6.8	9.7	7.9	8.8
(2.4) St. 15cm	3.6	5.1	6.8	9.7	7.9	8.8
(8.5) St. 20 cm)	9.7	11.2	12.9	15.8	14.0	14.9

snowmelt water for all storage capacities and the lake surfaces were calculated. It was assumed that soil moisture storage levels on the Cooking Lake Moraine would be equal to those at the Edmonton International Airport.

The large variation in snowmelt water content from the six inch (15 cm) storage capacity to the eight inch (20 cm) storage capacity was a result of two variables: First there were many small openings (small pastures, small sloughs, and small ponds) combined with sparse tree growth in the 6 inch (15 cm) storage capacity area, these combined to induce drifting in the 6 inch (15 cm) storage capacity. Secondly, the number of sampling sites for the 6 inch (15 cm) storage capacity was very limited as compared to the number of sampling sites in the 8 inch (20 cm) capacity (refer to Appendix D). These calculations were also made assuming that average snow depth and water content measurements, for each storage level, would be representative of the area. This was not a totally correct assumption because the snow cover was not uniform.

From Table 10 it was possible to calculate how much snowmelt water was contained in each soil moisture storage capacity on April 10, 1975 and its relationship to the total area sampled. The objective was to determine what effects snow patterns had on snowmelt runoff. To do this the areas snow drifting patterns had to be mapped, and estimated. The potential yield of snowmelt water for the lakes was calculated without considering a different evaporation rate. Assuming this each lake would have risen five inches as a result of winter snowfall, aside

Table 10

Potential Surplus Snowmelt Water Available in the Study Area in April of 1975

Storage Capacity	Snowmelt Water Content	October Soil Moisture Storage	Total	Surplus	% of Area	Potential Surplus in Acre Feet
4"	4.9"	0"	4.9"	.9"	34.3	7,785.6
6"	7.6	.46	8.06	2.06	4.9	1,205.9
8"	3.9	2.46	6.36	0	44.0	0
Lakes	5.0	0	0	5.0	16.7	9,975.5

Table 10A

Potential Surplus Snowmelt Water Available in the Study Area in April of 1975 (metric)

Storage Capacity	Snowmelt Water Content	October Soil Moisture Storage	Total	Surplus	% of Area	Potential Surplus in Acre Feet
10 cm	12.3 cm	0 cm	12.3 cm	2.2 cm	34.3	961.1
15	19.0	1.15	20.2	10.5	4.9	148.9
20	9.8	6.46	16.3	6.3	44.0	0
Lakes	12.5	0	0	12.5	16.7	1,230.5

from runoff from land surfaces. This would have left lake levels 1.4 inches (3.5 cm) below the levels at the end of April 1974, again without considering runoff from land surfaces. This statement was based on Thornthwaite calculation for potential evapotranspiration (18.4 inches or 46 cm) and precipitation (12.9 inches or 32.3 cm) for the period of May to October 1974. It should also be noted that there was probably a greater groundwater storage lag for 1974 than in 1975 because of increased precipitation during the winter of 1974.

There would also have been greater amounts of storage recharge in the 8 inch (20 cm) storage capacity than the calculations indicate due to runoff from the 4 inch (10 cm) and the 6 inch (15 cm) storage capacity areas. A portion of the surplus snowmelt water available in the 4 inch (10 cm) and the 6 inch (15 cm) storage capacities shown in Table 10, would have been utilized to recharge the 8 inch (20 cm) storage capacity supplies.

Density Slicing

Under the subheading "Density Sliced LANDSAT I Imagery", procedures for enhancing images of snow concentration and distribution patterns were discussed. These procedures were used to show snow pattern variations for soils of different moisture storage capacities (Plate 10, Overlay 1).

Table 11 was used to show the total areas, snow depths, snowmelt water contents, and the amount of snowmelt water available for soil

Table 11

Snow Depth, Water Content, and Potential Snowmelt Water Available for Soil Moisture Recharge and Surplus in Each Color Density Level on April 10, 1975

Density Level	Total Area	Snow Depth	Water Content	Potential Snowmelt Water
1	25.2 sq. mi.	9.4 inches	2.8 inches	3,679.6
2	33.2	11.9	4.2	7,526.4
3	18.0	24.9	7.6	7,263.6
4	78.0	17.3	3.9	16,307.2
5	31.0	15.2	4.1	6,857.4
6	32.6	25.5	8.2	13,717.8
7	6.0	18.7	6.2	2,222.1

Table 11A

Snow Depth, Water Content, and Potential Snowmelt Water Available for Soil Moisture Recharge and Surplus in Each Color Density Level on April 10, 1975 (metric)

Density Level	Total Area	Snow Depth	Water Content	Potential Snowmelt Water
1	65.3 sq. km.	23.5 cm	7.0 cm	453.9
2	88.6	29.8	10.5	928.4
3	46.6	62.3	19.0	895.9
4	211.3	43.3	9.8	2,011.5
5	82.4	38.0	10.3	845.8
6	87.0	63.8	20.5	1,691.7
7	15.5	46.8	15.5	274.1

moisture recharge and surplus in each of the seven density level classes. The snow depth and water content measurements were obtained by relating density levels (by color) to actual snow measurements at snow survey sites for April 10, 1975 (Plate 10). Appendix E was used to show density levels, snow depth and water content relationships.

The next step was to relate the predetermined soil moisture storage capacities for each land use (taken from subheading "Scale 1:250,000 LANDSAT I Imagery") to the various density levels to determine percentages of areas in each. Percentages were obtained by using the same grid system as before. Table 12 is a summary of these interrelationships.

Table 12A was used to show potential surplus snowmelt water for each storage capacity and the lake surfaces by image density levels. Surplus figures were obtained by adding the moisture available in each storage capacity at the end of October (1974) with the snowmelt water available in each density level and then by subtracting each storage capacity from each total. The figures obtained represent the available surplus for each storage capacity by density level. Again the final step was to calculate potential acre feet of surplus snowmelt water for the storage capacities and the lake surfaces by density level (Table 12B).

From Table 12B it was possible to infer that the 4 inch (10 cm) storage capacity areas were affected noticeably more by snowdrifting than the other two storage level areas. This is shown by the lack of storage moisture at the end of October (1974) and the lack of surplus in April 1975, thus the potential surplus snowmelt water shown in Table 12B

Table 12

Areal Relationships of Image Density Level Classes to Soil Moisture Storage and Lake Classes

Density Levels	4" or 10 cm	6" or 15 cm	8" or 20 cm	Lakes
1	20.1%	--%	1.5%	17.1%
2	20.1	--	.8	29.7
3	--	63.2	12.9	1.6
4	15.4	36.8	1.2	15.6
5	21.9	--	6.8	10.9
6	19.5	--	6.8	18.8
7	3.0	--	0	6.3

Table 12A

Snowmelt Water Plus the End of October's Soil Moisture Storage in Excess of Storage Capacities for Each Image Density Level

Density Levels	4"	or 10 cm	6"	or 15 cm	8"	or 20 cm	Lakes	cm
1	0	0	0	0	0	0	2.8	7.0
2	0.2	.5	0	0	0	0	4.2	10.5
3	3.6	9	2.06	5.15	2.06	5.15	7.6	19.0
4	0	0	0	0	0	0	3.9	9.8
5	0.1	.25	0	0	0	0	4.1	10.3
6	4.2	10.5	2.66	6.65	2.66	6.65	8.2	20.5
7	2.2	5.5	0.66	1.65	0.66	1.65	6.2	15.5

Table 12B

Potential Surplus for Areas in Each Image Density Level and Each Storage Capacity - April 10, 1975

Density Levels	Acre Feet 4" or	Hectare Metres 10 cm	Acre Feet 6" or	Hectare Metres 15 cm	Acre Feet 8" or	Hectare Metres 20 cm	Acre Feet Lakes	Hectare Metres cm
1	0	0	0	0	0	0	955.0	117.9
2	164.7	20.3	0	0	0	0	2488.1	307.1
3	0	0	761.7	94.0	1396.9	172.4	242.5	29.9
4	0	0	0	0	0	0	1213.5	149.8
5	89.7	11.1	0	0	0	0	891.4	110.0
6	3354.6	414.1	0	0	950.8	117.4	3075.0	379.6
7	270.3	33.4	0	0	0	0	779.1	96.2
Total	3879.3	478.9	761.7	94.0	2347.7	289.8	9644.7	1190.6

Table 13

The Comparative Surpluses Indicated Using Standard and Density Slicing Based Calculations

Storage Capacities	Standard*	Density Sliced**
4 inch	0 acre feet	3,879.3 acre feet
6	0	761.7
8	0	2,347.7
Lakes	7,721.0	9,644.7

Table 13A

Comparitive Amounts of Surplus Snowmelt Water Between Standard and Density Sliced Calculations Assuming No Precipitation Variation in the Standard Column

Storage Capacities	Standard	Density Sliced
10 cm	0 hectare metres	478.9 hectare metres
15	0	94.0
20	0	289.8
Lakes	953.1	1190.6

*Assume no precipitation distribution variation or drifting.

**Assume drifting and precipitation distribution variation.

represents drifting. From Table 12B it was possible to determine in what storage capacities and in what density level areas snowfall had accumulated; assuming that established snowfall concentration and distribution patterns would not change dramatically from January 10, 1975 to April 10, 1975 (snow depth and snowmelt water content measurements are considered to be the only variables).

The level of accuracy was lower than the calculations presented show. The calculations were computed with a calculator and rounded off to the nearest tenth (for the values available).

The differences between standard water balance calculations assuming no precipitation variations and density slicing based calculations, were precipitation variations were considered, are shown in Table 13.

By referring back to Table 9 and the storage capacity values for April 1975, it was possible to determine that there was no surplus water available in any of the storage capacity areas. The acre feet of potential surplus snowmelt water shown in the standard column for the lakes were calculated by adding together the precipitation from November 1974, to April 1975, and then proceeding to calculate acre feet of surplus water (evaporation was not considered in these calculations).

Larger variations could have been expected in normal (50" or 125 cm) or above normal snowfall seasons.

The largest variation occurred in the 4 inch (10 cm) storage level, 3,879.3 acre feet (478.9 hectare metres). Table 14 was constructed to show the uniqueness of this remote sensing technique in detecting differences in snow patterns (primarily drifting).

By combining Table 11, Table 14, and Plate 10 the author was able to determine exact areas, within the 4 inch (10 cm) soil moisture storage capacity, where surpluses would occur. For instance, measureable snowmelt runoff would occur in 57% of the 4 inch (10 cm) soil moisture storage level areas (primarily due to drifting patterns). Thus, with this remote sensing procedure it was possible to estimate areas having surplus (again possible runoff) not only for the entire area of each soil moisture storage capacity, but also for each portion of these areas (Table 14).

The procedure was taken one step further to calculate snowmelt runoff potential for two small areas, one surrounding Joseph Lake and one surrounding Hastings Lake (17.6 square miles or 45.6 square kilometres and 19.3 square miles or 50 square kilometres respectively). Maps were prepared showing the soil moisture storage capacities for the areas surrounding each lake (Figures IX and X). Overlays were then prepared to show the seven density levels as they related to each soil moisture storage capacity and to the lake surfaces (as shown in Table 14). These overlays were constructed with a zoom transfer scope located at the Alberta Remote Sensing Center. By using the overlays in conjunction with Table 12B (showing the potential acre feet of surplus snowmelt water it was possible to determine snow patterns for each lake and its surrounding area.

The next step was to calculate the area encompassed by each soil moisture storage capacity as well as each density level (following

Table 14

Potential Acre Feet of Surplus Snowmelt Water in the Four Inch Soil Moisture Storage Capacity Areas on April 10, 1975

Density Level	% of Area	Snowmelt Water	Surplus	Potential Acre Feet of Surplus Snowmelt Water
1	20.1	2.8 inch	0	0
2	20.1	4.2	.2	164.7
3	0	7.2	0	0
4	15.4	3.9	0	0
5	21.9	4.1	.1	89.7
6	19.5	8.2	4.2	3,354.6
7	3.0	6.2	2.2	270.3

Table 14A

Potential Hectare Metres of Surplus Snowmelt Water in the 10 cm Soil Moisture Storage Capacity Areas on April 10, 1975 (metric)

Density Level	% of Area	Snowmelt Water	Surplus	Potential Hectare Metres of Surplus Snowmelt Water
1	20.1	7.0 cm	0	0
2	20.1	10.5	.5	20.3
3	0	0	.9	0
4	15.4	9.8	0	0
5	21.9	10.3	.25	11.1
6	19.5	20.5	10.5	414.1
7	3.0	15.5	5.5	33.4

Legend for Figure IX

The Potential Soil Moisture Storage Levels for the Joseph Lake Area

4 inch (10 cm) = Crop and Pasture Land

6 inch (15 cm) = Mixed Scrub Forest Land Combined with
Small Sloughs and Ponds

8 inch (20 cm) = Mixed Mature Forest with
Dense Cover

Legend for the Overlay

The Density Level Variations Representing Snow Depth and Water Content
For the Joseph Lake Area on January 10, 1975

1 = Density level that represents 9.4 inches (23.5 cm) with
2.8 inches (7 cm) water content

2 = Density level that represents 11.9 inches (29.8 cm)
with 4.2 inches (10.5 cm) water content

3 = Density level that represents 24.9 inches (62.3 cm)
with 7.6 inches (19.0 cm) water content

4 = Density level that represents 17.3 inches (43.3 cm)
with 3.9 inches (9.8 cm) water content

6 = Density level that represents 25.5 inches (63.8 cm)
with 8.2 inches (20.5 cm) water content

7 = Density level that represents 18.7 inches (46.8 cm)
with 6.2 inches (15.5 cm) water content

Figure IX

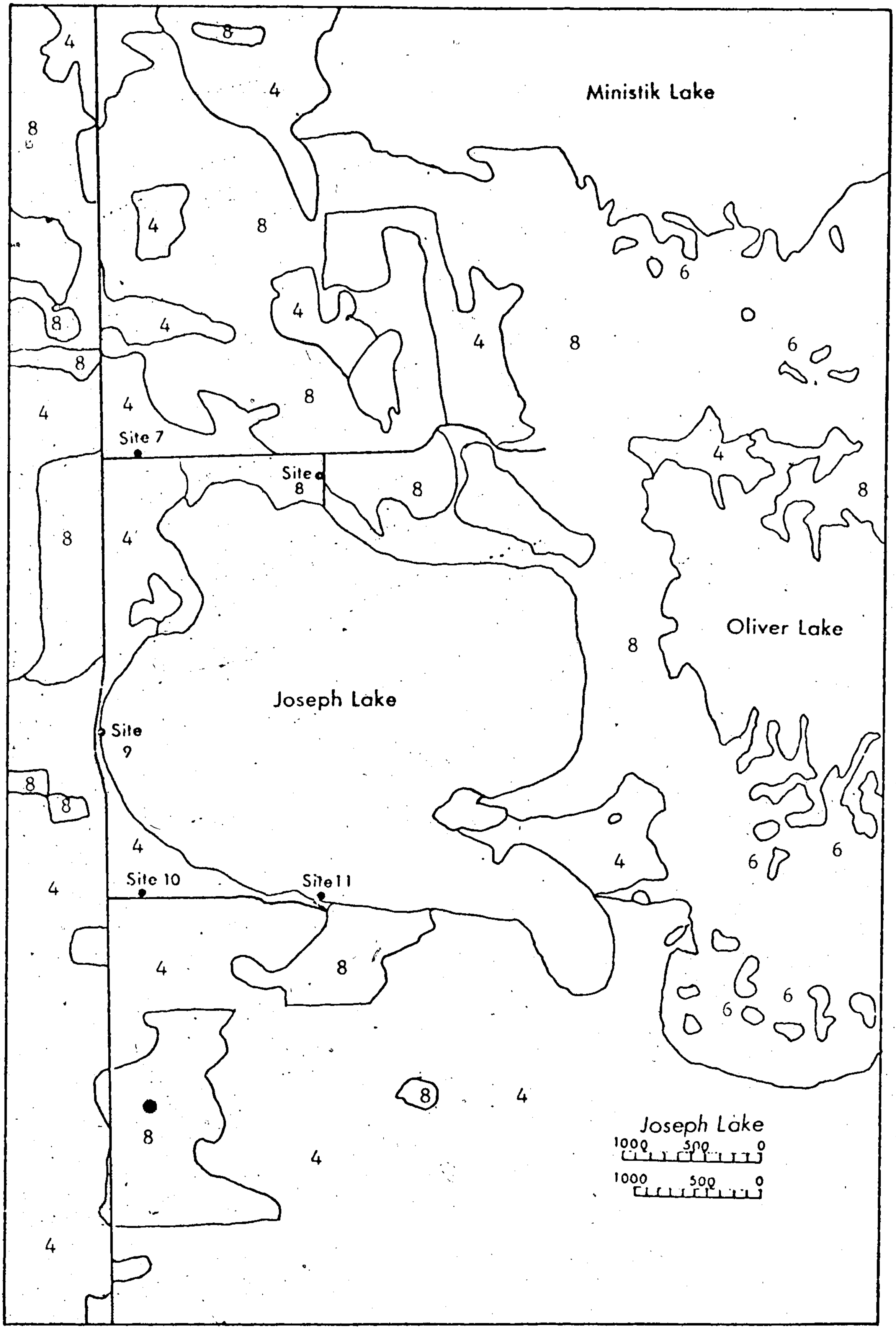
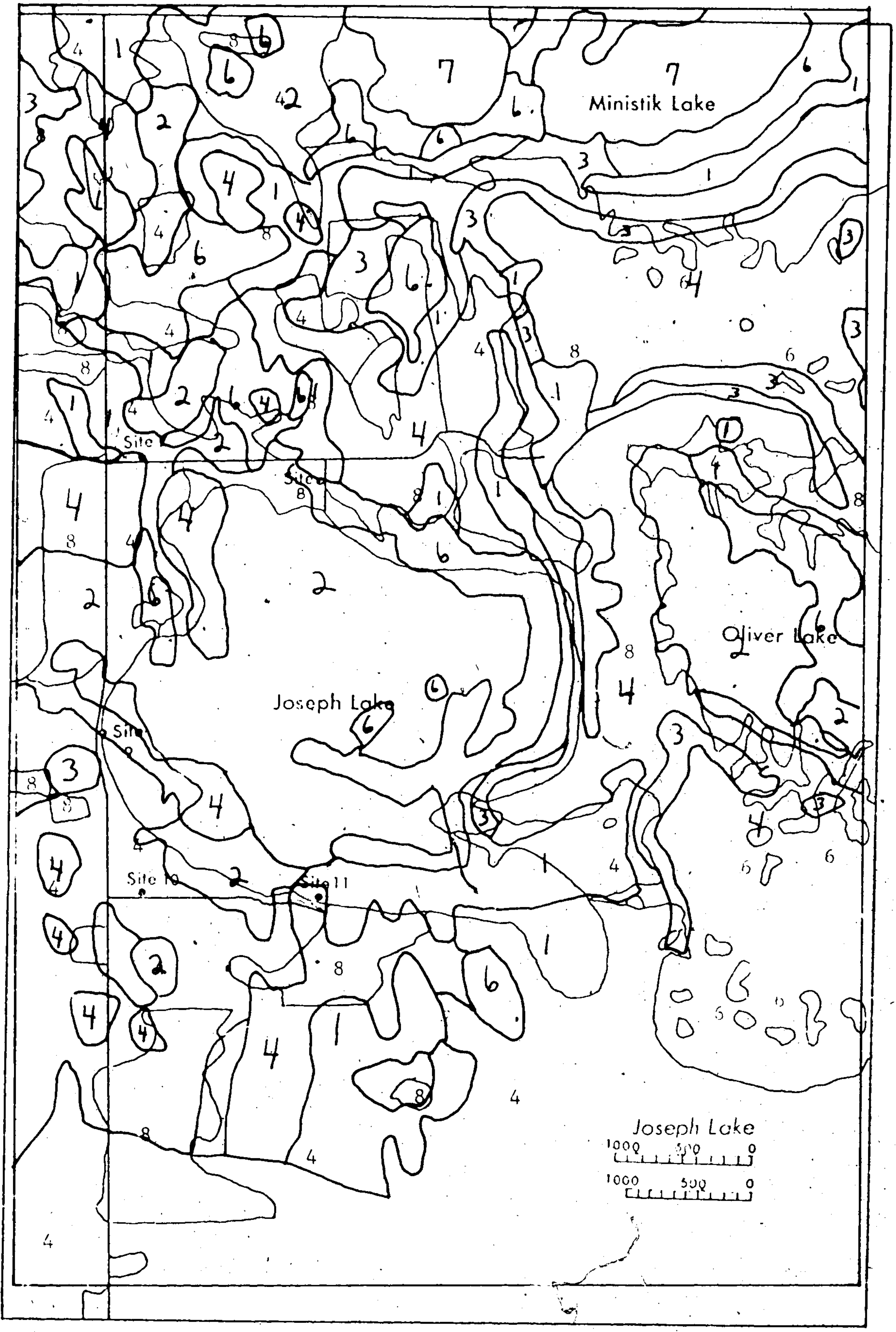

Ministik Lake
Oliver Lake
Joseph Lake
Site 7
Site 8
Site 9
Site 10
Site 11
4
8
6
Joseph Lake
1000 500 0
1000 500 0

Figure IX


Ministik Lake
Joseph Lake
Oliver Lake
Site
Site 8
Site 9
Site 10
Site 11
Joseph Lake
1000 500 0
1000 500 0

Legend for Figure X

The Potential Soil Moisture Storage Levels for the Hastings Lake Area

4 inch (10 cm) = Crop and Pasture Land

6 inch (15 cm) = Mixed Scrub Forest Land Combined with Small Sloughs and Ponds

8 inch (20 cm) = Mixed Mature Forest with Dense Cover

Legend For the Overlay

The Density Level Variations Representing Snow Depth and Water Content for t[illegible] Hastings Lake Area on January 10, 1975

1 = Density level that represents 9.4 inches (23.5 cm) with 2.8 inches (7 cm) water content

2 = Density level that represents 11.9 inches (29.8 cm) with 4.2 inches (10.5 cm) water content

3 = Density level that represents 24.9 inches (62.3 cm) with 7.6 inches (19.0 cm) water content

4 = Density level that represents 17.3 inches (43.3 cm) with 3.9 inches (9.8 cm) water content

6 = Density level that represents 25.5 inches (63.8 cm) with 8.2 inches (20.5 cm) water content

7 = Density level that represents 18.7 inches (46.8 cm) with 6.2 inches (15.5 cm) water content

Figure X

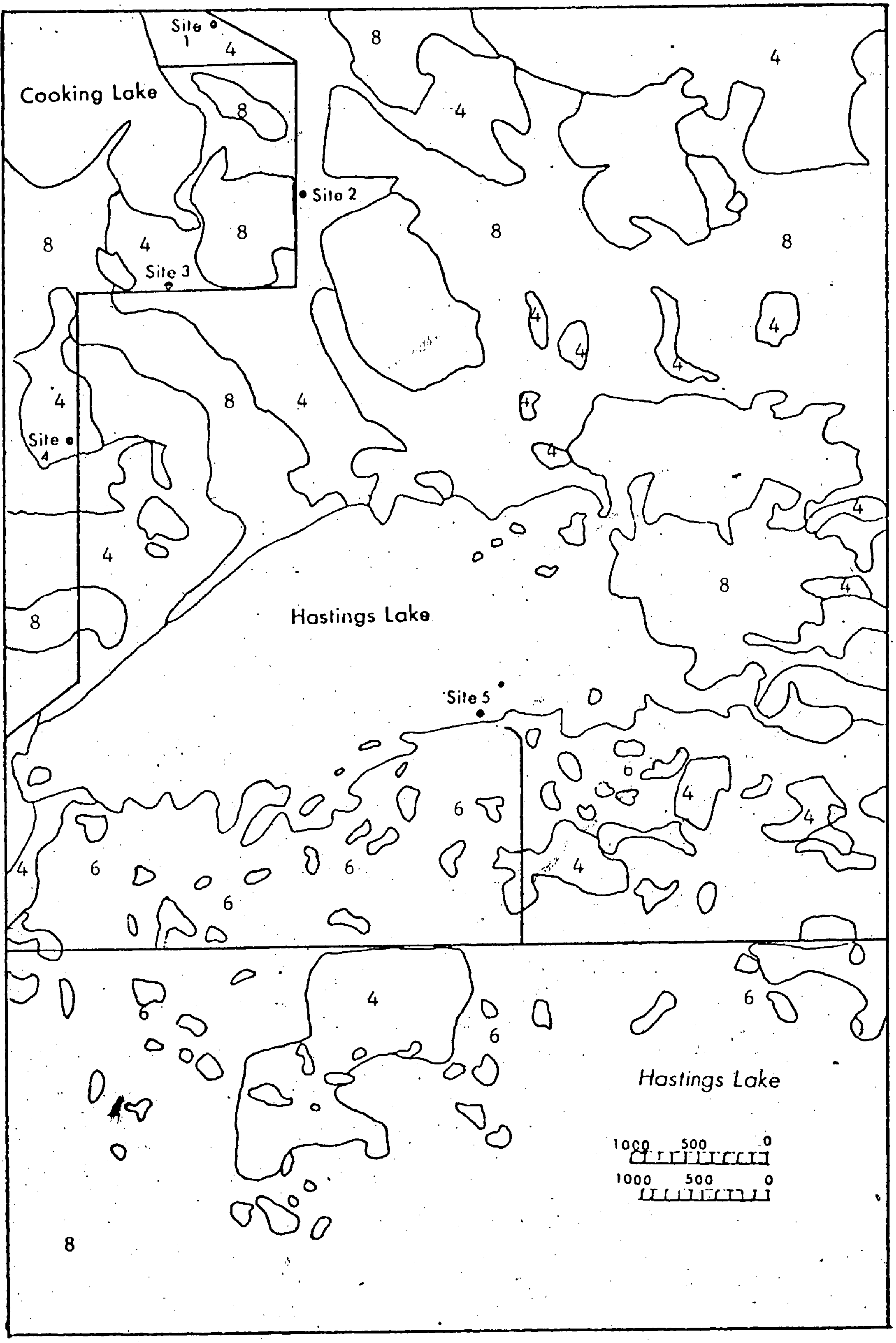
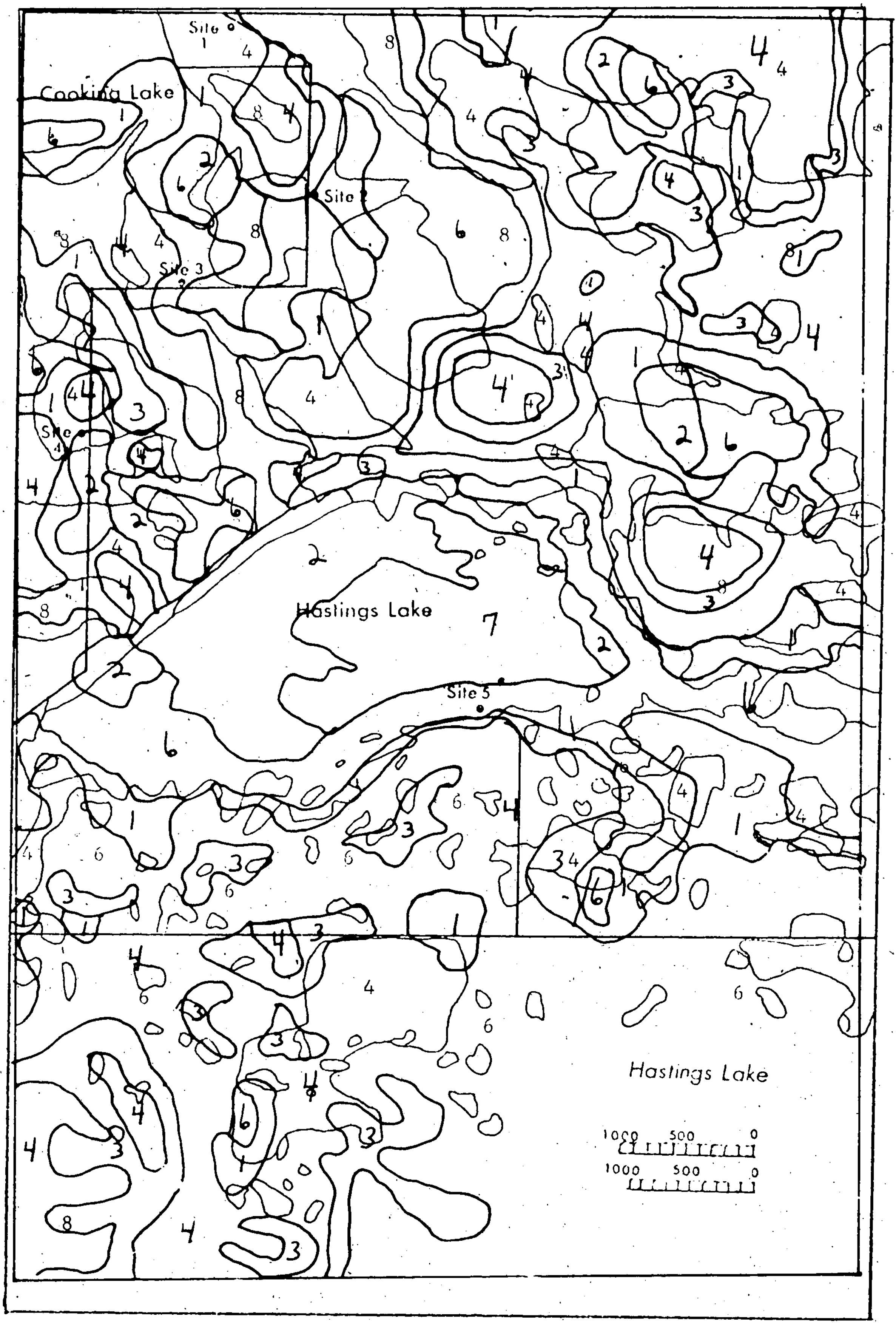

Site 1
4
Cooking Lake
8
Site 2
Site 3
Site 4
Site 5
Hastings Lake
Hastings Lake
4
6
8
1000 500 0
1000 500 0

Figure X


Site 1
Cooking Lake
Site 2
Site 3
Site 4
Hastings Lake
7
Site 5
Hastings Lake
1000 500 0
1000 500 0

procedures outlined in the discussion for 12). Tables 15 and 16 show the results of these calculations.

By combining the total calculations in Tables 15 and 16 with actual field measurements it was possible to calculate acre feet of surplus snowmelt water contained in the soil moisture storage capacity by density level. Tables 17 and 18 show these calculations for both Joseph and Hastings Lakes.

Noteable variations in potential acre feet of surplus snowmelt water for the soil moisture storage capacities occurred between the Joseph Lake and the Hastings Lake areas. The largest variation in a soil moisture level occurred in the 6 inch (15 cm) capacity, 29.0 acre feet (3.6 hectare metres) for Joseph Lake and 148.4 acre feet (18.3 hectare metres) for Hastings Lake. Most of the variation was due to differences in land use patterns, which caused a variation in drifting patterns from Joseph Lake to Hastings Lake (farmland to forest land respectively). These variations had marked effects on snow drifting patterns in the two study areas. For example the trees surrounding Hastings Lake acted as natural snow fences, thus accumulating more snow than the agricultural land (4" or 10 cm) surrounding Joseph Lake. Yet, comparisons of the 4 inch (10 cm) at Joseph Lake to the 8 inch (20 cm) at Hastings Lake by density level, showed that more snowmelt surplus could be expected from the agricultural land (4.7 square miles) than from the forest land (7.4 square miles)(Tables 19 and 20).

For Joseph Lake and the surrounding area, measurable surpluses occur in 3 density levels. For Hastings Lake and the surrounding area

Table 15

The Percentage Area of Soil Moisture Storage Capacities in the Density Levels as Depicted on LANDSAT I Imagery for the Joseph Lake Area

Density Levels	4" or 10 cm	6" or 15 cm	8" or 20 cm	Lakes
1	38%	--%	21%	12%
2	16	--	11	30
3	5	28	14	11
4	34	72	45	11
5	--	--	--	--
6	7	--	9	20
7	--	--	--	12

Table 16

The Percentage Area of Soil Moisture Storage Capacities in the Density Levels as Depicted on LANDSAT I Imagery for the Hastings Lake Area

Density Levels	4" or 10 cm	6" or 15 cm	8" or 20 cm	Lakes
1	30%	16%	13%	20%
2	8	5	3	25
3	11	21	17	1
4	40	46	54	9
5	--	--	--	--
6	11	12	13	30
7	--	--	--	--

Table 17

Potential Acre Feet and Hectare Metres of Surplus Snowmelt Water From Each Soil Moisture Storage Capacity Area Surrounding Joseph Lake

Storage Levels	Acre Feet	Hectare Metres
4" or 10 cm	177.4	21.9
6" or 15 cm	29.0	3.6
8" or 20 cm	0	0
Lakes	1,971.2	243.3

Table 18

Potential Acre Feet and Hectare Metres of Surplus Snowmelt Water From Each Soil Moisture Storage Capacity Area Surrounding Hastings Lake

Storage Levels	Acre Feet	Hectare Metres
4" or 10 cm	166.7	20.6
6" or 15 cm	148.4	18.3
8" or 20 cm	0	0
Lakes	1,389.6	171.5

Table 19

Potential Acre Feet of Surplus Snowmelt Water Contained in the Four Inch Soil Moisture Storage Capacity Area Surrounding Joseph Lake on April 10, 1975

Density Level	% of Area	Water	Surplus	Potential Acre Feet of Surplus Snowmelt Water
1	38	2.8"	0	0
2	16	4.2	.2	30.0
3	5	7.6	3.6	168.9
4	34	3.9	0	0
5	0	0	0.1	0
6	7	8.2	4.2	275.9
7	0	0	0	0

Table 19A

Potential Hectare Metres of Surplus Snowmelt Water Contained in the 10 Centimetre Soil Moisture Storage Capacity Area Surrounding Joseph Lake on April 10, 1975

Density Level	% of Area	Water	Surplus	Potential Hectare Metres of Surplus Snowmelt Water
1	38	7.0 cm	0	0
2	16	10.5	.5	3.7
3	5	19.0	9.0	20.8
4	34	9.8	0	
5	0	0	0	0
6	7	20.5	10.5	34.1
7	0	0	0	0

Table 20

Potential Acre Feet of Surplus Snowmelt Water Contained in the Eight Inch Soil Moisture Storage Capacity Area Surrounding Hastings Lake on April 10, 1975

Density Levels	% of Area	Water	Surplus	Potential Acre Feet of Surplus Snowmelt Water
1	13	2.8"	0	0
2	3	4.2	0	0
3	17	7.6	2.06	360.5
4	54	3.9	0	0
5	0	0	0	0
6	13	8.2	2.66	355.9
7	0	0	0	0

Table 20A

Potential Acre Feet of Surplus Snowmelt Water Contained in the Twenty Centimetre Soil Moisture Storage Capacity Area for the Area Surrounding Hastings Lake on April 10, 1975.

Density Levels	% of Area	Water	Surplus	Potential Hectare Metres of Surplus Snowmelt Water
1	13	7.0 cm	0	0
2	3	10.5	0	0
3	17	19.0	5.2	44.5
4	54	9.8	0	
5	0	0	0	0
6	13	20.5	6.65	43.9
7	0	0	0	0

measureable surplus occurred from only 2 density levels. The 8 inch (20 cm) storage capacity around Hastings Lake had only 59% (4.7 inches or 11.7 cm) as much surplus moisture available as did the 4 inch (10 cm) storage capacity (7.9 inches or 19.7 cms) around Joseph Lake. This was primarily the result of land use variations (in drifting patterns) and a moderate snowfall (1975) combined with a dry summer and fall in 1974. Consequently, each storage level was kept below its full capacity.

In the past it was necessary to have a net work of weather gauging stations, which would be representative of soil moisture storage capacities for the exact runoff potential calculations. Yet, it was possible to show the variations in surplus on the entire moraine (Table 10) as well as in select areas (Tables 19 and 20) within the moraine. By combining remote sensing procedures, outlined in this chapter, with Thornthwaite water balance tables (Table 9) it was possible to determine the effects of snow drifting patterns on potential surplus levels of the Cooking Lake Moraine (Table 12B).

Under the present circumstances, with a substituted image, the water balance calculations presented are weakly based yet they represent a significant improvement over previous calculations made for the Cooking Lake Moraine. Other researchers who have used Thornthwaite water balance equations and tables to explain snow patterns in this region are MacIver, Landals, Wight, Erxleben, and Kakela. Other excellent sources dealing with runoff from snowmelt are the U.S. Army Corp of Engineers (1956) and Garstka (1964, refer to Bibliography).

Chapter V

PROBLEMS ENCOUNTERED AND RECOMMENDATIONS

The purpose of this chapter is to provide background information concerning the problems encountered during the study, to propose solutions to those problems, and to recommend several methods which would add significantly to further studies. The chapter is organized under two major subheadings: Problems Encountered During the Study and Recommendations for Further Snow Survey Studies.

Problems Encountered During the Study

The major problem encountered was attempting to obtain the April 10, 1975 LANDSAT I image. On the morning of April 10, 1975 the author took snow depth and water content measurements on the Cooking Lake Moraine. It was a sunny, cloud free day. Accordingly, the author believed that a quality LANDSAT I image could be obtained. After sending eight letters (four to the EROS Data Center and four to the Canada Centre for Remote Sensing), making two long distance phone calls, and waiting seven months for replies, the author was informed that the image could not be obtained. Ms. Jean Heffernan, Manager of the Order Desk for Space Imagery, at the Canada Centre for Remote Sensing, called, saying that the April 10, 1975 LANDSAT I image was not available because it had been deemed of too poor quality to print and the magnetic tape had been destroyed (Heffernan, phone call, 1975); with the magnetic tape destroyed, the image could not be obtained from the CCRS.

Two days after Ms. Heffernan called, Mr. Leo A. Braconnier, Acting Chief, User Services at the EROS Data Centre, called, saying that EROS may no longer ship LANDSAT I or II imagery of Canada to anyone, anywhere without first ordering from Canada (Braconnier, phone call, 1975). Braconnier explained that Canada had sought to stop the U.S. from selling LANDSAT imagery of Canada (Brazil has sought the same type of injunction). Braconnier was not able to confirm the exact date that no additional imagery of Canada could be sold, but did indicate that the April 10, 1975 images would not be shipped.

The last option was to enlarge a micro-film image produced by Donald Fisher and Associates Ltd., Prince Albert, Saskatchewan. These images are not photographically corrected for distortion and are usually of poor quality. The image was "noise" (distortion) free over the study area, but it was of such poor tonal quality that the enlargement was not useable. Consequently, it was necessary to substitute the January 10, 1975 image for the April 10, 1975 image.

Problems encountered of lesser importance were: image quality deficiencies, inadequate tonal contrast on black and white prints, enlargement size, color brightness on 35 mm photographs, and the lack of gauging stations on the Cooking Lake Moraine. After acquiring the LANDSAT I imagery available for the study area (up to and including the January 10, 1975 imagery) it was found that EROS's and CCRS' image quality varied greatly. In every instance, the imagery from EROS was of superior quality, clarity and definition.

Tonal contrasts on a black and white print made from a positive transparency and color brightness on 35 mm photography created problems. An example of the problems encountered involved the December 5, 1974 image used in Chapter I. It appeared from the print that the entire area was under a blanket of snow. In reality, there was less than an inch of snow on the study area (personal field work and snow pillow readings from the Edmonton International Airport). The technician, who printed the photograph, used too high a light intensity. The color prints were dull because of a low light intensity used during printing.

The size of enlargements varied dramatically with the desired scale. A 1:500,000 print of an entire LANDSAT image is approximately 24 inches (60 cm) by 24 inches (including the border), while a 1:250,000 print is approximately 48 inches (120 cm) by 48 inches. In both cases the print would be too large to be included in the normal text of a paper. In snow survey studies where large areas are involved, overlays depicting land use and snow survey sites can be made from enlargements and photographically reduced to fit into the text.

The lack of weather gauging stations (temperature and precipitation) on the Cooking Lake Moraine made it necessary to calculate Thornthwaite water balance tables with Edmonton International Airport data. This was an adequate arrangement, but not an ideal one. If time and funds did exist, a network of weather gauging stations would be beneficial in the study area.

Recommendations for Further Snow Survey Studies

Although it is impossible for the average researcher to change governmental policies, there are several steps which can be taken. Firstly, a trip to the Canada Centre for Remote Sensing (or EROS Data Center) to familiarize oneself with the equipment, facilities, and key personnel who could aid in the study, would be beneficial. Secondly, a standing order for all magnetic tapes, as they become available, of the study area would save time and anxiety. This type of order can be cancelled for specific dates with a phone call if cloud cover was too extensive.

The magnetic tapes should be incorporated into the snow survey. The tapes can provide a digital computer printout from which land use patterns can be related to soil moisture recharge levels. The key magnetic tapes (those just prior to the runoff) should be taken to the CCRS and displayed on the Imager 100, in a falsely colored digital format. The Imager 100 would enable a greater degree of accuracy to be obtained in the larger study areas.

Intensive field work on the days of satellite passage is recommended. A network of predetermined snow survey sites should be set up by reviewing the previous winter's imagery with a density slicer. In this manner, snow concentration and distribution patterns could be established so that an appropriate number of field sites and locations could be determined.

A skilled photo-technician, who has adequate laboratory facilities, is a necessity for any remote sensing study. The photo-technician can control definition, tone, and uniformity in all forms of photography.

The final recommendation would be to have a low level flight (multi-band) flown just prior to the major snowmelt period. The flight should be aligned with the passage of the LANDSAT satellites. Complete coverage of a small study area is essential, in larger study areas, high level flights could be aligned with predetermined transects to incorporate as many snow survey sites as possible. This would give an excellent base from which interpretation could be made.

If some or all of the previous recommendations would prove to be too costly, the procedures used in Chapter 4 of this thesis can be used. Complete preparation, execution of field work, and photographic processing, as outlined in Chapter 4, would cost approximately \$500 (excluding salary and publication costs). Since the major objectives had to be narrowed from regional to local precipitation patterns it was only possible to indicate local drifting patterns and to estimate their effects on the water balance of the study area. If the study was enlarged to include regional variations in preci[illegible]tation patterns the costs would increase proportionately with the size of the area being studied.

Chapter VI

SUMMARY AND CONCLUSIONS

Water quality and quantity problems are widely present on the Cooking Lake Moraine, making it unfit for many recreational activities. Several water importation schemes involving pipelines were proposed for the improvement of water supplies but these involved large cost for limited return.

Alternative proposals involving better management of local water supplies appear to have promise, but they must be studied more thoroughly. Some of these involve management of snow distribution patterns using remote sensing techniques.

Some of the factors which may affect snowfall concentration and distribution patterns on the Cooking Lake Moraine, were considered to be contributing factors in some snowfall variation patterns (relative to five local climate stations). The snow accumulation patterns from these storm tracks might be heavier on some portions of the moraine than other portions. Topographic differences may be responsible for variations in precipitation patterns, but without local long term weather gauging stations and appropriate imagery (late winter) it was impossible to establish patterns on a regional scale. Strong winds (especially WNW at the Edmonton International Airport) have contributed to variation in snow distribution in local as well as regional patterns of drifting.

Four basic techniques for determining snowfall distribution patterns were described. The techniques used were: Interpretation of scale 1:1,000,000 LANDSAT I Imagery, Enlargement to scale 1:250,000 for LANDSAT I Imagery and more intensive interpretation, ensity licing of LANDSAT I Imagery for separation of snow depth categories, and tri-color projected LANDSAT I Imagery. The most accurate results were obtained by using a combination of LANDSAT I positive transparencies, density sliced images, field data, topographical maps, and enhancement with a zoom transfer scope. The snow patterns (tonal) on LANDSAT I imagery at a scale of 1:1,000,000 were almost non-existant, but by combining enlarged LANDSAT I imagery with Andersons' Level II Classification System the potential for snowmelt runoff patterns was estimated.

Enhancement by density slicing provided the best separation of snow concentration and distribution patterns on the LANDSAT I imagery. These snow patterns were mapped and related to potential snowmelt runoff variations for the study area, and for two more intensively studied parts of the study area. The runoff potential was also estimated for several soil moisture storage capacities.

The major problem encountered during the study was the attempt to obtain the April 10, 1975 LANDSAT I images. The images were not available for two reasons: Firstly, the Canada Centre for Remote Sensing in Ottawa, had classified the images of the Cooking Lake Moraine for April 10, 1975 as being of too poor quality to print, consequently, they destroyed the magnetic tape. Secondly, the EROS

Data Center, at Sioux Falls, South Dakota, may no longer sell LANDSAT imagery of Canada to anyone, anywhere. This arrangement was sought earlier this year (1975) by Canada. Substitution of the January 10, 1975 images for the April 10, 1975 images was the best option available.

Based on the problems encountered in this study three recommendations were made: Firstly, visiting the Canada Centre for Remote Sensing to familiarize the researcher with the equipment, facilities, and key personnel that might aid in the researcher's study. Secondly, maintaining a standing order for all magnetic tapes of the study area, as they become available, could assure obtaining the image. This would speed up the processing of data for interpretation. Thirdly, having a low level flight (multi-band ideally side looking airborne radar) flown prior to the major snowmelt period (in conjunction with a LANDSAT passage) would ensure ~~that~~ useable imagery would be available.

The purpose of this study was to develop a more accurate means of estimating regional patterns of snowmelt runoff using remote sensing techniques. To fulfill the purpose of the study six objectives were formulated as the basis for research.

Objectives

The first objective was to establish what variations in winter snowfall are present in the Cooking Lake Moraine area. This objective was not fulfilled completely for two reasons: Firstly, it was impossible to obtain the April 10, 1975 LANDSAT I imagery. This made it necessary to use January 10, 1975 LANDSAT I imagery in conjunction with April 10, 1975 snow depth and water content data. In making this substitution it was necessary to assume that snowfall concentration and distribution patterns would not vary appreciably from January 10, 1975 to April 10, 1975. Secondly, snowfall in 1974-75 (to January 10, 1975) was much lighter than normal and the major regional variation at that stage appeared to be due to drifting rather than to snowfall differences, thus it was decided to focus upon drifting effects. With greater snowfall, more apparent regional differences might have been present and the procedure should not be discarded for use in other years.

To develop a procedure using LANDSAT I imagery for determining snow concentration and distribution patterns was the second objective. With the aid of a density slicer (using settings 1-16, 28, and 29), a zoom transfer scope, and positive transparencies of LANDSAT I imagery it was possible to fulfill this objective (for local patterns). A positive band 5 transparency was used as a basis for density slicing procedures and as a basis for the mapping of snow drifting patterns. The drifting patterns were mapped from density sliced prints with a zoom transfer scope.

The drifting patterns were established and mapped on clear overlay material. The next step was to construct maps showing regional soil moisture storage capacity patterns. The overlays were placed over the (area surrounding Joseph and Hastings Lakes) maps and relationships were established. Thus it was possible to determine the effects of snow drifting on a variety of scales with LANDSAT I imagery. These procedures should have been supplemented with more field data. The data should have been equally representative of all of the color density levels used.

The third objective was to investigate the relationship between LANDSAT I images' tonal variations and snow concentration and distribution patterns. Comparisons of LANDSAT I imagery at scales of 1:1,000,000 and 1:250,000 showed little or no variations in the snow cover. The major contribution of black and white LANDSAT prints was their use as base maps for determining land use patterns. Once the land use patterns had been determined, relationships were drawn between those patterns and the soil moisture storage capacities of the study area. It was then possible to estimate potential snowmelt runoff for each area on the moraine.

To experiment with various enhancement devices to maximize discrimination of snow cover variations was the fourth objective. Three forms of enhancement were used in this study; enlargement, density slicing, and tri-color projection. Enlargement provided a better scale base map for distinguishing land use patterns on the moraine. Density slicing combined with snow survey data provided a bases for which snow drifting patterns could be mapped. Problems in registry rendered tri-color projections nearly useless in this study. If the registry could have been improved a useful image might have been obtained.

The fifth objective was to compare regional soil moisture recharge capacities and snow water content levels which were required to produce runoff. Long term water balance tables were calculated (Thornthwaite procedures) to show precipitation patterns for five weather gauging stations surrounding the moraine. They were: the Edmonton International Airport, the Edmonton Industrial Airport, Edmonton Namao, Camrose, and Vegreville CDA stations. Variations in gauging equipment (nipher gauges for the three Edmonton stations and stick measurements for the Camrose and Vegreville stations) made comparisons after 1960 difficult.

Monthly water balance tables were calculated for the Edmonton International Airport station. These tables were used to determine the amount of water needed to recharge the soil moisture storage capacities. These data were compared to April 10, 1975 field measurements. Potential surplus water calculations were then made to determine the amounts of runoff which could be expected in each area. By combining the expected runoff data with maps derived from density sliced imagery it was possible to separate areas of different runoff potential from one another. It was also possible to estimate potential surplus snowmelt water within a given storage capacity and break that data down into as many as seven different components (by color density level). This objective was fulfilled for localized areas.

The final objective was to investigate the relationship of snow concentration and distribution patterns to soil moisture storage capacities so that runoff potential might be estimated. This was accomplished for a 224 square mile (580 square kilometres) area of the Cooking Lake Moraine. By averaging the data obtained from the snow survey sites and relating that data, to the seven density levels, it was possible to estimate runoff. This procedure was also used on two small areas within the major study area, the area surrounding Joseph Lake and the area surrounding Hastings Lake.

The major difficulty with this portion of the study was the limited number of snow survey sites used, consequently, some density levels were represented by five or more sites, while some levels were represented by as few as three sites. Yet, with limited data it was possible to show runoff trends in the study area.

Many snow surveys and investigations of drifting patterns can be completed utilizing the techniques and procedures described in this thesis. Particularly, it has been possible to show the effects of localized drifting in the Cooking Lake Moraine area. It should be possible to expand the mapping of snow patterns to a regional scale based upon the procedures outlined in Chapter IV. More complete snowmelt runoff relationships could also be determined. Future research should be undertaken to further refine the techniques and procedures upon which this thesis is based and to reinforce and expand its conclusions.

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APPENDIX A

Surplus and Deficiency Patterns for Edmonton 1883-1972, Westaskiwin 1921-1956 (33 years), and North Cooking Lake 1921-1929 (7 years) using Thornthwaite procedures (1948) with an average soil moisture storage capacity of four inches

Edmonton -- inches

	Surplus	Deficiency	Lake A	Level B	Change* C
1883	4.0	9.9	-10.9	+ 1.1	+13.1
1884	0	4.0	- 6.0	- 6.0	- 6.0
1885	0.1	5.5	- 8.2	- 7.9	- 7.6
1886	0	5.9	- 8.9	- 8.9	- 8.9
1887	0	8.0	-12.0	- 12.0	-12.0
1888	3.0	1.4	+ 0.9	+ 9.9	+18.9
1889	0	14.9	-22.4	- 22.4	-22.4
1890	0	0	0	0	0
1891	1.0	3.2	- 3.2	- 0.8	+ 2.2
1892	0	5.0	- 7.5	- 7.5	- 7.5
1893	0.4	2.6	- 3.5	- 2.3	- 1.1
1894	0.8	5.2	- 7.0	- 4.6	- 2.2
1895	0.2	7.1	-10.5	- 9.9	- 9.3
1896	0.8	7.0	- 9.7	- 7.3	- 4.9
1897	9	8.5	-12.8	- 12.8	-12.8
1898	0.5	10.7	-15.7	- 14.5	-13.3
1899	0	0	0	0	0
1900	5.0	0	+ 5.0	+ 20.0	+35.0
1901	7.3	0	+ 7.3	+ 29.2	+51.1
1902	4.3	2.8	+ 0.1	+ 13.0	+25.9
1903	0.3	0	+ 0.3	+ 1.2	+ 2.1
1904	4.2	5.2	- 3.6	+ 9.0	+21.6
1905	0	6.3	- 9.5	- 9.5	- 9.5
1906	0	7.4	-11.1	- 11.1	-11.1
1907	4.0	0.7	+ 2.9	+ 14.9	+26.9
1908	0	7.2	-10.8	- 10.8	-10.8
1910	0	7.3	-11.0	- 11.0	-11.0
1911	0	0	0	0	0
1912	0	0.2	- 0.3	- 0.3	- 0.3
1913	0.2	1.4	- 1.9	- 1.3	- 0.7
1914	0.8	0	+ 0.8	+ 3.2	+ 5.6
1915	0.6	2.5	- 3.2	- 1.4	+ 0.4
1916	0	0.8	- 1.2	- 1.2	- 1.2
1917	2.4	5.8	- 6.3	+ 0.9	+ 8.1
1918	0	3.2	- 4.8	- 4.8	- 4.8

(Appendix A continued)

	Surplus	Deficiency	Lake A	Level B	Change* C
1919	0.2	7.9	-11.7	-11.1	-10.5
1920	5.8	2.3	+ 2.3	+19.7	+37.1
1921	0.4	6.5	- 9.4	- 8.2	- 7.0
1922	0	8.2	-12.3	-12.3	-12.3
1923	0	7.4	-11.	-11.	-11.1
1924	0	4.3	- 6.5	- 6.5	- 6.5
1925	2.6	6.0	- 6.4	+ 1.4	+ 9.2
1926	0	5.9	- 8.9	- 8.9	- 8.9
1927	2.6	2.2	- 0.7	- 7.1	+14.9
1928	0.9	3.9	- 5.0	- 2.3	+ 0.4
1929	0.3	8.4	-12.3	-11.4	-10.5
1930	0	8.0	-12.0	-12.0	-12.0
1931	0	1.6	- 2.4	- 2.4	- 2.4
1932	0.7	7.5	-10.6	- 8.5	- 6.4
1933	1.1	3.3	- 3.9	- 0.6	+ 2.7
1934	3.4	1.9	+ 0.5	+10.7	+20.9
1935	3.6	3.8	- 2.1	+ 8.7	+19.5
1936	4.0	6.1	- 5.2	+ 6.8	+18.8
1937	0	3.0	- 4.5	- 4.5	- 4.5
1938	0.7	2.9	- 3.7	- 1.6	+ 0.5
1939	3.5	6.4	- 6.1	+ 4.4	+14.9
1940	5.8	6.2	- 3.5	+13.9	+31.3
1941	0	5.0	- 7.5	- 7.5	- 7.5
1942	2.1	0.2	+ 1.8	+ 8.1	+14.4
1943	3.9	1.5	+ 1.6	+13.3	+25.0
1944	0	2.6	- 5.4	- 5.4	- 5.4
1945	0.7	6.6	- 9.2	- 7.1	- 5.0
1946	0.2	3.0	- 4.3	- 3.7	- 3.1
1947	1.5	3.6	- 3.9	+ 0.6	+ 5.1
1948	4.8	8.5	- 8.0	+ 6.4	+20.8
1949	0	8.3	-12.5	-12.5	-12.5
1950	0	7.4	-11.2	-11.2	-11.2
1951	1.1	1.4	- 1.0	+ 2.3	+ 5.6
1952	1.7	4.6	- 5.2	- 0.1	+ 5.2
1953	3.1	0	+ 3.1	+12.4	+21.7
1954	0.9	0	+ 0.9	+ 3.6	+ 6.3
1955	1.4	5.2	- 6.4	- 2.2	+ 2.0
1956	2.6	2.5	- 1.2	+ 6.6	+14.4
1957	0	10.0	-15.0	-15.0	-15.0
1958	0.7	5.6	- 7.7	- 5.6	- 3.5
1959	0	2.3	- 3.5	- 3.5	- 3.5
1960	0.1	0.8	- 1.1	- 0.8	- 0.5
1961	0	9.3	-14.0	-14.0	-14.0
1962	1.2	4.2	- 5.1	- 1.5	+ 2.1

(Appendix A continued)

	Surplus	Deficiency	Lake A	Level B	Change* C
1963	0.2	9.2	-13.6	-13.0	-12.4
1964	0	7.3	-11.0	-11.0	-11.0
1965	5.1	4.0	- 0.9	+14.4	+29.7
1966	0	5.2	- 7.8	- 7.8	- 7.8
1967	0.7	7.6	-10.7	- 8.6	- 6.5
1968	0	6.1	- 9.2	- 9.2	- 9.2
1969	0	4.7	- 7.1	- 7.1	- 7.1
1970	0.5	3.9	- 5.4	-.3.9	- 2.4
1971	0.9	7.0	- 6.3	- 3.6	- 0.9
1972	2.5	1.9	- 0.4	+ 7.1	+15.6
1973					

*Lake Level Change; A. Assuming no drainage from areas surrounding the lake; B. Assuming drainage from an area three times as large as the lake; and C. Assuming drainage from an area six times as large as the lake. Lake evaporation is assumed to be P.E. plus 1/2 D, thus the net level change without inflow would be 1 1/2 D-S.

Source: Laycock, 1973.

APPENDIX A - Metric Conversion

	Surplus	Deficiency	Lake A	Level B	Change* C
1883	10.0	24.8	-27.3	+ 2.8	+32.8
1884	0.0	10.	-15.0	-15.0	-15.0
1885	.3	13.8	-20.5	-19.8	-19.0
1886	0.0	14.8	-22.3	-22.3	-22.3
1887	0.0	20.0	-30.0	-30.0	-30.0
1888	7.5	3.5	+ 2.3	+24.8	+47.3
1889	0	37.3	-56.0	-56.0	-56.0
1890	0	0	0	0	0
1891	2.5	8.0	- 9.5	- 2.0	+ 5.5
1892	0	12.5	-18.8	-18.8	-17.6
1893	1.0	6.5	- 8.8	- 5.8	- 2.8
1894	2.0	13.0	-17.5	-11.5	- 5.5
1895	.5	17.8	-26.3	-24.8	-23.3
1896	2.0	17.5	-24.3	-18.3	-12.3
1897	0	21.3	-32.0	-32.0	-32.0
1898	1.0	26.8	-39.3	-36.3	-33.3
1899	0	0	0	0	0
1900	12.5	0	+12.5	+50.0	+87.5
1901	18.3	0	+18.3	+73.0	+127.8
1902	10.8	7	+ .3	+32.5	+64.8
1903	.8	0	+ .8	+ 3.0	+ 5.3
1904	10.5	13.0	+ 9.0	+22.5	+54.0
1905	0	15.8	-23.8	-23.8	-23.8
1906	0	18.5	-27.8	-27.8	-27.8
1907	10.0	1.8	+ 7.3	+37.3	-67.3
1908	0	18.0	-27.0	-27.0	-27.0
1909	.3	2.7	-25.3	-24.5	-23.8
1910	0	18.3	-27.5	-27.5	-27.5
1911	0	0	0	0	0
1912	0	.5	- .8	- .8	- .8
1913	.5	3.5	- 4.8	- 3.3	- 1.8
1914	2.0	0	+ 2.0	+ 8.0	+14.0
1915	1.5	6.3	- 8.0	- 3.5	+ 1.0
1916	0	2.0	- 3.0	- 3.0	- 3.0
1917	6.0	14.5	+15.8	+ .4	+20.3
1918	0	8.0	-12.0	-12.0	-12.0
1919	.5	19.8	-29.3	-27.8	-26.3
1920	14.5	5.8	+ 5.8	+49.3	+92.8
1921	1.0	16.3	-23.5	-20.5	-17.5
1922	0	20.5	-30.8	-30.8	-30.8
1923	0	18.5	-27.8	-27.8	-27.8
1924	0	10.8	-16.3	-16.3	-16.3
1925	6.5	15.0	-16.0	+ 3.5	+23.0

(Appendix A continued)

	Surplus	Deficiency	Lake	Level	Change*
			A	B	C
1926	0	14.8	-22.3	-22.3	-22.3
1927	6.5	5.5	-1.8	-17.8	+37.3
1928	2.3	9.	-12.5	- 5.8	+ 1.0
1929	.8	21.0	-30.8	-28.5	-26.3
1930	0	20	-30.0	-30.0	-30.0
1931	0	4.0	- 6.0	- 6.0	- 6.0
1932	1.8	18.8	-26.5	-21.3	-16.0
1933	2.8	8.3	9.8	- 1.5	+ 6.8
1934	8.5	4.8	+ 1.3	+26.8	+52.3
1935	9.0	9.5	- 5.3	+21.8	+48.8
1936	10.0	15.3	-13.0	+17.0	+47.0
1937	0	7.5	-11.3	-11.3	-11.3
1938	1.8	7.3	- 9.3	- 4.0	+ 1.3
1939	8.8	16.0	-15.3	+11.0	+37.3
1940	14.5	15.5	- 8.8	+34.8	+78.3
1941	0	12.5	-18.8	-18.8	-18.8
1942	5.3	.5	+ 4.5	+20.3	+36.0
1943	9.8	3.8	+ 4.0	+33.3	+62.5
1944	0	9.0	-13.5	-13.5	-13.5
1945	1.8	16.5	-23.0	-17.8	-12.5
1946	.5	7.5	-10.8	- 9.3	- 7.8
1947	3.8	9.0	- 9.8	+ 1.5	+12.8
1948	12.0	21.3	-20.0	+16.0	+52.0
1949	0	20.8	-31.3	-31.3	-31.3
1950	0	18.8	-28.0	-28.0	-28.0
1951	2.8	3.5	- 2.5	+ 5.8	+14.0
1952	4.3	11.5	-13.0	- .3	+13.0
1953	7.8	0	+ 7.8	+31.0	+54.3
1954	2.3	0	+ 2.3	+ 9.0	+15.8
1955	3.5	13.0	-16.0	- 5.5	+ 5.0
1956	6.5	6.3	+ 3.0	+16.5	+36.0
1957	0	25.0	-37.5	-37.5	-37.5
1958	1.8	14.0	-19.3	-14.0	- 8.8
1959	0	5.8	- 8.8	- 8.8	- 8.8
1960	.25	2.0	- 2.8	- 2.0	- 1.3
1961	0	23.3	-35	-35	-35
1962	3.0	10.5	-12.8	- 3.8	+ 5.3
1963	.5	23.0	-34.0	-32.5	-31
1964	0	18.3	- 27.5	-27.5	-27.5
1965	12.8	10.0	- 2.3	+36.0	+74.3
1966	0	13.0	-19.5	-19.5	-19.5
1967	1.8	19	-26.8	-21.5	-16.3
1968	0	15.3	-23.0	-23.0	-23.0
1969	0	11.8	-17.8	-17.8	-17.8
1970	1.3	9.8	-13.5	- 9.8	- 6.0
1971	2.3	17.5	-15.8	- 9	- 2.3
1972	6.3	4.8	- 1.0	+17.8	+39.0

APPENDIX B

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(Source: Canada Centre for Remote Sensing)

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APPENDIX C

Table 4

Water Balance For Edmonton Namao A 1952-1974

(Thornthwaite procedures using 10 cm storage level)

Metric Conversions

	Precipitation	=	(P.E.cm - Dcm)	+	Surplus cm	±Storage Change cm
1957	35.0	=	(53.8 - 25)	+	0	+ 6.3
1958	44.8	=	(55.3 - 18)	+	6.3	+ 1.3
1959	45.3	=	(46.5 - 3.5)	+	3.3	- 1
1960	47.3	=	(53.0 - 4.3)	+	2	- 3.5
1961	44.0	=	(54.3 - 13.3)	+	2.5	+ .5
1962	42.3	=	(53.8 - 16.5)	+	8	- 3
1963	28.8	=	(55.5 - 27.5)	+	1.5	- .8
1964	39.8	=	(55.3 - 19.3)	+	0	+ 3.8
1965	52.8	=	(51.8 - 9.8)	+	13.5	- 2.8
1966	38.0	=	(49.0 - 11.5)	+	1.3	- .8
1967	35.0	=	(52.3 - 22.3)	+	1.3	+ 3.8
1968	36.0	=	(49.8 - 13.0)	+	1	- 1.8
1969	44.8	=	(52.0 - 11.8)	+	.25	+ 4.3
1970	43.8	=	(53.3 - 11.3)	+	4	+ 2.3
1971	39.8	=	(54.5 - 18.5)	+	3	+ .8
1972	50.5	=	(49.5 - 5)	+	7.8	+ 1.8
1973	56.5	=	(54.5 - 1.5)	+	0	+ 3.5
1974	54.5	=	(52.0 - 2.5)	+	9.5	- 4.5
	43.3	=	(52.5 - 13)	+	3.5	+ .3

Source: Edmonton International Airport Monthly Meteorological Records.

APPENDIX C

Table 2

Water Balance For Edmonton International Airport 1962-1974

(Thornthwaite procedures using 10 cm storage level)

Metric Conversions

	Precipitation	=	(P.E.cm - Dcm)	+ Surplus cm	± Storage Change cm
1962	53.4 cm	=	(53.0 - .8)	+ 6.0	- 4.8
1963	41.5	=	([illegible] -14.8)	+ 3.0	- .3
1964	44.0	=	(49.8 - 9.0)	+ 0	+ 3.3
1965	55.8	=	(48.8 - 1.5)	+ 10.8	- 2.3
1966	40.8	=	(47 - 4.3)	+ 1	- 3
1967	33.0	=	(49.5 - 19.3)	+ .75	+ 2
1968	34.5	=	(45.3 - 9)	+ 0	- 1.8
1969	45.5	=	(48.5 - 9)	+ 0	+ 6
1970	17.5	=	(50.5 - 9.5)	+ 4.8	+ .5
1971	40.5	=	(51 -14.3)	+ 5	- 1.8
1972	55	=	(46 - 0)	+ 6	+ 3
1973	57.5	=	(50.3 - 0)	+ 5	+ 2.3
1974	46.8	=	(50.3 - 6.3)	+ 11.8	- 9
	45.5	=	(49.6 - 7.5)	+ 4.2	- .8

Source: Edmonton International Airport Monthly Meteorological Records.

APPENDIX C

Table 3

Water Balance For Edmonton Industrial Airport 1950-1974

(Thornthwaite procedures using 10 cm storage level)

Metric Conversions

	Precipitation	=	(P.E.cm - Dcm)	+	Surplus cm	±Storage Change cm
1950	32.3	=	(51.3 - 18.8)	+	0	- .3
1951	51.0	=	(48.8 - 5.5)	+	3.8	+ 4.8
1952	41.0	=	(58.3 - 15.5)	+	4.3	- 6
1953	63.8	=	(56.3 - 0)	+	5.3	+ 2.3
1954	49.8	=	(49.8 - 0)	+	1.8	- 1.8
1955	50.3	=	(57.3 - 14.5)	+	3.0	+ 4.5
1956	50.3	=	(56.3 - 8.5)	+	6.3	+ 3.8
1957	32.8	=	(55.8 - 25)	+	0	+ 2.0
1958	43.0	=	(60.8 - 18)	+	2.0	- 1.8
1959	44.0	=	(52.5 - 9.3)	+	0	+ .8
1960	49.0	=	(56.5 - 6)	+	0	- 1.5
1961	31.0	=	(58.8 - 25)	+	0	- 2.8
1962	46.0	=	(55.5 - 11.5)	+	2.5	- .5
1963	33.5	=	(59.3 - 24.8)	+	.5	- 1.5
1964	40.3	=	(57.0 - 20.0)	+	0	+ 3.3
1965	53.5	=	(54.3 - 10.5)	+	12	- 2.3
1966	38.8	=	(54.5 - 15.3)	+	0	- .5
1967	38.5	=	(56.8 - 22.5)	+	1.8	+ 1.8
1968	33.5	=	(55.5 - 19.8)	+	0	- 2.3
1969	47.3	=	(56.8 - 12.3)	+	0	+ 3.3
1970	46.3	=	(60.3 - 14)	+	1	- 1

(Table 3 Continued)

	Precipitation	=	(P.E.cm - Dcm) +	Surplus cm	±Storage Change cm
1971	39.5	=	(59.3 - 22) +	1.5	+ .8
1972	50.8	=	(53.8 - 7) +	6.3	- 2.3
1973	54.8	=	(54.5 - 2.3) +	0	+ 3
1974	52.0	=	(53.0 - 3.5) +	6.3	- 3.8
	44.5	=	(55.8 - 13.3) +	2.3	+ 0

Source: Edm[illegible]ial Airport Monthly Meteorological Records.

APPENDIX C

Table 5

Water Balance For Camrose 1951-1974

(Thornthwaite procedures using 10 cm storage level)

Metric Conversion

	Precipitation	=	(P.E.cm - Dcm)	+	Surplus cm	±Storage Change cm
1951	42.3	=	(49.8 - 9.8)	+	2.3	+ 0
1952	33.8	=	(54.5 - 17.8)	+	0	+ 3
1953	46.5	=	(50.5 - 6.8)	+	0	+ 2.8
1954	55.0	=	(46.0 - 0)	+	8.5	+ .5
1955	40.5	=	(51.8 - 13)	+	.5	+ 1.3
1956	41.8	=	(51.0 - 9.5)	+	1.5	- 1.3
1957	37.8	=	(52.8 - 14.5)	+	0	- .5
1958	28.5	=	(53.5 - 25)	+	0	+ 0
1959	41.3	=	(50.0 - 13.8)	+	0	+ 5
1960	--	=	-- --		--	--
1961	--	=	-- --		--	--
1962	--	=	-- --		--	--
1963	--	=	-- --		--	--
1964	--	=	-- --		--	--
1965	--	=	-- --		--	--
1966	45.5	=	(51.5 - 7.5)	+	0	+ 1.5
1967	33.5	=	(53.3 - 23.8)	+	1.8	+ 2.3
1968	34.0	=	(50.5 - 14)	+	0	- 2.5

(Table 5 Continued)

	Precipitation	=	(P.E.cm - Dcm)	+	Surplus cm	±Storage Change cm
1969	45.3	=	(54.0 - 14.8)	+	.5	+ 5.5
1970	42.3	=	(56.0 - 17)	+	6.3	- 3
1971	35.8	=	(53.8 - 20.5)	+	3.5	- 1
1972	51.5	=	(52.3 - 8)	+	7.8	- .5
1973	72.3	=	(50.8 - 0)	+	13.3	+ 8.3
1974	50.3	=	(50.3 - 9.5)	+	19.3	- 9.8
	43.3	=	(51.8 - 12.5)	+	3.5	+ .5

Source: Edmonton International Airport Monthly Meteorological Records.

APPENDIX C

Table 6

Water Balance for Vegreville CDA 1964-1974

(Thornthwaite procedures using 10 cm storage level)

Metric Conversion

	Precipitation	=	(P.E.cm - Dcm)	+	Surplus cm	±Storage Change cm
1964	34.5	=	(50.3 - 20.3)	+	0	+ 4.8
1965	46.3	=	(50.3 - 4.8)	+	2	- 1.3
1966	28.0	=	(51.0 - 22.3)	+	0	- 1
1967	29.5	=	(50.5 - 22.8)	+	0	+ 1.8
1968	35.5	=	(47.3 - 11.3)	+	0	- .5
1969	33.5	=	(53.5 - 21.3)	+	0	- 1.3
1970	37.8	=	(51.5 - 14.8)	+	0	+ 1
1971	36.3	=	(52.0 - 15.0)	+	0	- .8
1972	39.3	=	(48.0 - 9.8)	+	1.5	- .5
1973	53.8	=	(51.8 - 2.3)	+	0	+ 4.3
1974	39.0	=	(49.8 - 9.3)	+	4.8	- 6.3
	37.5	=	(50.5 - 14)	+	.8	+ .2

Source: Edmonton International Airport Monthly Meteorological Records.

APPENDIX D

The Number of Sampling Sites Used to Obtain Average Snow Depth and Water Content Data For Each Density Level

Density Level	Number of Samples	Average Depth	Average Water Content
1	4	9.4", 23.5cm	2.8", 7.0 cm
2	3	11.9", 29.8cm	4.2", 10.5 cm
3	4	24.9", 62.3cm	7.6", 19.0 cm
4	5	17.3", 43.3cm	3.9", 9.8 cm
5	4	15.2", 38.0cm	4.1", 10.3 cm
6	4	25.5", 63.8cm	8.2", 20.5 cm
7	2	18.7", 46.8cm	6.2", 15.5 cm

Source: April 10, 1975, Fieldwork by the author.

APPENDIX E

Density Levels Ranked in Order of Snow Depth and Water Content

Density Level	Snow Depth	Water Content
6	25.5 inches, 63.8 cm	8.2 inches, 20.5 cm
3	24.9 inches, 62.3 cm	7.6 inches, 19.0 cm
7	18.7 inches, 46.8 cm	6.2 inches, 15.5 cm
2	11.9 inches, 29.8 cm	4.2 inches, 10.5 cm
5	15.2 inches, 38.0 cm	4.1 inches, 10.3 cm
4	17.3 inches, 43.3 cm	3.9 inches, 9.8 cm
1	9.4 inches, 23.5 cm	2.8 inches, 7.0 cm

APPENDIX F

Land-Use Classification System for Use With Remote Sensor Data

Level I	Level II
01. Urban and Built-up Land.	
	01. Residential.
	02. Commercial and services.
	03. Industrial.
	04. Extractive.
	05. Transportation, Communications, and Utilities.
	06. Institutional.
	07. Strip and Clustered Settlement.
	08. Mixed.
	09. Open and Other.
02. Agricultural Land.	
	01. Cropland and Pasture.
	02. Orchards, Groves, Bush Fruits, Vineyards, and Horticultural Areas.
	03. Feeding Operations.
	04. Other.
03. Rangeland.	
	01. Grass.
	02. Savannas (Palmetto Prairies).
	03. Chaparral.
	04. Desert Shrub.
04. Forest Land.	
	01. Deciduous.
	02. Evergreen (Coniferous and Others).
	03. Mixed.
05. Water.	
	01. Streams and Waterways.
	02. Lakes.
	03. Reservoirs.
	04. Bays and Estuaries.
	05. Other.

06. Nonforested Wetland.
    - 01. Vegetated.
    - 02. Bare.

07. Barren Land.
    - 01. Salt Flats.
    - 02. Beaches.
    - 03. Sand Other Than Beaches.
    - 04. Bare Exposed Rock.
    - 05. Other.

08. Tundra.
    - 01. Tundra.

09. Permanent Snow and Icefields.
    - 01. Permanent Snow and Icefields.

Source: Geological Survey Circular 671.

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