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SOURCE REGIONS OF SNOWMELT IN PRAIRIE ENVIRONMENTS

by

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Source Regions of Snowmelt in Prairie Environments.

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ABSTRACT

This thesis has examined the impact of heterogeneous snow cover on the measurement of snowpack as an index of snowmelt runoff. Under Prairie conditions it was found that multiple-point snow survey courses appear to be most efficient and economical and that the Mount Rose volumetric snow sampler is preferred for sampling numerous sites in a short time period. In conditions of below normal winter precipitation it was also found that for one small Prairie drainage basin, snowmelt runoff occurred almost exclusively from natural and man-improved drainageways with upland agricultural areas contributing only minor quantities. It was concluded that existing snow course index sites operated by agencies such as the Water Control and Conservation Branch of the Manitoba Department of Mines and Natural Resources should be supplemented by measurement of snowpack in areas of greatest accumulation.

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CHAPTER I

PROBLEM STATEMENT

Introduction

Methods of predicting snowmelt runoff are subject to many uncertainties. In part discrepancies arise in utilizing point snowfall measurements rather than direct measurement of the quantity of snow available within the snowpack. Determination of either the actual snow water-equivalent within a drainage basin or the potential snowmelt by means of index values (gauged at representative sites within the basin) presents many difficulties primarily because snow is very easily displaced by wind. Consequently, the snow accumulates on the ground in a highly heterogeneous manner and it becomes difficult to obtain representative measurements.

The estimation of snowmelt runoff from a given drainage basin may be viewed along a continuum: at one extreme is the use of point snowfall as index of potential runoff while at the other end is a very intense monitoring of the basin snowpack water-equivalent (Figure 1.1). Clearly, both extremes are unacceptable, the former because of crudeness and the latter due to financial constraints. What is required is the best approximation of the absolute water-equivalent within the basin. Much current research has focused on developing sophisticated remote-sensing techniques of estimating areal values of water-equivalent but it is apparent that many problems still exist with these approaches (Ferguson and Pollock, 1971).

Snow Accumulation

Although several point measurement techniques have been adopted to

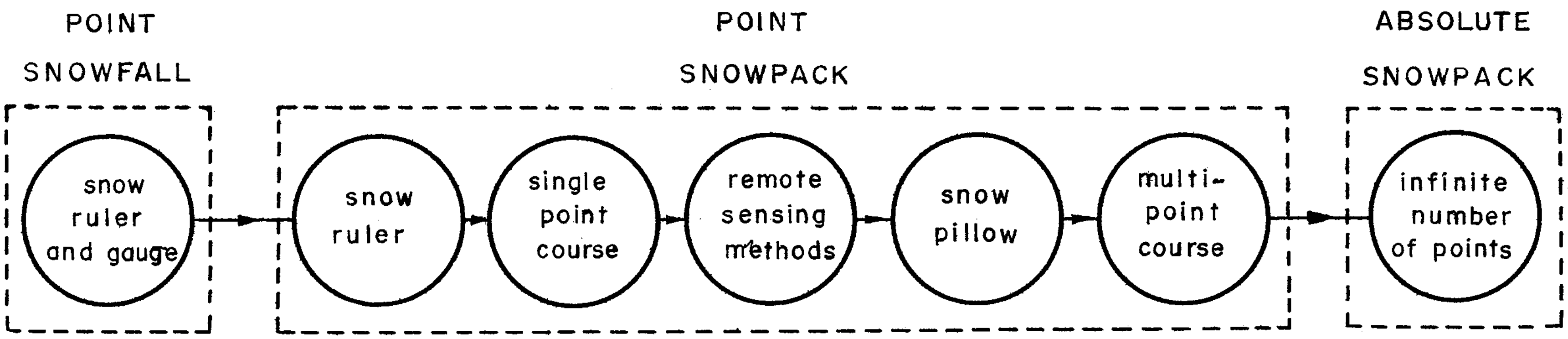


FIGURE 1.1. Estimates of the Absolute Water Equivalent in a Basin Snowpack.

measure both snowpack and snowfall, both types of measurements are subject to uncertainties (see, for example, McKay and Blackwell, 1961).

Point Snowfall Measurement: Snowfall measurements at Canadian climatological stations are taken by measuring snow thickness several times with a ruler. In addition, synoptic weather stations have utilized Nipher-shielded snow gauges since 1960.

Probing of snowfall with a ruler may involve errors because the depth of newly-fallen snow is converted to an equivalent water content on the assumption that 10 inches of snow equals one inch of water. McKay and Blackwell (1961, p.28) state that new snow densities have been observed to vary from 0.035 to 0.175.

Certain problems arise in using snow gauges for the measurement of snowfall. Unshielded-gauge catch accuracies have been observed to decrease rapidly with wind speed, from 80% at 5 miles per hour to 40% at 25 miles per hour, while shields tend to improve the gauge catch accuracy by 40% (U.S. Army Corps of Engineers, 1956). Gray, Norum and Dyck (1970b) collected data on highly exposed fields in Saskatchewan to compare "ground catch" with measurements taken with shielded Fischer-Porter precipitation gauges and found that the "gauge catch" represented only 47% of the average water equivalent of the snowpack on the ground. These results are in apparent contradiction to an earlier study (McKay, 1963) which found that most prairie snow courses retained about 60% of the snow reported at adjacent climatological stations. The results are not directly comparable, however, because: (1) McKay's study was based on freshly fallen snow whereas Gray, Norum and Dyck used the entire snowpack; (2) McKay's data were obtained from standard unshielded M.S.C.

gauges rather than Fischer-Porter shielded gauges; and (3) many measurements used by McKay were taken from gauges in sheltered farmyards and not in exposed positions as in Gray's study.

Point Snowpack Measurement: Point snowpack measurement is either done by probing with a ruler or by sampling five or ten points at each snow course with snow sampling tubes. The latter provide cores of snow which, when weighed, give the actual water equivalent of the snowpack. For assessing basin snowpack the snow tube has been found to provide more accurate measurements than snow gauges, although difficulties may arise in sampling shallow packs because of the problem of obtaining earth-free samples. However, with care this shortcoming can be eliminated.

Many researchers have investigated the reliability of various precipitation gauges and the problems involved in snowpack measurement (Black, 1954; Thomas, 1964; Bogdanova, 1968; Ferguson and Pollock, 1971). Peck (1972a, p. 247) recently stated that: "attempts during the past 100 years to use precipitation gauges to obtain a reliable and consistent measurement of snowfall have been unsuccessful. Using point or snow course measurements to obtain an accurate areal coverage of the water equivalent of the snow cover has likewise been unsatisfactory".

Runoff Forecasting Techniques

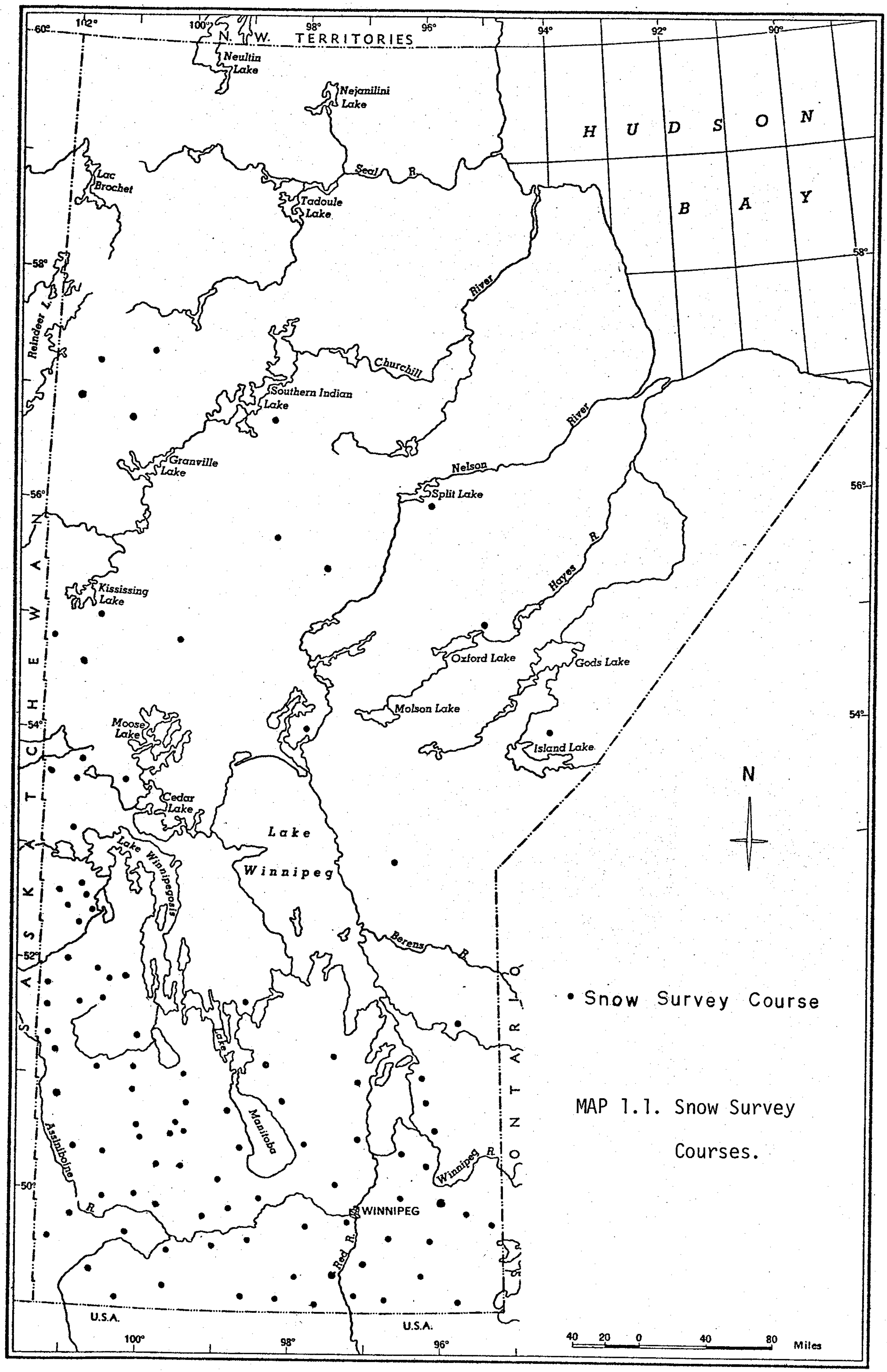
Preliminary flood forecasts for various watersheds in Manitoba are issued at the end of February and March of each year. Three different techniques have been utilized with varying success: a co-axial graphical relationship and multiple regression approach; snow survey sites; and, index basins.

The co-axial graphical runoff-prediction method is based on accumulated snowfall, precipitation during the melt period, a degree-day melt index, and a soil-priming or baseflow index. Accumulated snowfall is the precipitation expressed as a water equivalent that occurs from freezeup to March 31 (including the total precipitation for November unless freezeup occurs unusually late) and is commonly observed to be greater than the water equivalent of the snow cover (Red River Basin Investigation, 1953, pp. 54-55).

The reliability of this approach for forecasting runoff may be illustrated for the Red River at Emerson, Manitoba for a 34 year period of high flows between 1913 and 1970. The correlation coefficient, r, is 0.88 with a standard error of estimate of 0.28 inches and a mean of 0.87 inches between forecasted and observed runoff. Similarly, the correlation between forecast and actual peak flows at Emerson during March was 0.71, based on 17 spring forecasts issued since 1954. The standard error of estimate was 12,980 c.f.s. and the mean peak flow was 26,650 c.f.s. (Manitoba Department of Mines and Natural Resources, Water Control and Conservation Branch, 1971, p. 10).

Information relating to winter snowpack is obtained during the third week of February and March at designated snow survey courses operated by Manitoba Water Control and Conservation (see Map 1.1). Most of these sites have been in continuous operation since 1951. However, the results of these snow surveys are not used directly in runoff forecasting models but the information is critically examined to provide an indication of the over-winter depletion of the snowpack.

The original criteria used in selecting snow survey sites in Manitoba are unknown (personal communication with Mr. Alf Warkentin of



MAP 1.1. Snow Survey Courses.

Water Control and Conservation). However, some of the apparent considerations have been outlined by the Manitoba Water Control and Conservation Branch in a 1962 report and are reproduced in the Appendix. Briefly these include locating snow survey sites in clearings within upland bush areas, and in open, wind-swept locations. Also, the "surveys should be made on a sufficient number of courses properly located on each drainage basin to cover the variability of storms over the area) (p.1). Finally, in order for these sites to be useful as indices, it is essential that no change in land use has occurred during the period of record. Unfortunately, no data on the vegetative cover have been kept although it was observed during 1972-73 that the snow course west of St. Norbert (C-18) had changed from pasture to crop. Most sites appear to be in exposed, grassy locations.

Because these previous techniques correlated poorly with snowmelt runoff, Water Control and Conservation established three index basins in Southern Manitoba, near Rosengart, Joubert Creek, and Morden. The Rosengart basin was discontinued after its first year (1969) as snowpack/snowmelt relationships could not be established. The Morden site has been monitored since 1967 while Joubert Creek has records from 1971 and 1972. No measurements were taken at either in 1973 due to unusually light snowfall although runoff was significant. In all three index basins 37 3-point snow courses were established with most being in exposed locations and the remainder in bush. No agreement between snowpack and runoff could be ascertained.

Conclusion

In many drainage basins in Manitoba and quite possibly elsewhere, little correlation appears to exist between measured snowpack at sites representative of large areas and spring runoff. Siddoway (1970, p. 182) suggests that this is partly because "snowfall in the Northern Plains [including the Canadian Prairies] and the depth of snow cover on an open field are, more often than not, uncorrelated. In the absence of vegetation or other surface roughness, fields are swept bare. Snow that would otherwise provide cover and a water source terminates in gullies, fence rows or behind other obstacles that reduce wind velocity and cause deposition". Yet it is equally obvious that snowmelt and snowpack <u>are</u> directly related.

It is the contention of this thesis, therefore, that existing snowfall and snowpack measurements are not providing an accurate input to snowmelt predictions primarily because the sites being sampled are not contributing significantly to runoff. As Gray (1970, pp. 2.41-2.42) observed: "Unrepresentative sites are frequently the major or only areas contributing to runoff. If a relationship between snowpack and runoff from Prairie watersheds is often entirely from gully accumulation, and the snow disappears from the representative sampling points well before there is any measurable runoff through the stream-gauging station". By identifying potential source regions of snowmelt runoff from Prairie watersheds, it is hoped to better estimate an index value for runoff which takes into account the factors which determine the heterogeneous character of snowpack formation and the implications on runoff regimes.

CHAPTER II

SNOWPACK FORMATION

Introduction

In order to identify source regions of snowmelt runoff from Prairie Watersheds, it is first necessary to examine those factors that control the spatial distribution of snow on the ground. These may be classified as either surficial or meteorological. Surficial variables include the structure and density of vegetation as well as surface irregularities such as depressions and stream channels. Some of the meteorological parameters include: snowfall intensity; wind duration, direction and velocity; and, factors which influence the mobility of snow such as the shapes and sizes of crystals, air temperature and absolute humidity.

Surficial Variables

The ability of the ground to catch and retain snow is largely a function of surface roughness. In general, the snow retention coefficient or ratio of snow retained to recorded snowfall increases with permeability of the vegetation although height is a complicating parameter. The size, shape, orientation to winds, and number of surface irregularities also complicate the formation of a snowpack. These surficial variables may be conveniently examined under three sub-headings, namely forest environments, prairie agricultural land use and surface irregularities.

Forest Environments: An examination of the literature pertinent to this thesis reveals little detailed research on the snow catch and retention properties of vegetation. It appears that most research has centered around alpine studies and in particular the effects of forest management on snow accumulation and interception and subsequent spring melt (see, for example, Maule, 1934; Haupt, 1951; Miller, 1964; Wilken, 1967; Gary and Coltharp, 1967). Packer (1962) found that canopy density was most significant in explaining the water stored as snow in forests. However, Connaughton (1935) could not explain the fluctuation of canopy interception from year to year in terms of air temperature, wind movement and precipitation other than to say that "presumably climatic conditions accompanying and following each storm throughout the winter materially influence the quantity of snow and water which reaches the forest floor" (p. 566). Kienholz (1940) suggested a continuum of snow interception varying from open vegetation to hardwood stands and finally to coniferous trees. He also suggested that where canopy density increases, the susceptibility to drifting decreases.

Field windbreaks have also been of considerable interest with regard to the collection of snow (Stoeckeler and Dontignac, 1941; Staple and Lehane, 1955; George, Broberg and Worthington, 1963). Such factors as the height and density of trees and bushes have been postulated to explain snow accumulation. Potter, Jongwell and Mode (1952) found that tall trees had little or no effect on snow accumulation as compared to dense shrubs or well-branched small rows of trees. They also noted the effect of trees in reducing fetch. It was observed that the snow deficiency on stubble fields as compared to non-shelterbelt fields was evident for one-quarter mile to leeward of the shelterbelt.

Prairie Agricultural Land Use. Snow drifts may be induced by very slight perturbations in the airflow caused by tufts of grass, ploughing or other land use practices. According to McKay (1968) snow accumulation continues until the snow depth reaches stubble height at which time the ground becomes effectively smooth and the transport of snow uniform. However, since Prairie snowpacks are usually shallow, variations in snow cover are pronounced. Any change in agricultural practice will vary the snow retention characteristics.

In general, studies done in Prairie environments have been mostly concerned with the impact of vegetation on snow distribution insofar as it relates to frost penetration and soil moisture recharge (see, for example, Matthews, 1940; Post and Dreibelbis, 1942; Staple and Lehane, 1952; Staple, Lehane and Wenhardt, 1960; Timmons and Holt, 1968; Willis and Haas, 1969; Willis, Haas and Carlson, 1969). Staple and Lehane (1954) examined soil moisture recharge between stubble fields and summerfallow at Conquest and Aneroid, Saskatchewan and Lyleton, Manitoba, but suggested that the only net gain from snow in a shelterbelt project was due to snow loss prevention along roadsides and gullies since the height of the stubble was the main factor determining snow depth.

Although mainly concerned with soil moisture recharge on alfalfa, picked corn and fall-ploughed areas at Mandan, North Dakota, Timmons and Holt (1968) observed that "snow accumulation is influenced by many factors...snow moved by wind can increase or decrease the amount of snow cover, depending on soil surface conditions and crop cover" (p.179). Also, the "amount of snow trapped was influenced by the presence or absence of plant stubble and by the stubble height", but that all three field conditions retained less water as snow catch than was received as precipitation (p.180). Other than to say that some of this additional snow accumulated at adjacent snow fences, no mention was made of snow accumulating in other areas (Table 2.1).

Post and Dreibelbis (1942) concluded from their study that the "principal functions which vegetation served were to provide standing, dormant, or dead plant materials for the retardation of drifting snow, and to form a supporting framework which tended to maintain the snow in the loose condition in which it originally fell" (p. 99). Siddoway (1970, p. 183) suggested that "stubble height...governs snow depth on fields, but the short stubble (6-12 inches) from spring grains does not have sufficient roughness to trap blowing snow from contributing areas or to catch and hold an entire winter's snowfall". Richter (1945) also observed that "in areas with cut or cropped grass growth, snow is lacking almost completely [while] areas with untouched grass or with stalks of corn, sunflowers, or sorghum left standing there over the winter present one huge snowpack".

Finally, various researchers have investigated techniques of redistributing and retaining winter precipitation, such as using snow fences (Berndt, 1964; Martinelli, 1965; Schmidt, 1970; Swank and Booth, 1970) or snow ridging on agricultural fields (Matthews, 1940). Pawlowski and smith (1966) suggested utilizing sunflowers instead of fallow for conserving snow and enhancing soil moisture recharge but no data were presented, while Siddoway (1970) observed that, for some farmers in North Dakota, strips of flax one foot wide, 14 to 16 inches tall, and spaced 12 feet apart produced a uniform snow cover. He also found that strips with a spacing of 10 to 12 times the height of the vegetation produced a more uniform snow distribution over a large field "under

Crop Type	Ppt. from Freezeup to Thaw, (in.)	Snow Water Equivalent, (in.)	Snow Retention Coefficient	Year
Corn		3.9	0.91	
Alfalfa	4.3	3.1	0.72	1963-64
Fall-ploughed		1.6	0.37	
Corn		3.9	0.61	
Alfalfa	6.4	1.5	0.24	1964-65
Fall-ploughed		1.1	0.17	

TABLE 2.1. Variation of Snow Water Equivalent with Crop Type, North Dakota, 1963-65. (After Timmons and Holt, 1968, p. 178).

variable wind drift directions for short barriers than for tall barriers. Deep drifts would not form behind short barriers, and in the event of uneven drifting between barriers, the probability of uniform distribution of snowmelt on the narrow interval would likewise be greater" (p. 183).

Surface Irregularities. Research on the effects of variations in micro-topography on snow accumulation is sparse. Recently, the Saskatchewan Research Council has undertaken measurement of snow on summerfallow and stubble as influenced by minor variations of topography (Lakshman, 1971). Their preliminary results suggest that the greatest depth of snow and water content occur in channels with a stubble cover while the smallest snow accumulation occurs on flat summerfallow land (Table 2.2). However, no information is provided on channel characteristics, height of stubble or snowfall recorded.

Meteorological Variables

The initiation of snow transportation is a complex process involving water budget, energy budget and surface roughness variables. Anderson (1968) evaluated the effects of 23 independent variables on snow accumulation in forests, forest opening and forest margins and observed that storm characteristics (precipitation in particular) explained most of the variation in snow accumulation. However, the regression coefficients were extremely low. Bilello (1958, 1969a) studied the relationships between climate and regional variations in snow-cover density in North America and observed that wind speed and average air temperature provided only an estimate of density for a general area. However, no attempt was made to examine snow depth and water content in terms of climatic variables.

Crop Type		Topography			
		Flat	Slope	Channel	Depression
Stubble	Snow Depth, (in.)	9.8	10.6	11.2	10.2
	Water Content, (in.)	2.4	2.6	2.6	2.3
	Snow Density, (%)	24.6	23.6	23.0	22.9
	No. of Samples	204	198	45	34
Summer-Fallow	Snow Depth, (in.)	6.4	7.1	8.0	6.6
	Water Content, (in.)	1.8	2.1	2.2	1.6
	Snow Density, (%)	27.4	28.3	24.8	24.3
	No. of Samples	260	191	12	18

TABLE 2.2. Snowpack Variation with Crop Type and Topography, Saskatchewan, 1969-70. (After Lakshman, 1971).

Much research has been directed toward evaluating the quantity of snow transported under varying meteorological conditions but much still remains to be done (Dyunin, 1954, 1961, 1967; Chepil, 1965; Budd, 1966; Tabler and Schmidt, 1972). It would appear that the total snow flux is best equated to wind velocity to not less than the third order of magnitude although the size of the snow-collecting area and the nature of the adjacent locality are important considerations (Komarov, 1954).

The quality of snow flakes varies widely from light to heavy depending primarily upon air temperature. Granular snow flakes are easily rolled making prediction of snow transportation even more difficult (Theakston and Naraine, 1967). A snow cover composed of loose, dry crystals 1 or 2 millimeters in diameter is susceptible to drifting under fairly light winds in the order of 3 meters per second (McKay, 1968). Glaze from condensation and melting may not inhibit transportation even under very strong winds.

Fraser (1964) analyzed blowing snow data for 15 Arctic weather stations on the basis of 3-hourly observations and suggested that time elapsed since last snowfall, duration of winds of a given speed, surface wind speed and direction, and depth of snow on the ground are important in explaining snow drifting.

Summary

From the preceding it is apparent that snowpack formation is a complex process. Meteorological and surficial parameters interact to produce large variations in snow cover. Consequently, the identification of unique snowmelt runoff sites within a study area is difficult.

CHAPTER III

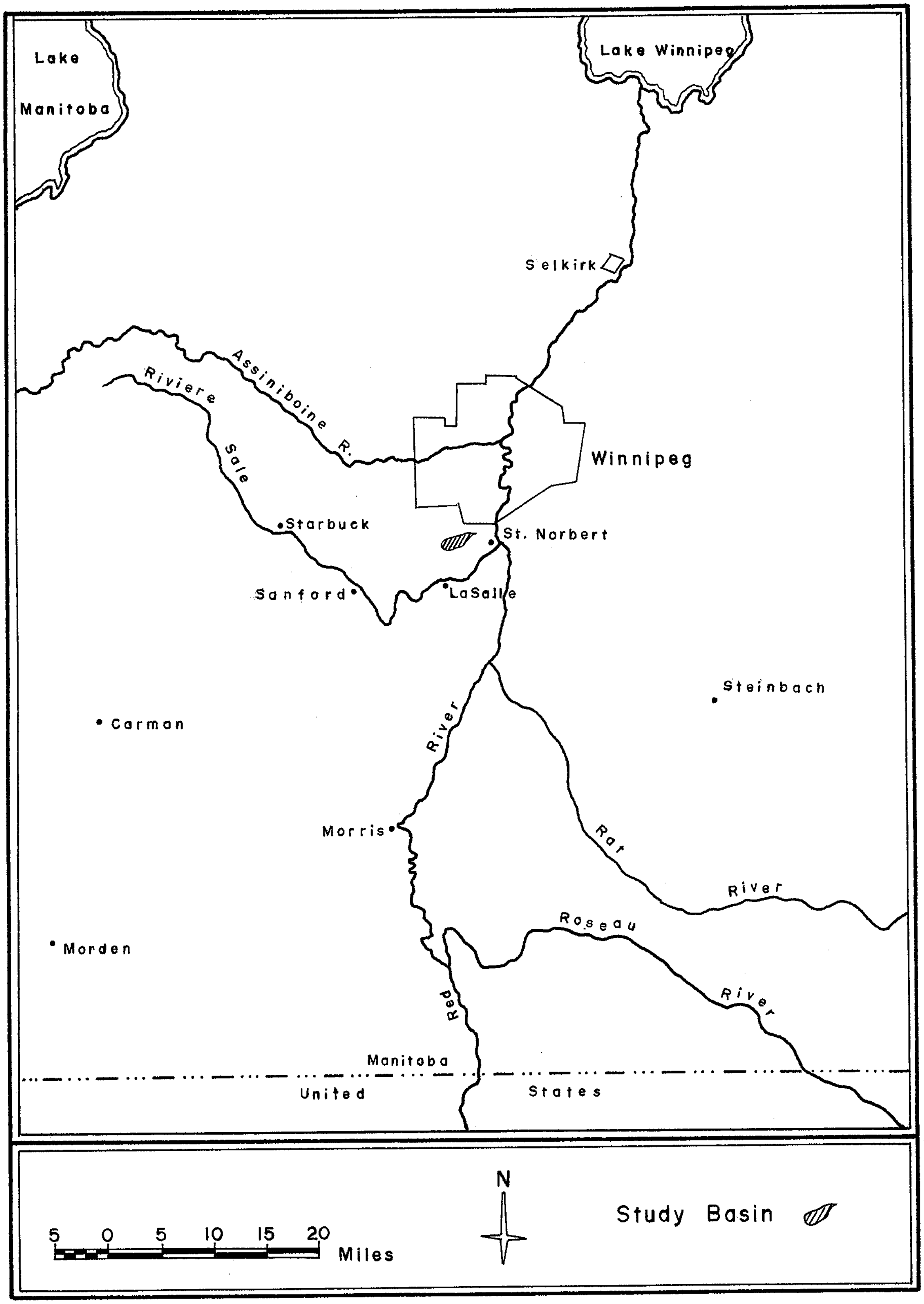
METHODOLOGY

Study Basin Characteristics

Basin Selection. The selection of a study area had to satisfy four conditions: (a) exhibit a variety of land use; (b) have both natural and man-improved drainage channels; (c) be characteristic of a fairly large region; and (d) be easily accessible from Winnipeg.

Accordingly, a small drainage area approximately ten miles south of Winnipeg and one mile west of the village of St. Norbert, in what Ehrlich *et al* (1953, p. 1) described as the Red River Plain Sub-Area of the Manitoba Central Lowland was selected (Map 3.1). Specifically, the basin is located in Township 9, Range 2 East and the western part of Range 3 East. Other towns in the area include La Salle to the south, Sanford to the southwest, Starbuck to the west, and Ft. Whyte to the north.

Basin Delimitation. The flat nature of much of the Prairies makes it very difficult to delimit watersheds. Existing topographic maps with a contour interval of ten feet and aerial photographs are of limited utility in demarcating drainage divides for basins with available relief in the order of 20 to 30 feet. However, from examination of directions of flow of surface runoff along road-side drainage ditches in the Spring of 1972, it was apparent that many sub-basins are determined at least in part by artificial boundaries such as roads. To verify this observation at points where surface runoff could be in two or more directions, the direction of flow was determined by leveling along the drainage ditches. At other



MAP 3.1. Location of Study Basin With Respect to Southern Manitoba.

points of contention traverses were run approximately perpendicular to the roads to determine more accurately the drainage boundaries. Map 3.2 shows the physical features of the study basin thus delimited. The drainage area as determined from planimetering is 6.67 square miles (4270 acres).

Basin Description.

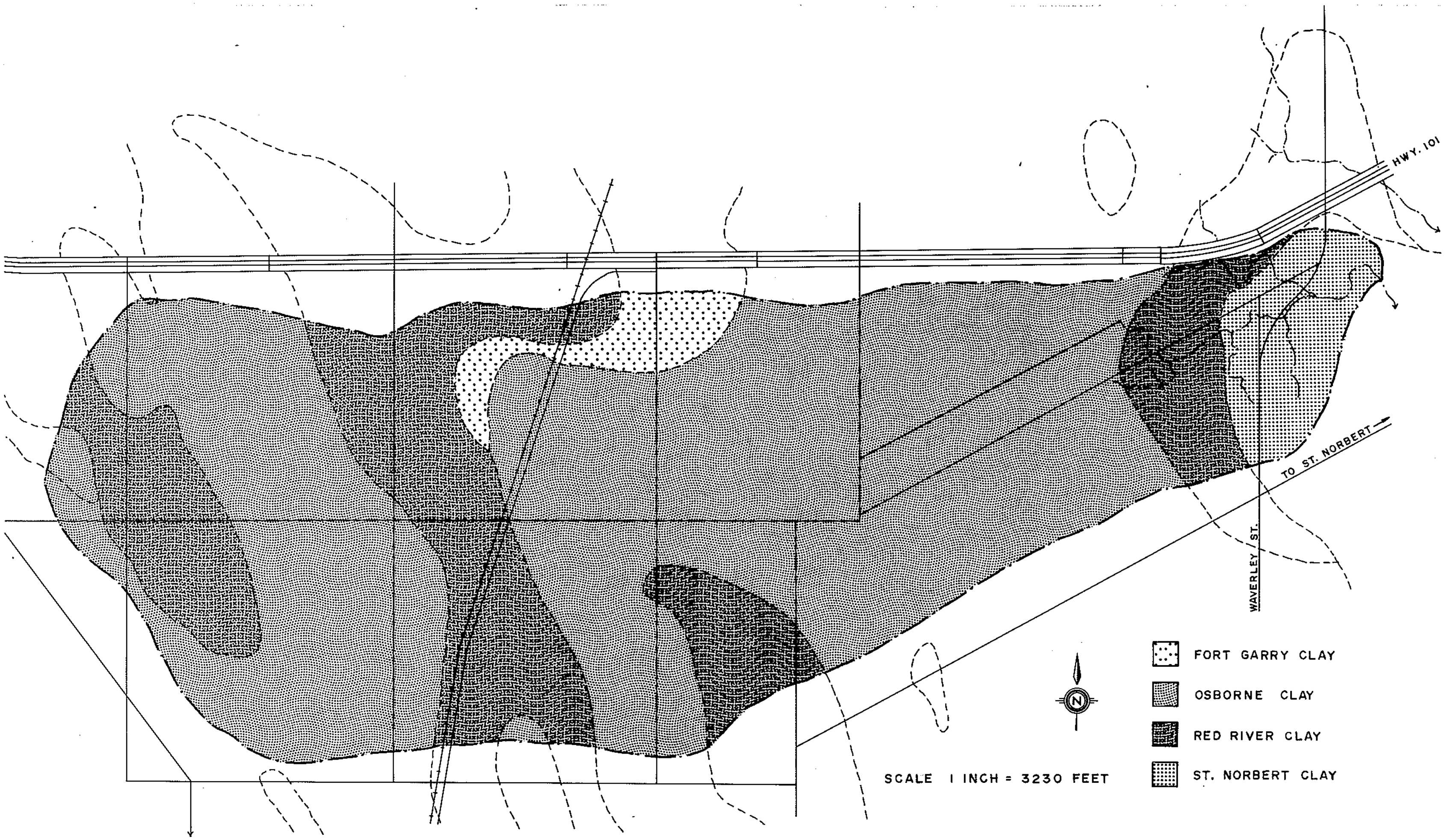
(a) Geology:

The rocks underlying the Red River Plain range in age from the Precambrian to the Cretaceous periods. Sedimentary rocks of the Paleozoic Era (Ordovician, Silurian and Devonian periods) dip westward and are principally limestones and dolostones with minor quantities of shales, sandstones and evaporities. The Mesozoic is represented by Jurassic and Cretaceous shales and interbedded sandstones and limestones.

The Red River Plain lies entirely within the margins of glacial Lake Agassiz which covered much of Manitoba to varying depths as late as 7800 B.P. Much of the plain is underlain by glacial drift up to 200 feet thick (Davies et al, 1962, p. 152). During the time of occupance of Lake Agassiz, streams were responsible for carrying and depositing fine material within the lake basin. The thickness of these water laid sediments differs widely but in the Central Lowlands may be as much as 60 feet. No detailed information is available for the study basin.

(b) Topography and drainage:

Largely in response to the geologically-recent glacial history, most of the Red River Plain may be designated as flat. This broad



MAP 3.2 MAJOR SOIL TYPES WITHIN THE STUDY AREA

expanse of terrain slopes almost imperceptibly from the margins to the Red River and from south to north. The study basin itself slopes from approximately 775 feet above sea level in the west to about 750 feet above sea level in the east. The only natural breaks in the landscape are the stream channels cutting through the lacustrine clays and their associated natural levees. An extensive system of drainage ditches for reclamation of wet meadow areas is also a noticeable feature of the area.

(c) Climate:

Data for Winnipeg provide an indicator of general climatic conditions for the study area. By virtue of its location, Winnipeg's climate is typically continental with an early summer precipitation maximum with wide ranges of annual, seasonal and diurnal temperatures. The monthly mean temperature varies from -2^{o} F in January to 67^{o} F in July with the average yearly temperature being 35.4^{o} F (Labelle _et al_, 1966, p. 29). The mean annual precipitation (1931-1960) is 20.35 inches of which 15.22 falls as rain (Labelle _et al_, 1966, pp. 34-36). In other words the mean annual snowfall is 51.3 inches. The greatest snowfall, 99.5 inches, was recorded in 1955-56 and the least, 22.7 inches, in 1928-29 over the period 1874 to 1963 (Thomas, 1964). Snowpack, as recorded by the snow course at Winnipeg International Airport (1966-1973), shows a maximum depth range of 8.6 to 16.1 inches and a variation in maximum water equivalent from 2.5 to 4.2 inches. These values bear little relation to snowfall or to each other. Yearly snowfall as recorded by ruler during 1971-72 and 1972-73 at the St. Norbert Climatological Station was 41.2 and 34.5 inches while the maximum depth of snow on the ground was 16 and 11 inches, respectively.

(d) Soils:

The Red River Plain is in the Blackearth soil zone. The soils located within the study basin include Osborne, Red River, St. Norbert and Fort Garry clays and represent 65%, 26%, 6% and 3% of the drainage area, respectively (Table 3.1, Map 3.2).

The Osborne soils have developed on flat or depressional topography under meadow or swale grass vegetation. Due to the flat topography and heavy texture of the soil, ponding of surface water is common and surface drainage is essential (Ehrlich, et al, 1953, p. 22).

The Red River clays are fine-textured, well to intermediately drained soils. For these soils improved surface drainage is essential where natural drainage is insufficient to remove excess surface water.

The St. Norbert clay is a wooded associate that occurs predominantly along river channels where woodland invasion of prairie has developed to the greatest extent.

Finally, soils of the Fort Garry association are developed on a clay and silty-clay mantle. Although most soils of this association are well to intermediately drained, poor drainage can occur locally.

(e) Vegetation:

The native vegetation of this lacustrine plain region originally consisted of tall-prairie grass, meadow-prairie grass and meadow grass associations with trees growing only as a fringe delineating stream channels. Since settlement, agricultural crops have replaced much of the original vegetative cover. In general, soils developed on the Red River, St. Norbert and Fort Garry clays are best suited to grain

Blackearth Association	Description and Drainage	Area in Acres	% of Total Area	Parent Material
Red River				
(1) Red River Clay (Rc)	well to intermediately drained; some slow internal drainage	1125	26	lacustrine fine clay
(2) Osborne Clay (Oc)	poorly drained; ponding in Spring or after heavy rains	2759	65	lacustrine fine clay
(3) St. Norbert Clay (Nc)	wooded associate; generally well drained	252	6	lacustrine fine clay
Fort Garry				
(1) Fort Garry Clay (Fc)	intermediate and poorly drained; localized ponding during wet seasons	134	3	deltaic and lacustrine deposits; clay over sandy clay calcareous subsoil
	TOTAL	4270	100	

TABLE 3.1. Basin Soil Types and Contributing Areas, St. Norbert.

crops, row crops, grasses, alfalfa and other legumes. Osborne soils are utilized for grain or hay production. Trees still exist along streams and intermittent watercourses as well as in occasional clumps around farmsteads and as windbreaks.

Site Characteristics

Site Selection. In order to relate snowpack accumulation to snowmelt runoff it was necessary to select sites within the study basin which would show the spatial variability of the snowpack throughout the winter. This heterogeneity of snow cover is related to wind direction and velocity and the surface relief and plant cover of the area.

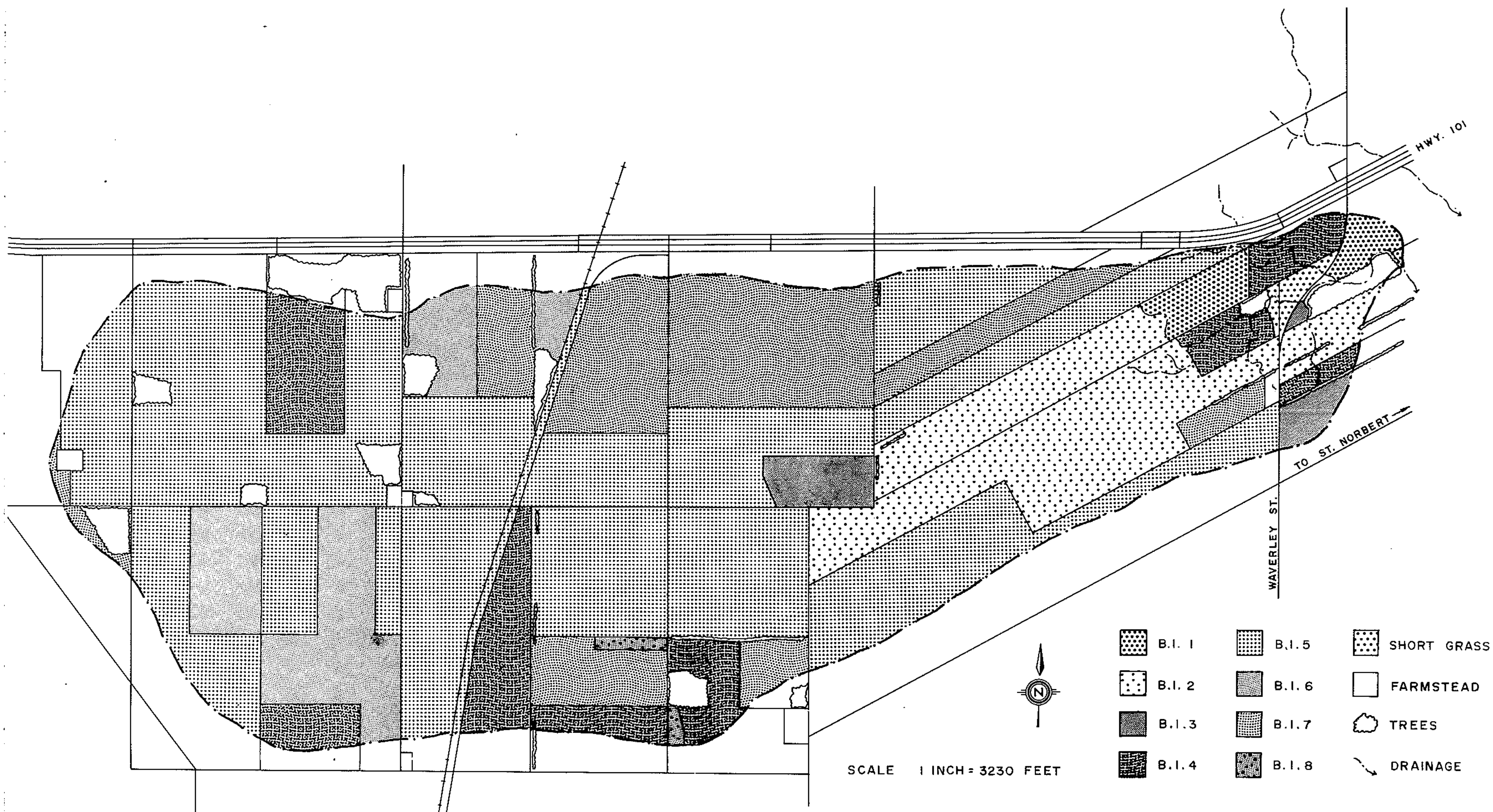
Drifting of snow is most pronounced when sustained, strong winds occur over a long fetch and less pronounced when the winds are varied in direction. For the purpose of this thesis fetch is defined as the openness, measured in the four cardinal directions, of each sampling site. It was felt that a line or stand of trees would be sufficiently impermeable to the passage of transported snow if tree heights were in the order of 30 feet and stand densities approximated 70 percent. Although this definition is subjective, it should be noted that sites were selected only when there was no ambiguity as to the definition of fetch.

In Prairie regions surface relief may be simplified by assuming a fairly uniform and essentially flat topography. However, micro-variations due to natural gullies and man-improved drainage ditches are very important to the redistribution of snow, especially for shallow snowpacks (Kakela, 1971). Insufficient research, however, has been conducted on the interrelationships of gully morphology, orientation, etc. with snowpack accumulation to understand the complexities of such relationships (see, for example, Kuz'min, 1960; Lakshman, 1971).

Finally, variations in vegetative cover influence the amount of snow retained within the basin and subsequent Spring runoff. An inventory of land-use within the study basin completed in October 1972 (Map 3.3) provided the basic information on which ten agricultural sites were selected to account for the most significant variations of plant cover and fetch (Tables 3.2 and 3.3). It should be noted that every potentially different site was not monitored since it was felt desirable for comparative purposes to complete a set of measurements on the same day and that it would have been impossible to adequately sample more sites than were chosen. However, from examination of the basin inventory, the sites not sampled represent an insignificant area when compared to the total drainage area (Table 3.2).

A number of gullies and man-improved drainage ditches as well as a windbreak were studied at various times throughout the 1972-73 winter (Table 3.4). Variations in gully morphology and orientation were selected. Whenever possible, readings were taken on the same day as those of the agricultural fields.

Site Location. Map 3.4 shows the locations of the sites monitored within the study basin during the 1972-73 winter. In total ten agricultural fields, one hedgerow and sixteen drainage channels were selected within this area. In addition, snow survey course C-18 (St. Norbert), operated by the Province of Manitoba Department of Mines, Resources and Environmental Management, Water Resources Branch, is included within the drainage area.



MAP 3.3 BASIN LAND USE INVENTORY, 1972 - 1973

Basin Inventory Number	Description	Sites Monitored	Area (Acres)	Area (%)
1	disced; 25% short stubble	F1	71.2	1.6
2	disced; 50% short stubble	F2	476.1	11.1
3	(disced; rough grazing	F3, F5	81.5	2.0
4	(12" stubble)	F4,	403.2	9.4
5	harrowed; 50% short stubble	F6, F8	2035.2	47.7
6	alfalfa	F7, F9	337.4	8.0
7	harrowed; no stubble	F10	670.1	15.7
8	scrubland	none	14.1	0.3
T	trees and low bushes	H1	99.3	2.5
SG	short grass	none	18.7	0.4
H	farmyards	none	14.1	0.3
D	drainage channels	P1-P16	28.2	0.6
R	rights-of-way	none	19.2	0.4
			4268.3	100.00

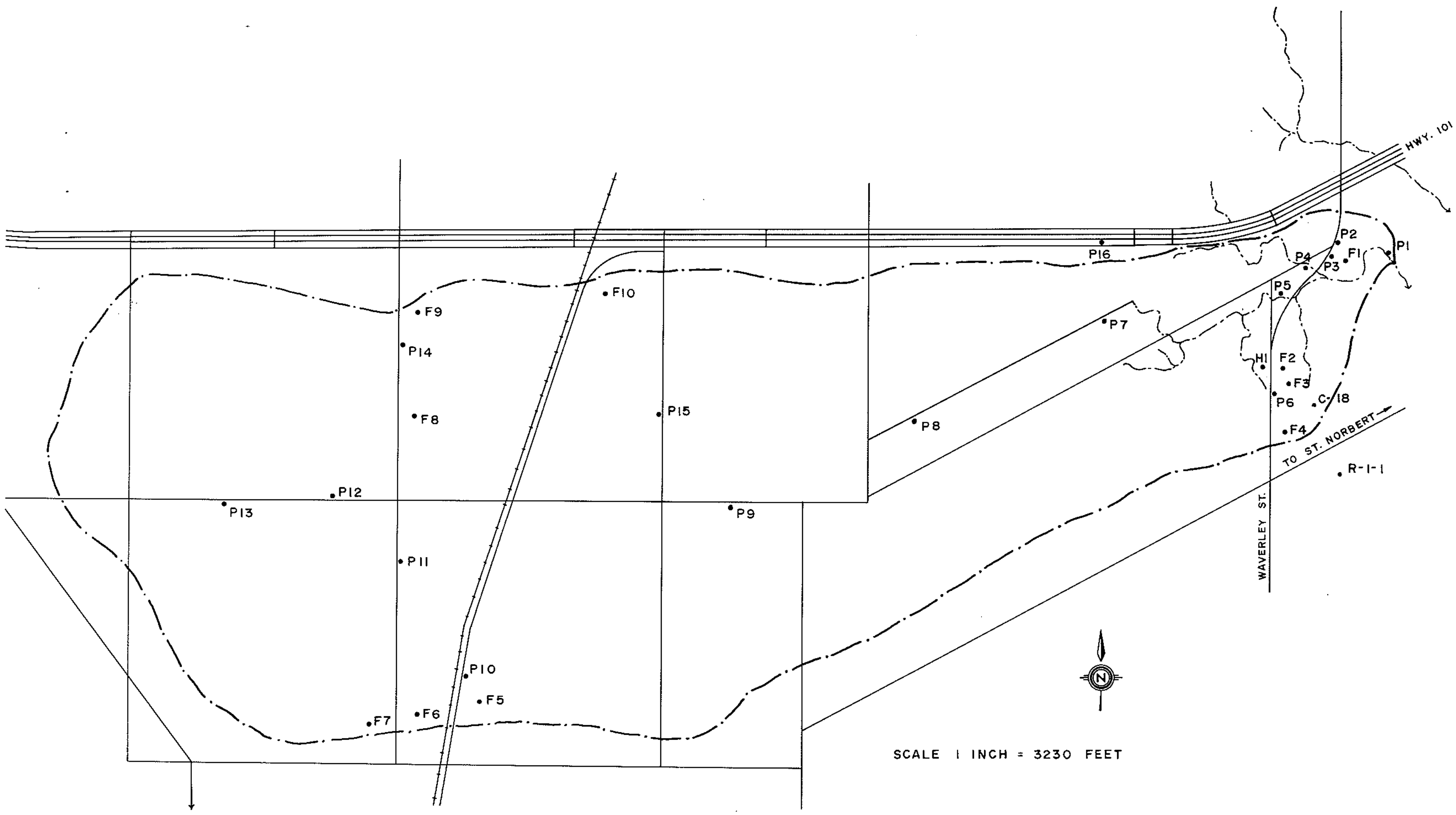
TABLE 3.2. Drainage Areas by Land Use Inventory, 1972-73, St. Norbert.

Snow Course	Azimuth (Degrees)	Fetch (Feet) N	S	E	W	Number of Sample Points	Number of Sample Days
F1	145	-	300	-	-	5	9
F2	151	400	600	-	-	3	9
F3	151	300	800	-	-	2	10
F4	144	600	-	-	-	5	10
F5	162	-	-	-	-	5	10
F6	161	-	-	-	-	5	10
F7	155	-	-	-	-	5	10
F8	163	700	-	-	-	5	10
F9	156	2000	2000	-	400	5	10
F10	153	-	-	-	-	5	10

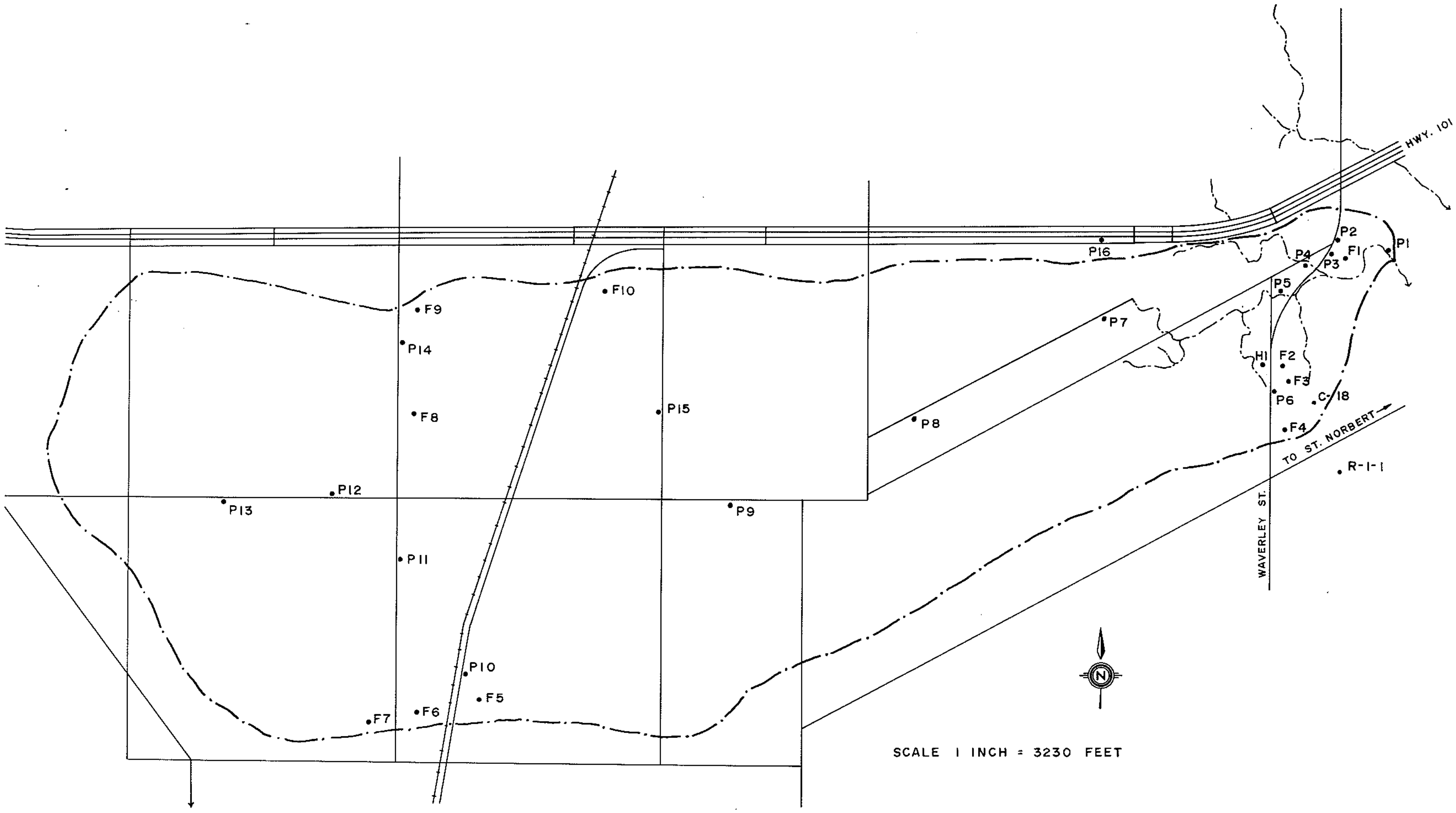
TABLE 3.3. Fields Sampled During the Winter of 1972-73, St. Norbert.

Profile Number	Maximum Width (Ft.)	Maximum Depth (Ft.)	Width/ Depth Ratio	Profile Orientation	Sample Points	Sample Days
P1	65	3.83	17	E-W	1	1
P2	25	3.72	7	N-S	5	10
P3	30	3.65	8	E-W	6	10
P4	160	4.60	35	N-S	1	1
P5	120	7.58	16	N-S	1	1
P6	28	3.38	8	E-W	6	1
P7	35	5.73	6	N-S	9	1
P8	30	6.07	5	N-S	8	1
P9	30	7.70	4	N-S	8	1
P10	40	4.09	10	E-W	10	3
P11	23	3.25	7	E-W	5	1
P12	30	5.72	5	N-S	7	10
P13	22	4.75	5	N-S	8	1
P14	17	2.27	7	E-W	8	1
P15	35	4.11	9	E-W	8	1
P16	100	4.80	21	N-S	19	1
H1	-	-	-	N-S	22	1

TABLE 3.4. Drainage Channels Sampled During the Winter of 1972-73, St. Norbert.



MAP 3.4 LOCATION OF SAMPLING SITES, 1972 - 1973



MAP 3.4 LOCATION OF SAMPLING SITES, 1972 - 1973

Site Description. Land use within the study basin may be classified according to 13 categories, seven of which relate to utilization of the land for agricultural purposes. The other six categories generally comprise a very small percentage of the total basin area (Table 3.2) and include clumps of bushes, isolated stands of trees and windbreaks, grass-covered areas, the land directly adjacent to farm buildings, drainage channels, and wasteland.

By far the largest proportion of the basin (47.7%) is devoted to land which had been harrowed but with 50% of the field containing short stubble (Basin Inventory 5). Two snow courses were established on this cover-type: F6 was selected in a completely exposed location while F8 had a restricted northern fetch of approximately 700 feet.

The second largest field category (Basin Inventory 7) was characterized by very smooth harrowed land containing no stubble. This type represents approximately 15.7% of the total drainage area. One site was monitored on this type of land-use, F10, which had an open fetch.

Field-type F2 can be classified as having been disced with about 50% of the area being short stubble. This represents 11.1% of the basin (Basin Inventory 2). This site was exposed from the west and east but the fetch was restricted to 600 and 400 feet from the south and north, respectively.

Basin Inventory 6 (alfalfa) represents only a small portion of the study area (8.0%) yet from discussions with one of the local farmers (Mr. J.M. Fisher) who made the observation that these fields were favourite sites for snowmobilers, it was suspected that the reason for this popularity was the ability of the field to catch and retain snowfall throughout the winter season. It was decided, therefore, to establish two snow courses on this land-use type, F7 and F9, with the former being in a completely exposed location while the latter had restricted fetches of 2000 feet from the north and south and 400 feet from the west.

Basin Inventory 3, representing 9.4% of the drainage area, consisted of 12-inch high stubble. Again, two snow courses were established on this type of land-use. Field F5 was in an exposed location while F3 had restricted fetches of 300 feet from the north and 800 feet from the south.

Field number F4 (Basin Inventory 4) was classified as unimproved pasture which had been recently disced. This land-use type comprised 2.0% of the study basin. The snow course had a restricted northern fetch of 600 feet.

Basin Inventory 1 (F1) represents 1.6% of the basin. The land had been disced but contained 25% short stubble. The snow course had an unrestricted fetch except from the south where it was equivalent to 300 feet.

Basin Inventory 8, described as wasteland, contains bushes 2 to 3 feet high, rough clods of earth and some tree debris and represents only 0.3% of the basin area. No attempt was made to study snow accumulation on this site.

Although stands of trees are scattered throughout the study basin (representing 2.5% of the total area), they are generally poor retainers of snow, except in their periphery, due to their impermeable nature. They do have a significant impact, however, on restricting the length of fetch of various fields. On the other hand, lines of low-branching trees with intermixed low bushes are very efficient snow collectors. One such windbreak, H1, was examined during the 1972-73 winter to determine the quantity of snow trapped.

Patches of short grass and farmyards comprise 0.4% and 0.3% of the drainage area, respectively. In view of the extremely small contributing areas and restrictions of time, no attempt was made to sample these sites. However, casual observation during the winter revealed that snow catch was negligible for the short grass cover but quite substantial around farm-yards.

Finally, significant attention was devoted toward measurement of snow accumulation in both natural and man-improved drainage channels. Sixteen sites were monitored throughout the basin at various times. In total this type of land-use represents 0.6% of the watershed. Nine of these sites were ditches trending east/west while the remainder were oriented essentially north/south. Thirteen of them could be considered man-improved. Although drainage channels were selected with a variety of widths and depths (Table 3.4), all had a similar short grass vegetation cover. Only three (P1, P4 and P5) were not directly adjacent to access roads and of these P1 was the only channel selected without a completely open fetch, being entirely restricted from the west.

Snowpack Accumulation

Snow Courses. As pointed out previously, measurement of point snowpack depth and water equivalent is usually accomplished with a snow sampling tube. However, individual points are likely to be representative of only small areas and extending these point values to an areal value is tenuous unless an intense sampling program is undertaken. Therefore, the multipoint snow course, when used as an index, appears to be the best alternative as this method samples the snowpack in a number of places yet is fairly economical in time and labour. To determine the nature of these snow courses, careful examination of existing snow survey networks was undertaken.

Meteorological stations in Canada operate either Type A or Type B snow survey courses. At the former station a fixed ten point snow course with points 100 feet apart is established, such that the stakes are apportioned in relation to the major vegetation classes. That is, if 70 percent of the area is forested, 7 out of ten snow course points should be protected from wind action by trees. As these courses may be at some distance from the station, observations are normally taken on the first and fifteenth of each month. Type B courses, such as at the Winnipeg International Airport, consist of five sample points 100 feet apart in or near the instrument enclosure and are, thus, not intended to be representative of the dominant vegetative and topographic characteristics of the area. Snowpack observations are made on the first, eighth, fifteenth and twenty-third of each month.

Codd and Work (1955) have established certain criteria for snow courses in mountainous terrain. They suggest that the number of sampling points should be at least ten but not more than fifteen per course, with each sample being taken as close as possible to the same spot each time but at least within a diameter of four feet. The spacing of sample points was not believed to be critical but for convenience is usually established as 25, 50 or 100 feet.

Leaf and Kovner (1972) found that snow courses using 50 sampling points spaced at 264 foot intervals in forested sub-alpine watersheds "with one, and at most two, samples at a location adequately measure watershed snow storage" (p. 715).

Various researchers, such as McKay (1968), have suggested that more snow depth measurements be used than density measurements. Hegedus and Szesztay (1967) utilized the theory of random errors and determined that, assuming point water equivalent and depth measurements were accurate to 0.1 and 1.0 cm, respectively, 4, 9 and 16 depth measurements for respective densities of 0.2, 0.3 and 0.4 g/cm^3 produced reliable water equivalent estimates.

Snow courses, as operated by the United States Soil Conservation Service, usually consist of not fewer than 10 sampling points located along a predetermined pattern at a spacing of 50 to 100 feet. The ends of the patterns are permanently marked.

Finally, the snow survey sites monitored by the Water Control and Conservation Branch of the Province of Manitoba vary both in the number of points sampled (from 2 to 6) and in the spacing of the observations (from 100 to 1,000 feet), and are usually not consistent in orientation. However, the sites within the index basins are more uniform with orientations being predominantly north-south and secondarily east-west and the spacing between sample points being 150 feet. In all cases three sample points per site are utilized.

From the above brief discussion it is evident that no concensus exists as to the establishment of snow courses. Therefore, for the purposes of this research it was decided to establish on each of the selected agricultural fields fixed snow courses similar to Type B courses as operated by the Atmospheric Environment Service of Canada. Single observations of snow depth, density and water equivalent were made at each stake approximately every ten days, commencing on November 27, 1972 and terminating on March 4, 1973. Both natural and man-improved drainage channels were monitored throughout the 1972-73 snow season with all readings being taken on the same days as the fields, although usually not as frequently. Readings were recorded at approximately six foot intervals at right angles to the trend of the ditches. Only the terminal points of the profile were marked due to the narrow widths of the channels.

Snowpack Sampling. Before establishing a sampling plan for the sites to be monitored during the 1972-73 winter, preliminary measurements were undertaken in the St. Norbert area during March of 1972. Seven types of land-use were examined with the particular intention of determining the effect of direction of snow survey on the reliability of data (Table 3.5). Except in the case of Field 7, two observers were used with the writer running north-south traverses with the Mount Rose snow tube and the second observer sampling in an east-west

Field Number	Description	Traverse	Sampler	Snow Depth N	Snow Depth $\bar{x}$	Snow Depth s	Snow Depth t	Snow Depth v	Snow Depth 95% Confid.	Water Equivalent N	Water Equivalent $\bar{x}$	Water Equivalent s	Water Equivalent t	Water Equivalent v	Water Equivalent 95% Confid.
1	50% plowed stubble	N-S	MR	108	9.09	3.84	1.02	211	x	11	3.90	1.12	1.08	20	x
		E-W	AD	105	8.58	3.64				11	3.36	1.14			
2	plowed, no stubble	N-S	MR	80	7.61	4.11	0.27	140	x	8	3.00	1.32	2.15	12	-
		E-W	AD	62	7.81	4.44				6	1.86	0.47			
3	12-inch stubble	N-S	MR	90	9.29	2.70	2.90	176	-	9	3.94	1.16	0.80	16	x
				88	10.51	3.05				9	3.53	0.97			
4	25% plowed stubble	N-S	MR	60	7.52	3.36	3.51	108	-	6	3.00	1.25	1.39	9	x
		E-W	AD	50	9.56	2.74				5	4.20	1.32			
5	short grass pasture	N-S	MR	50	5.22	3.15	0.97	99	x	5	1.80	0.87	1.93	8	x
		E-W	AD	51	5.92	4.02				5	3.00	0.89			
6	unpicked corn	N-S	MR	23	24.71	5.03	2.74	56	-	3	5.66	1.88	1.85	4	x
		E-W	AD	35	28.00	3.18				3	8.50	1.07			
7	sunflowers	N-S	MR	75	13.61	4.34	0.24	123	x	6	3.91	2.40	0.80	9	x
		E-W	AD	50	13.40	4.91				5	4.90	1.24			

TABLE 3.5. Analysis of Snow Depth, Water Equivalent and Snow Survey Direction, March 14, 1972, St. Norbert.

NOTE: MR = Mount Rose sampler, AD = Adirondack sampler, x = not reject null hypothesis, - = reject hypothesis.

direction using the Adirondack sampler (see section on Sampling Instruments).

Variations in observations may result from inherent differences in the samplers used and different sampling techniques as well as sampling direction. Hopkins (1955, p. 31) found no significant difference between the Mount Rose and Adirondack snow samplers for water equivalents of about 2.5 inches and reported that another researcher drew similar conclusions for a water equivalent of about 6 inches. Since only one traverse produced a mean water equivalent greater than this value (Table 3.5), it is reasonable to assume that the two samplers produced similar results.

To eliminate the operator as a source of variance, comparisons of snow depth and water equivalent at adjacent points were undertaken in the field. No significant differences could be found. Therefore, any differences in field sampling can be attributed to the direction of traverse.

Based on the t-test for comparison of sample means, the hypothesis that there is no significant difference between mean snow depth as determined from north-south and east-west traverses can not be rejected at the 95% confidence level for fields 1, 2, 5 and 7 (50% plowed stubble, plowed with no stubble, short-grass pasture and sunflower field). The hypothesis is rejected, however, for the fields containing 12-inch high stubble, 25% plowed stubble and unpicked corn (fields 3, 4 and 6). In other words, for these three cover-types sampling direction appeared to influence the accumulation of snow recorded during the 1971-72 winter.

Analysis of snow water content according to direction of traverse is more tenuous, however, because of the small sample sizes. According to the t-test for comparison of sample means, the hypothesis that traverse direction does not influence snow water content accumulation can be rejected at the 95% confidence level only for field 2 (plowed with no stubble). In other words 6 out of 7 fields appeared to exhibit changes in snow water content with traverse direction. However, these conclusions may not be too reliable if we examine the magnitude of observational and instrumental error for the snow samplers (see section on Sampling Instruments). For water equivalent determination using the Mount Rose sampler readings are accurate to only within $\pm$ 0.5 inches. For fields 1 and 3 (50% plowed stubble and 12-inch stubble) the differences in water content with direction of survey can apparently be explained by sampling error since the north-south and east-west traverses varied by less than 0.5 inches water equivalent.

From the above discussion it would seem reasonable to conclude that both snow depth and water content are independent of direction of surveying for fields 1 and 2 (50% plowed stubble and plowed with no stubble) and dependent in part on direction for fields 4 and 6 (25% plowed stubble and unpicked corn). The apparent disagreement between snow depths and water contents for fields 3, 5 and 7 (12-inch stubble, short-grass pasture and sunflowers) suggests that snow <u>density</u> may have a directionality bias within a given field-type. Based on the t-test for comparison of sample means, it was found that the hypothesis that no significant difference in snow density exist between north-south and east-west traverses could be rejected at the 95% confidence level for these fields. However, whether this condition is controlled by vegetation and/or meteorological processes is not apparent.

For purposes of this thesis, therefore, it must be stated that sampling direction does appear to influence snow accumulation on relatively exposed, flat-lying agricultural fields. To overcome this problem it would be necessary to either select a large random sample of snow measurements (it was felt that a small random sample would not have significantly improved the reliability of the data) or sample each field in two or more directions. Unfortunately, time restrictions prohibited these alternatives.

From analysis of wind directions associated with drifting snow over the period 1966 to 1972 at Winnipeg International Airport, it was decided to orient the snow sampling courses at an azimuth of approximately 155 degrees to coincide with the prevailing peak winter wind direction (Table 3.6). For comparison it is noted that the snow course at Winnipeg International Airport is placed with an azimuth of 140 degrees.

Sampling Instruments.

(a) Description:

The most commonly accepted method of measuring snowpack depth, density and water equivalent is by means of volumetric snow samplers. These instruments are hollow tubes of varying length and diameter which, when driven vertically through a snowpack to the underlying ground surface and subsequently removed, retain a core of snow. Snowpack depth is usually read from calibrations (usually in half inches) on the outside of the tube while the water content of the snow is determined by weighing the snow core and tube on either a scale designed

Peak Wind Direction	1966-67 Freq.	%	1967-68 Freq.	%	1968-69 Freq.	%	1969-70 Freq.	%	1970-71 Freq.	%	1971-72 Freq.	%	1966-72 Freq.	%
N-S	39	50	32	63	23	43	44	69	26	51	39	53	203	55
NE-SW	4	5	0	0	3	6	1	2	3	6	6	8	17	5
E-W	9	12	6	12	10	19	7	11	4	8	6	8	42	11
SE-NW	26	33	13	25	17	32	12	18	18	35	22	31	108	29
TOTAL	78	100	51	100	53	100	64	100	51	100	73	100	370	100

TABLE 3.6. Analysis of Peak Wind Direction Associated with Drifting Snow, Winnipeg International Airport, 1966-72.

specifically for the snow sampler or on some other convenient scale and adjusting for the diameter of the tube. The ratio of water content to snow depth is a measure of the density of the snowpack and is usually expressed as a decimal fraction with water being 1.00 or as a percent.

In general, volumetric snow samplers can be subdivided into two main types: the small diameter tube such as the Mount Rose, and the large diameter ones such as the Adirondack type. The larger samplers can only be used with snow depths less than four to five feet as it becomes difficult to cut through excessive snowpacks. Unfortunately, the large diameter samplers exhibit difficulty in retaining snow cores so it is usually necessary to dig down and hold the core in the tube with a shovel or similar device (Beaumont, 1966a). The small diameter tubes have traditionally been used for determining snow water equivalents for deep snowpacks. Although the writer had access to both the Mount Rose and Adirondack types, it was found impractical to complete the proposed sampling schedule within a given day with the latter type as too much time would have been consumed in retrieval of snow cores using a small shovel. Thus, in spite of the general acceptance of using large diameter snow samplers for shallow Prairie snowpacks, the Mount Rose tube was used exclusively for field measurements taken during the 1972-73 winter.

The Mount Rose sampler developed by Dr. James Church in 1909, was one of the first volumetric snow samplers and remained essentially unchanged until 1932, when George D. Clyde substituted aluminum for steel and reduced the interior diameter from 1.50 to 1.4872 inches. The change to aluminum reduced the weight by half. Reducing the inside diameter established the weight of one inch of water equivalent in the tube at one ounce, instead of one inch depth of water in the tube being 1.02229 ounces (Beaumont and Work, 1963, p. 15). Thus, water equivalent could now be measured directly with any commercial scale. This sampler is designed with interconnected 30-inch long sections.

The Adirondack sampler is a 60.5 inch long fiberglass tube with an inside diameter of 2.655 inches. One-half inch graduations on the outside of the tube define snow depth while a stainless steel cutting edge facilitates sampling. Both these features are similar to the Mount Rose sampler.

(b) Measurement error:

In order to establish the reliability of the data used in this thesis, it is important to examine the Mount Rose sampler for possible sources of error as well as the degree of accuracy and precision. Accuracy refers to the closeness of the observed value of a parameter to the actual or target value whereas precision may be defined as the agreement of a set of measurements without regard to the true value of the measured parameter.

Measurement error may be classified into four types: observer error, instrument error, method error and random error (Topping, 1972). The first type may be further subdivided into accidental or gross error and operator bias. Gross error may occur through carelessness in the measuring process or during reading or recording. Fortunately, this source of error seldom occurs and may be effectively eliminated by performing a second measurement. Operator bias on the other hand exists to some degree in each measurement but cannot be considered a constant. It may occur at any stage of the measurement process but may be minimized by employing only one operator and instructing him thoroughly in the measurement procedure.

Instrument error involves assessment of the inherent limitations of measurement and mechanical errors. The absolute threshold of sensitivity is defined as the smallest change which can be registered by the instrument. This value is equivalent to the finest calibration. Further refinement may be obtained by rounding-off the measured value to the "rounded-off threshold of sensitivity", defined here as one-half the absolute threshold of sensitivity. Mechanical errors are generally referred to as systematic instrument error and may be increasing, decreasing or constant. Repetitive measurement during the study acts as a control on this type of instrument error.

Finally, methodological errors may arise from subjective interpretations of operational definitions whereas random error may occur in repeatedly measured values even if all sources of error are either absent or controlled.

In summary, gross observer error and random error may be viewed as compensating errors while operator bias, instrument and methodological errors are generally non-compensating.

In order to examine the specific sources of error inherent in the Mount Rose sampler used in this study, it is convenient to separate the functions of snow sampling into: (a) determination of snow depth, and (b) determination of snow water equivalent. The emphasis of this section is on evaluating instrument error, although other forms of error may be substantial.

The absolute threshold of sensitivity of the Mount Rose sampler in determining depth of snow is 0.5 inches with the rounded-off threshold being 0.25 inches. In other words, depths can be measured to half inches $\pm$ 0.25 inches.

One source of error in measuring the depth of snow may arise in establishing the ground surface. To counteract this, depth is usually overestimated by removal of the coring tube with soil or litter on the end. Subsequent careful removal of this debris and adjustment of the actual snow depth may compensate for this.

Freeman (1965) has suggested that there are several elements that may affect water equivalent determination by tube samplers. These include: (a) critical dimensions of the tube (diameter of the cutting point); (b) the accuracy and precision of the scales over the entire working temperature range; (c) precision in reading and recording the various readings; and (d) the ability of the tube to cut and retain accurate and representative snow cores. Tollan (1970) suggests additional sources of error as including the "varying texture of the snow; wet, clogging snow or snow with ice crusts being unfavourable for measurements. In extreme cases as much as 50% of the snow may evade the sampler. A skilled surveyor will discover such discrepancies, and to some extent manage to improve the sample" (p. 98).

H.H. Bindon theorized that: "The percentage error in measure of water equivalent due to edge effect is inversely proportional to the radius of the cutter" (Freeman, 1965, p. 2). That is, large samplers would be expected to exhibit greater accuracy in water equivalent determination.

To determine the accuracy of the Mount Rose scale over a range of water equivalents, gram weights varying from 5 to 700 grams (0.2 to 24.7 ounces) were applied to the scale at an inside temperature of 74^{o} F on two separate days (Table 3.7). The scale was interpolated to the first decimal place with observed readings being compared to the actual or target values.

From Figure 3.1 and Table 3.7 it is apparent that for a given temperature, the spring scale tends to underestimate the applied weight as the weight (water equivalent) increases. Within the range of water contents encountered during field sampling (up to approximately 450 grams or 15.9 ounces), the absolute error in the spring scale (defined as the difference between the true and measured quantities) is in all cases below the absolute threshold of sensitivity of 1.0 ounces (inches) of water equivalent. For 95% of the field samples the accuracy of the spring scale is within the rounded-off threshold of sensitivity of 0.5 inches (see Chapter IV).

To test the accuracy of the Mount Rose scale over the working temperature range, gram weights from 5 to 700 grams were applied under outside conditions and temperatures of -10, 0, 12, 21 and 31 degrees Fahrenheit. Days were selected on which wind was negligible since it was observed that wind acting on the supported sampling tube could increase the water equivalent reading by one or two ounces. The results of these tests are presented in Table 3.8 and Figure 3.1 and reveal the same trend of increasing error with increasing weight as observed in the tests conducted at 74^{o} F. However, although the error is consistently greater at -10^{o} F than at 31^{o} F, there is no apparent

Applied Weight grams	ounces	Scale Reading (ounces) trial 1	trial 2	Absolute Error (ounces) trial 1	trial 2	Variation in Absolute Error
0	0.0	0.0	0.0	0.0	0.0	0.0
5	0.2	0.2	0.3	0.0	0.1	0.1
10	0.4	0.5	0.5	0.1	0.1	0.0
15	0.5	0.7	0.7	0.2	0.2	0.0
20	0.7	0.9	0.9	0.2	0.2	0.0
25	0.9	0.9	0.9	0.0	0.0	0.0
30	1.1	1.0	1.0	-0.1	-0.1	0.0
35	1.2	1.1	1.2	-0.1	0.0	0.1
40	1.4	1.3	1.4	-0.1	0.0	0.1
45	1.6	1.6	1.7	0.0	0.1	0.1
50	1.8	1.8	1.9	0.0	0.1	0.1
75	2.7	2.7	2.7	0.0	0.0	0.0
100	3.5	3.6	3.6	0.1	0.1	0.0
125	4.4	4.3	4.1	-0.1	-0.3	0.2
150	5.3	5.1	5.1	-0.2	-0.2	0.0
175	6.2	5.9	5.9	-0.3	-0.3	0.0
200	7.1	6.9	6.8	-0.2	-0.3	0.1
250	8.8	8.8	8.7	0.0	-0.1	0.1
300	10.6	10.1	10.1	-0.5	-0.5	0.0
350	12.4	11.9	11.9	-0.5	-0.5	0.0
400	14.1	13.4	13.6	-0.7	-0.5	0.2
450	15.9	15.0	15.1	-0.9	-0.8	0.1
500	17.6	16.9	16.9	-0.7	-0.7	0.0
550	19.4	18.8	18.7	-0.6	-0.7	0.1
600	21.2	20.1	20.1	-1.1	-1.1	0.0
650	22.9	22.0	21.9	-0.9	-1.0	0.1
700	24.7	23.6	23.7	-1.1	-1.0	0.1

TABLE 3.7. Accuracy and Precision of Mount Rose Spring Scale with Varying Water Equivalents at 74^{o}F.

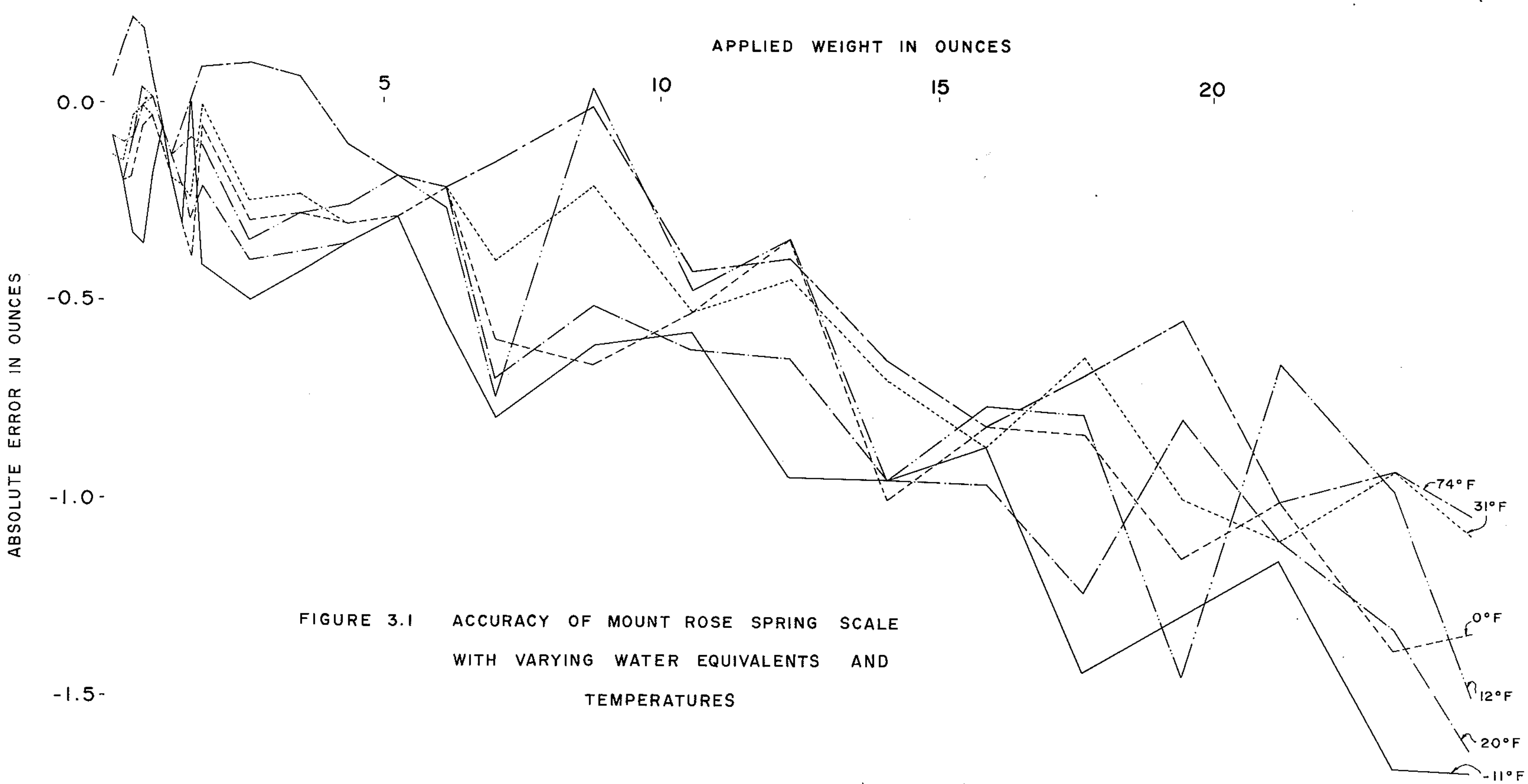


FIGURE 3.1 ACCURACY OF MOUNT ROSE SPRING SCALE WITH VARYING WATER EQUIVALENTS AND TEMPERATURES

Applied Weight grams	oz.	Scale Reading (oz.) Temperature (°F) 31	21	12	0	-10	Absolute Error (oz.) Temperature (°F) 31	21	12	0	-10
0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5	0.2	0.1	0.1	0.1	0.1	0.1	-0.1	-0.1	-0.1	-0.1	-0.1
10	0.4	0.2	0.1	0.3	0.1	0.2	-0.2	-0.3	-0.1	-0.3	-0.2
15	0.5	0.5	0.4	0.5	0.3	0.2	0.0	-0.1	0.0	-0.2	-0.3
20	0.7	0.7	0.7	0.8	0.6	0.4	0.0	0.0	0.1	-0.1	-0.3
25	0.9	0.9	0.9	0.9	0.8	0.7	0.0	0.0	0.0	-0.1	-0.2
30	1.1	1.0	1.0	1.0	0.9	1.0	-0.1	-0.1	-0.1	-0.2	-0.1
35	1.2	1.1	1.1	1.1	1.0	1.1	-0.1	-0.1	-0.1	-0.2	-0.1
40	1.4	1.2	1.2	1.3	1.1	1.1	-0.2	-0.2	-0.1	-0.3	-0.3
45	1.6	1.4	1.3	1.5	1.2	1.6	-0.2	-0.3	-0.1	-0.4	0.0
50	1.8	1.8	1.5	1.7	1.7	1.4	0.0	-0.3	-0.1	-0.1	-0.4
75	2.7	2.4	2.2	2.3	2.3	2.2	-0.3	-0.5	-0.4	-0.4	-0.5
100	3.5	3.3	3.1	3.3	3.2	3.1	-0.2	-0.4	-0.2	-0.3	-0.4
125	4.4	4.1	4.0	4.2	4.1	4.1	-0.3	-0.4	-0.2	-0.3	-0.3
150	5.3	5.0	5.0	5.1	5.0	5.0	-0.3	-0.3	-0.2	-0.3	-0.3
175	6.2	6.0	5.9	5.9	5.9	5.6	-0.2	-0.3	-0.3	-0.3	-0.6
200	7.1	6.7	6.3	6.3	6.4	6.3	-0.4	-0.8	-0.8	-0.7	-0.8
250	8.8	8.6	8.3	8.9	8.1	8.2	-0.2	-0.5	0.1	-0.7	-0.6
300	10.6	10.1	9.9	10.1	10.0	10.0	-0.5	-0.7	-0.5	-0.6	-0.6
350	12.4	11.9	11.7	12.0	12.0	11.4	-0.5	-0.7	-0.4	-0.4	-1.0
400	14.1	13.4	13.1	13.2	13.1	13.2	-0.7	-1.0	-0.9	-1.0	-0.9
450	15.9	15.0	14.9	15.1	15.0	15.0	-0.9	-1.0	-0.8	-0.9	-0.9
500	17.6	17.0	16.4	16.9	16.8	16.2	-0.6	-1.2	-0.7	-0.8	-1.4
550	19.4	18.4	18.6	18.0	18.2	18.1	-1.0	-0.8	-1.4	-1.2	-1.3
600	21.2	20.1	20.0	20.5	20.1	20.0	-1.1	-1.2	-0.7	-1.1	-1.2
650	22.9	22.0	21.6	22.0	21.5	21.3	-0.9	-1.3	-0.9	-1.4	-1.6
700	24.7	23.6	23.0	23.2	23.3	23.0	-1.1	-1.7	-1.5	-1.4	-1.7

TABLE 3.8. Accuracy of Mount Rose Spring Scale with Varying Water Equivalents and Temperatures.

inverse relationship between absolute error and temperature. All readings below approximately 175 grams (6 ounces) and 450 grams (16 ounces) are within the rounded-off threshold of sensitivity and the absolute threshold of sensitivity, respectively. Therefore, for field measurement purposes, scale readings appear to be sufficiently accurate over a temperature range of -10^{o} F to 31^{o} F.

The precision of reading the Mount Rose scale can be determined by examination of the absolute errors associated with weights from 5 grams to 700 grams for the two trials run at 74^{o} F (Table 3.8), without regard to the actual or correct weight. From this table it appears that the variation between each pair of readings is randomly distributed but in no case is it greater than 0.2 ounces. In other words the variation due to reading is less than the rounded-off threshold of sensitivity. This of course does not imply that there is no operator error but rather that any error due to operator bias is negligible throughout the range of water equivalents.

Beaumont (1966) determined from field tests that the Mount Rose sampler measures a snow water content about 10% greater than actually exists in the snowpack. It was also found that this percentage error tends to increase slightly with an increase in water content. Apparently this error was caused by the bluntness of the cutting point which forced a greater amount of snow into the tube than the inside diameter would indicate. Beaumont also found that overmeasurement could be reduced by half or more by simply sharpening the cutter.

(c) Summary:

In conclusion the Mount Rose sampler used in this thesis measures snow depth to an accuracy of one-half inch $\pm$ 0.25 inches and snow water content to whole inches $\pm$ 0.5 inches. Overestimation of 5 to 10 percent in water content may occur although no tests were run on the specific snow sampler used. However, it should be noted that this overestimation is not likely to be critical since 77% of the water content values were less than 5 inches (within the rounded-off threshold of sensitivity of the spring scale) and 92% were less than 10 inches (within the absolute threshold of sensitivity).

Snowmelt Runoff

The volume of snowmelt runoff from the study basin was established by a propeller-type water current meter produced by Weather Measure Corporation. Because significant runoff can occur at flows too low to be accurately measured by this instrument, a narrow, well-defined metering section was required. Accordingly, measurements were taken at the downstream end of a four-foot diameter corrugated steel culvert. At each metering time three equally-spaced measurements were taken at 0.6 of the depth of flow. Stream velocity was averaged for the three readings and when multiplied by the cross-sectional area of flow (as determined geometrically for a cylinder), produced runoff volumes in cubic feet per second. Total snowmelt runoff was then converted to acre-feet and finally to inches as applied over the total drainage area.

The use of culverts as metering sections is not uncommon. Straub and Morris (1950b), Neill (1962), Chow (1962) and Holtan, Minshall and Harrold (1968) all noted that since culverts are simple and regular in form and their hydraulic behaviour is well understood, they can be good runoff meters. Erxleben (1972) used a single staff gauge measurement of water depth, either upstream or downstream of a culvert end, in conjunction with rating curves, to produce what he considered were fairly reliable estimates of snowmelt runoff volumes for the Whitemud Creek basin in Alberta.

Runoff was measured twice daily at approximately 8:00 a.m. and 5:00 p.m. during the period of flow, March 8 to 26, 1973. As it was impractical to monitor flows more than twice a day, it was felt that these two times, approximating the times of low and high flows, respectively, would provide a reasonable estimate of daily runoff volume. To test this, automatic stage records of three small stream in Southern Manitoba, namely, Plum River near Rosenfeld (drainage area of 292 square miles), Elm Creek Channel Number 1 near Fannystelle (319 square miles), and South Tobacco Creek near Miami (36.5 square miles), were analyzed. Unfortunately, conversion of stage to corresponding discharge by means of stage/discharge tables for each stream produced erroneous values due to ice-cover and associated backwater effects. However, in spite of obvious limitations and although producing in all probability a conservative estimate (it was observed that flows increased markedly during cloudless above-freezing mornings and probably decreased rapidly at night), this procedure is believed to be fairly reliable.

CHAPTER IV

DATA

Basin Snowpack Accumulation

Point Snowfall. Precipitation as measured at the Winnipeg International Airport and at St. Norbert is estimated by probing with a ruler and converting to water equivalent on the assumption that new snow density is ten percent. Unfortunately, neither station provides an absolute value for snowfall as the former is located in a very exposed position while the latter is a 30 foot by 50 foot residential back garden which is sheltered to some extent on all sides by trees, fences or houses. Thus, it would appear that true snowfall is likely overestimated by the Climatological Station site which would be susceptible to drifts or underestimated at the Winnipeg International Airport which is exposed to snowpack-eroding winds. Both sites, however, have similar short grass vegetation cover.

Total winter precipitation from the first lasting snowfall (October 27, 1972) to the termination of spring runoff from the study basin (March 25, 1973) amounted to 2.83 inches as recorded at Winnipeg International Airport, of which 2.57 inches was snow. This compares to 3.36 inches measured at St. Norbert during the same period, with 3.28 inches being solid precipitation. However, records were not kept at St. Norbert from November 4 to 18, 1972, therefore, these values are conservative (Winnipeg recorded 0.24 inches during this period).

Snowpack Depth. Table 4.1 presents the average snow depths for the various agricultural fields and drainage ditches that were monitored through the 1972-73 winter in the study basin. In addition snow depth

Site	Date									
	November		December		January			Febuary		March
	27	8	17	27	7	17	28	7	22	4
F1	2.0	2.5	1.5	2.5	4.5	4.5	4.0	4.0	2.5	0.0
F2	3.0	3.5	2.0	2.0	4.0	5.0	5.0	4.5	5.0	0.0
F3	4.5	4.0	5.0	5.0	6.0	7.0	6.5	9.5	10.0	5.5
F4	2.5	4.0	2.5	4.0	5.0	5.5	4.5	5.0	5.5	1.5
F5	5.5	6.0	6.0	7.5	9.5	9.5	9.0	10.5	10.5	7.5
F6	4.5	4.0	3.5	4.0	4.5	5.0	5.0	8.0	7.0	4.0
F7	5.0	4.0	4.0	4.0	8.5	8.5	8.5	11.5	10.0	7.0
F8	3.0	3.5	3.0	4.0	6.5	8.0	7.5	7.5	8.0	3.5
F9	3.5	4.0	3.0	5.0	7.5	7.5	8.0	8.5	7.5	3.5
F10	3.5	4.0	3.5	4.0	5.0	6.0	5.5	6.5	6.0	3.0
P2	11.0	10.0	17.5	18.0	19.0	17.5	18.0	18.0	13.5	16.0
P3	5.0	5.0	6.5	15.0	14.5	17.0	20.0	23.5	19.5	15.5
P12	20.5	26.0	28.5	35.5	37.5	30.5	38.0	32.0	37.0	32.5

Site	Feb.		Mar.	Site C-18 Feb.	Mar.
	7	22	4	12	12
P1			6.0	5.5	0.0
P4			7.0		
P5			7.0		
P6			18.0		
P7			33.0		
P8			30.0		
P9			35.0		
P10	16.5	18.5	16.5		
P11			21.0		
P13			23.5		
P14			15.0		
P15			23.0		
P16			13.0		
H1	34.0				

TABLE 4.1. Mean Depth of Snow (inches $\pm$ 0.25 inch), St. Norbert, 1972-73.

data for the snow course monitored on February 12 and March 12, 1973 by the Water Control and Conservation Branch of the Manitoba government (c-18) have also been included.

Snowpack Density. Table 4.2 summarizes the average snow densities observed within the study basin during the 1972-73 snow season. These are obtained by determining the average ratio of snow water content to snow depth for each snow course on the specified days of observation.

Although data on snow course C-18 are included in the preceding table, caution must be used in comparing these values with the rest of the table since two instruments have been used. Water Control's volumetric snow sampler is non-standard being five feet long and having an interior diameter of approximately 4 inches. Water content is determined by weighing the snow core on a spring scale graduated in ounces and dividing this quantity by a tube factor of 3.8. Therefore, any discrpancies in water equivalent determination will be carried through to snow density calculations. To determine the magnitude of error between the Mount Rose sampler and that used by Water Control and Conservation, paired snowpack readings were undertaken on March 4, 1973 and are summarized in Table 4.3.

Since snow depths, owing to small surface irregularities, are not directly comparable, neither are the mean water contents. However, snow densities, being ratios, can be compared. Thus, although Water Control's sampler overestimates the Mount Rose tube by 0.5%, the snow density readings are similar enough to allow direct comparison without adjustment.

Site	November		December			January		February		March
	27	8	17	27	7	17	28	7	22	4
F1	0.29	0.23	0.25	0.27	0.20	0.28	0.21	0.17	0.37	-
F2	0.15	0.17	0.14	0.26	0.20	0.26	0.23	0.18	0.26	-
F3	0.20	0.21	0.15	0.26	0.12	0.19	0.19	0.24	0.25	0.31
F4	0.34	0.23	0.22	0.29	0.28	0.32	0.28	0.24	0.20	0.25
F5	0.22	0.20	0.21	0.20	0.19	0.24	0.22	0.22	0.18	0.27
F6	0.20	0.27	0.28	0.30	0.24	0.31	0.25	0.28	0.25	0.29
F7	0.24	0.25	0.19	0.28	0.24	0.31	0.23	0.25	0.23	0.24
F8	0.24	0.21	0.26	0.28	0.25	0.33	0.33	0.29	0.31	0.28
F9	0.34	0.26	0.35	0.29	0.26	0.33	0.31	0.28	0.27	0.21
F10	0.17	0.25	0.26	0.28	0.23	0.30	0.26	0.25	0.28	0.25
P2	0.25	0.25	0.30	0.32	0.30	0.34	0.33	0.34	0.25	0.30
P3	0.27	0.28	0.38	0.33	0.33	0.39	0.41	0.37	0.34	0.42
P12	0.28	0.33	0.35	0.35	0.33	0.36	0.36	0.39	0.43	0.31

Site	February		Mar.	Site C-18 Feb.	Site C-18 Mar.
	7	22	4	12	12
P1			0.41	0.17	-
P4					
P5					
P6			0.22		
P7			0.42		
P8			0.39		
P9			0.34		
P10	0.33	0.34	0.39		
P11			0.37		
P13			0.35		
P14			0.25		
P15			0.41		
P16			0.37		
H1	0.35				

TABLE 4.2. Mean Snow Densities, St. Norbert, 1972-73.

Snow Sampler	Mean Snow Depth (inches)	Mean Water Content (inches)	Mean Density
Mount Rose	16.53	5.47	0.331
Water Control	16.42	5.51	0.336

TABLE 4.3. Comparison of Mount Rose and Water Control Snow Samplers.

Snowpack Water Equivalent. The snow water contents of the basin sampling sites for 1972-73 are presented in Table 4.4, along with data for C-18. From analysis of Table 4.3 and assuming a snow depth of 16.42 inches with a density of 0.331, the equivalent water content for the Mount Rose sampler would be 5.43 inches. This represents an underestimate of the Water Control sampler of approximately 1.5%. Since this is well within the absolute threshold of sensitivity (see Chaper III), snow water content as measured by both samplers may be assumed to be similar.

Basin Snowmelt Runoff

Infiltration into Frozen Soils. No coclusive statements can be made about the infiltration of snowmelt water through frozen soils. In general, soil texture, fall moisture conditions and soil treatment would appear to influence ice formation and subsequent water penetration. Post and Dreibelbis (1942) found that if a soil is frozen when its moisture content is greater than field capacity, its infiltration rate will be very low and if saturated, the intake rate is virtually zero. Larin (1961) observed that infiltration into a frozen soil decreased as the soil moisture content of the preceding autumn increased

Site	November 27	December 8	17	27	January 7	17	28	February 7	22	March 4
F1	0.5	0.5	0.5	0.5	1.0	1.5	1.0	0.5	1.0	0.0
F2	0.5	0.5	0.5	0.5	1.0	1.5	1.0	1.0	1.5	0.0
F3	1.0	1.0	0.5	1.5	0.5	1.5	1.0	2.5	2.5	1.5
F4	1.0	1.0	0.5	1.0	1.5	2.0	1.5	1.0	1.0	1.5
F5	1.0	1.0	1.5	1.5	2.0	2.5	2.0	2.0	2.0	2.0
F6	1.0	1.0	1.0	1.0	1.0	1.5	1.0	2.0	1.5	2.0
F7	1.0	1.0	1.0	1.0	2.0	2.5	2.0	3.0	2.5	1.5
F8	0.5	0.5	0.5	1.0	1.5	2.5	2.5	2.0	2.5	1.5
F9	1.0	1.0	1.0	1.5	2.0	2.5	2.5	2.5	2.0	0.5
F10	0.5	1.0	1.0	1.0	1.0	2.0	1.5	1.5	1.5	1.0
P2	3.0	2.5	5.0	5.5	5.5	6.0	6.0	6.0	3.5	5.0
P3	1.5	1.5	2.5	5.0	4.5	6.5	8.0	8.5	6.5	6.5
P12	5.5	8.5	10.0	12.5	12.5	11.0	15.5	12.5	16.0	10.0

Site	February 7	22	Mar. 4	Site C-18 Feb. 12	Mar. 12
P1			2.5	1.0	0.0
P4					
P5					
P6			4.0		
P7			14.0		
P8			12.0		
P9			12.0		
P10	5.5	6.5	6.5		
P11			7.5		
P13			8.0		
P14			3.5		
P15			9.5		
P16			5.0		
H1	12.0				

TALBE 4.4. Mean Snow Water Equivalents (inches $\pm$ 0.25), St. Norbert, 1972-73.

and practically ceased when the autumn moisture content was high, although no information on specific moisture contents was provided. Gillies (1968) determined that water infiltration of frozen soils decreases exponentially with the moisture content of the surface layer.

Willis et al (1961) observed that wet soils thaw later and slower than dry soils and Mosiyenko (1958) discovered that the permeability of a clay loam was restored when its moisture content fell to 60 or 65 percent of field capacity. Finally, Stoeckeler and Weitzman (1960) noted that frost was more impermeable in grassland than under forest conditions.

The effects of soil surface conditions on moisture infiltration is shown by Mosiyenko (1957) who compared infiltration rates of snowmelt water in plowed and unbroken soil under field conditions and concluded that permeability of frozen soils is insignificant. However, no data were presented on the moisture content of the soil at time of freeze-up. Also, Staple, Lehane and Wenhardt (1960) found that the fall cultivation of fallow soils had no effect on infiltration of snowmelt, and that discing stubble fields after harvest reduced the subsequent intake of snowmelt water.

In summary, infiltration of snowmelt runoff in non-wooded areas is in all probability negligible if the following conditions are met: (a) preceding fall moisture has recharged soil moisture storage to approximately field capacity; (b) the soil surface temperature remains at or below 32^{o} F throughout any periods of snowmelt (that is, either the surface retains a snow cover sufficiently deep enough to effectively retard ground thaw during periods when the air temperature is above freezing, or the insolation received on the ground surface is insufficient to cause ground thawing; and, (c) soils are fine-textured, since where the soil pores are small, any liquid water entering the ground will refreeze within the surface layer and will retard further infiltration (U.S. Army Corps of Engineers, 1960).

It is apparent that the last two conditions have been met for the study basin during the 1972-73 winter. The soil temperature remained below or at 32^{o} F. from November 1972 until at least March 21, 1973, ten days after all the snow on the agricultural fields had disappeared and five days prior to the termination of surface runoff. Secondly, the soils are variants of fine-textured lacustrine clays.

With regard to Fall soil moisture conditions, data provided by the Manitoba Department of Mines and Natural Resources, Water Control and Conservation Branch, indicate that as of November 1972, the upper six inches of the soil zone at site R-I-1 (see Map 3.4) was 99.9% saturated (Table 4.5). This site is located on the Osborne Clay soil type which represents 65% of the total study basin and most of the upland agricultural area. It is, thus, felt that the soils in the study basin were recharged to approximately field capacity and infiltration of snowmelt runoff was negligible.

Depth of Sample (inches)	Moisture Content (%)	Degree of Saturation (%)
6	30.0	99.9
12	26.9	80.0
18	26.4	78.7
30	22.8	89.0

TABLE 4.5. Soil moisture retention at Manitoba Water Control and Conservation Site R-I-1, November 1972.

Gauge Runoff. Figure 4.1 shows the snowmelt runoff hydrograph for the study basin. The volume of runoff was 193.2 acre-feet (8,414 x 10^3 cubic feet). No flows were observed on the afternoon of March 8 or the morning of March 9, 1973 and little melting was evident. However, on the afternnon of March 11 flows of 5.6 cubic feet per second (d.f.s.) were recorded but no readings had been taken on the preceding two days. It was, therefore, necessary to extrapolate flows for this period. These are shown as broken lines on the hydrograph. However, it is evident that recorded flows would not have significantly altered the total runoff volume.

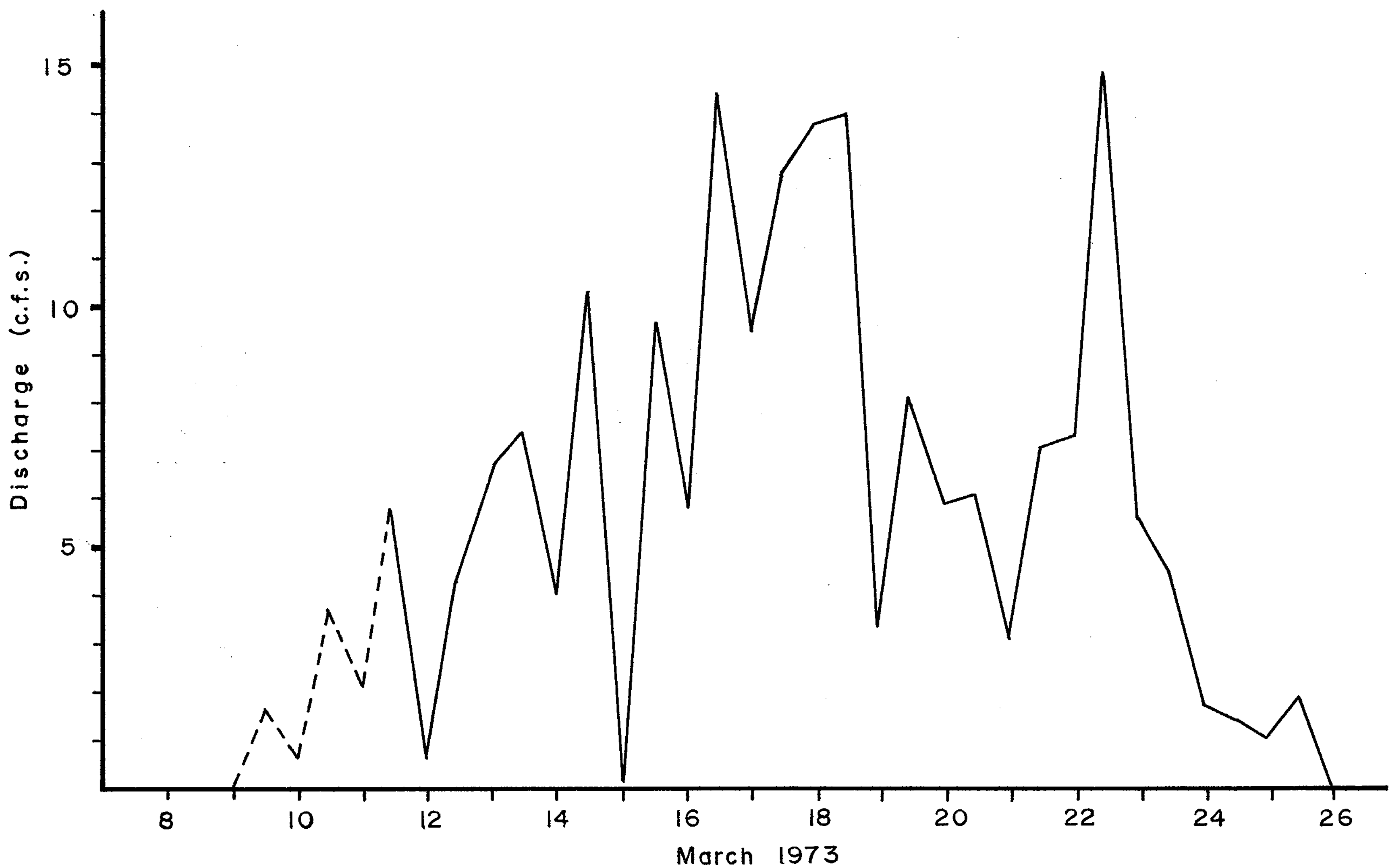


FIGURE 4.1. Hydrograph of Snowmelt Runoff, St. Norbert.

CHAPTER V

ANALYSIS OF DATA

Snow Retention

The ability of different ground surfaces to catch and retain snow throughout a winter may be expressed by the ratio of snow retained at a point to recorded snowfall. Kuz'min (1960) determined average snow retention coefficients for various surfaces ranging from 0.4 for open ice on lakes to 3.3 for forest edges (Table 5.1) but stated that these coefficients reflect only the most common ratios for average meteorological conditions and that snow retention coefficients vary considerably. For example, the coefficient for river beds can vary roughly within 1.5 to 8.0, depending upon the number, intensity and duration of snowstorms, the morphology of the bed and its orientation relative to the prevailing winter winds. Presumably, higher snow retention coefficients occur with an increase in snowstorm activity, especially when the river channel is normal to the storm winds. No data were presented on the impact of bed morphology on snow catch but it would seem reasonable that snow accumulation is dependent on the channel width, depth and side slopes although the relative importance of each factor is unknown.

Table 5.2 summarizes the snow retention properties of the agricultural fields and drainage channels monitored near St. Norbert during the 1972-73 winter. Due to time limitations these were selected for variations in orientations and width/depth ratios. P2 and P12 were oriented north and south (the drainage channel ran east/west) while P3 was oriented east/west. All channels were similar in width (25 to 30 feet) but width/depth ratios were 5, 7 and 8 for P12, P2 and P3, respectively. P2 and P3 were sheltered from the south and southeast by a stand of trees.

Surface	Snow Retention Coefficient
Open ice on Lakes	0.4 to 0.5
Arable Land	0.9
Virgin Soil	1.0
Hilly Districts	1.2
Large Forest Tracts	1.3 to 1.4
River Beds	3.0
Rush Growth Near Lakes	3.0
Forest Cuttings and edges	3.2 to 3.3

TABLE 5.1. Average snow retention coefficients for various surfaces (after Kuz'min, 1960, p. 59)

Coefficients are based on accumulated winter precipitation (rain and snow) as measured at the Winnipeg International Airport since St. Norbert's data were incomplete. No attempt has been made to adjust the accumulated precipitation for melt losses during the winter although it was observed that St. Norbert recorded several days with maximum air temperatures higher than 32 degrees Fahrenheit. To approximate the beginning of continuous snowmelt it is commonly accepted that air temperature must be above freezing. From St. Norbert's records relatively continuous above freezing maximum daily temperatures did not occur until March 2, 1973. That is, some melting occurred between the sampling days of February 22 and March 4, 1973. This is apparent from Table 5.3 which shows the changes in snow depth, density and water equivalent for the fields and gullies during this ten-day period. All sites except P2 show a decrease in snow depth and water content and most experienced increases in snow density.

Site	Date												Site			
	November		December			January		February		March	Means			February		Mar.
	27	8	17	27	7	17	28	7	22	4	to Feb.22	to Mar.4		7	22	4
F1	0.62	0.60	0.43	0.46	0.43	0.64	0.43	0.30	0.38	0.00	0.48	0.43	P1			1.08
F2	o.46	0.65	0.30	0.36	0.42	0.65	0.55	0.37	0.59	0.00	0.48	0.44	P6			1.74
F3	0.96	0.93	0.70	0.92	0.38	0.66	0.59	1.05	1.08	0.74	0.81	0.80	P7			6.08
F4	0.96	0.91	0.61	0.75	0.74	0.86	0.65	0.56	0.50	0.70	0.72	0.72	P8			5.14
F5	1.30	1.24	1.29	1.06	0.91	1.13	0.96	1.02	0.84	0.88	1.08	1.06	P9			5.22
F6	0.96	1.13	0.95	0.78	0.55	0.75	0.59	0.99	0.75	0.81	0.83	0.83	P10	2.47	2.80	2.85
F7	1.28	0.95	0.81	0.82	1.02	1.27	0.95	1.31	1.03	0.75	1.05	1.02	P11			3.35
F8	0.70	0.76	0.75	0.76	0.85	1.26	1.20	0.98	1.07	0.70	0.93	0.90	P13			3.57
F9	1.28	1.11	1.13	0.94	1.03	1.21	1.24	1.05	0.92	0.30	1.10	1.02	P14			1.59
F10	0.64	0.97	0.95	0.83	0.61	0.91	0.72	0.74	0.75	0.39	0.79	0.75	P15			4.12
Mean	0.92	0.93	0.79	0.77	0.69	0.93	0.79	0.84	0.79	0.59	0.83	0.80	P16			2.07
P2	2.95	2.53	5.28	3.90	2.90	2.93	2.85	2.87	1.49	2.12	3.08	2.98				
P3	1.42	1.41	2.56	3.36	2.42	3.20	3.96	3.89	2.93	2.87	3.19	3.16	H1	5.48		
P12	6.09	8.91	9.96	8.37	6.40	5.35	7.58	5.70	7.07	4.30	7.27	6.97				
Mean	3.49	4.28	5.93	5.21	3.91	3.83	4.80	4.15	3.83	3.10	4.51	4.37				

TABLE 5.2 Average Snow Retention Coefficients Based on Unadjusted Accumulated Winter Precipitation From October 27, 1972 to March 4, 1973, at St. Norbert.

Site	Changes in Snow: Depth	%	Density	%	Water Content	%
F1	-2.35	-100	-	-	-0.87	-100
F2	-5.03	-100	-	-	-1.33	-100
F3	-4.35	- 44	0.044	18	-0.75	- 31
F4	-3.97	- 71	0.062	31	0.47	42
F4	-2.82	- 27	0.085	46	0.12	6
F6	-3.06	- 44	0.046	19	0.17	10
F7	-3.04	- 30	0.011	5	-0.62	- 26
F8	-4.56	- 57	-0.021	- 7	-0.82	- 34
F9	-4.30	- 56	-0.062	-23	-1.38	- 66
F10	-3.26	- 53	-0.025	- 9	-0.80	- 47
P2	2.75	21	0.049	19	1.48	44
P3	-3.70	-19	0.078	23	-0.04	- 1
P10	-1.95	-10	0.052	15	0.20	3
P12	-4.75	-13	-0.127	-29	-6.7	-38

TABLE 5.3. Changes in Snow Depth, Density and Water Content at St. Norbert, February 22 to March 4, 1973.

It is apparent that most fields retained less snow than recorded as snowfall. Only fields F5, F7 and F9 (12-inch stubble and alfalfa) had snow retention coefficients greater than unity. The gullies and hedgerow retained between three and fifteen times as much snow water equivalent as the agricultural fields per unit area. That is, assuming similar soil moisture and snowmelt conditions, the gullies could produce in the order of fifteen times the unit volume of runoff as some of the fields.

Analysis of Tables 4.1 and 5.4 in conjunction with Figures 5.1 and 5.2 confirms the thesis that in prairie environments snow accumulates at a more rapid rate in depressions during early winter than on fields. In the case of P2 and P12 the greatest depth of snow was reached early (January 7, 1973 and December 27, 1972, respectively) and remained at or below this value throughout the winter. The latter experienced a pronounced decrease in depth on January 7, 1973 apparently as a combined result of consolidation (Table 4.2) and wind erosion (Table 4.4) as snow density increased but water content decreased. However, recovery to previous depths was rapid (Figures 5.1 and 5.2).

Profile P3 was markedly different since the greatest depth of snow was reached late (February 7, 1973) and relatively stable depth was not attained. The reasons for this are not clear but may be related to orientation as this was the only east/west profile selected. It may also relate to a higher width/depth ratio since it is probable that the narrower the channel with respect to its depth, the more the channel is likely to act as a snow trap and the more rapidly it fills.

Date	P2 Depth	P2 Density	P2 Water	P3 Depth	P3 Density	P3 Water	P12 Depth	P12 Density	P12 Water
Nov.27	16.0	0.248*	3.97*	8.5	0.265	2.25	46.0	.281*	12.93*
Dec. 8	14.0	0.243	3.40	7.0	0.275	1.93	43.0	.334*	14.36*
Dec.17	27.5	0.306	8.40	17.5	0.380	6.70	51.0	.345*	17.60*
Dec.27	29.6	0.347	10.30	28.0	0.325	9.10	65.0	.348*	22.62*
Jan. 7	32.0	0.316	10.10	26.0	0.325*	8.45*	65.0	.333*	21.65*
Jan.17	30.2	0.338	10.20	29.5	0.386	11.40	39.4	.360	14.20
Jan.28	31.5	0.327	10.30	31.0	0.410	12.70	63.0	.357*	22.49*
Feb. 7	30.5	0.359	10.95	39.5	0.366	14.45	65.0	.391*	25.42*
Feb.22	27.0	0.219	5.90	35.0	0.343	12.00	63.0	.432*	27.22*
Mar. 4	33.0	0.369*	12.18*	28.5	0.421	12.00	53.0	.305*	16.17*

TABLE 5.4. Recorded Maximum Depths of Snow (inches) and Associated Densities and Water Contents (inches), November 27, 1972 to March 4, 1973 at St. Norbert. (*Indicates Data Not Collected At Location of Maximum Snow Depth).

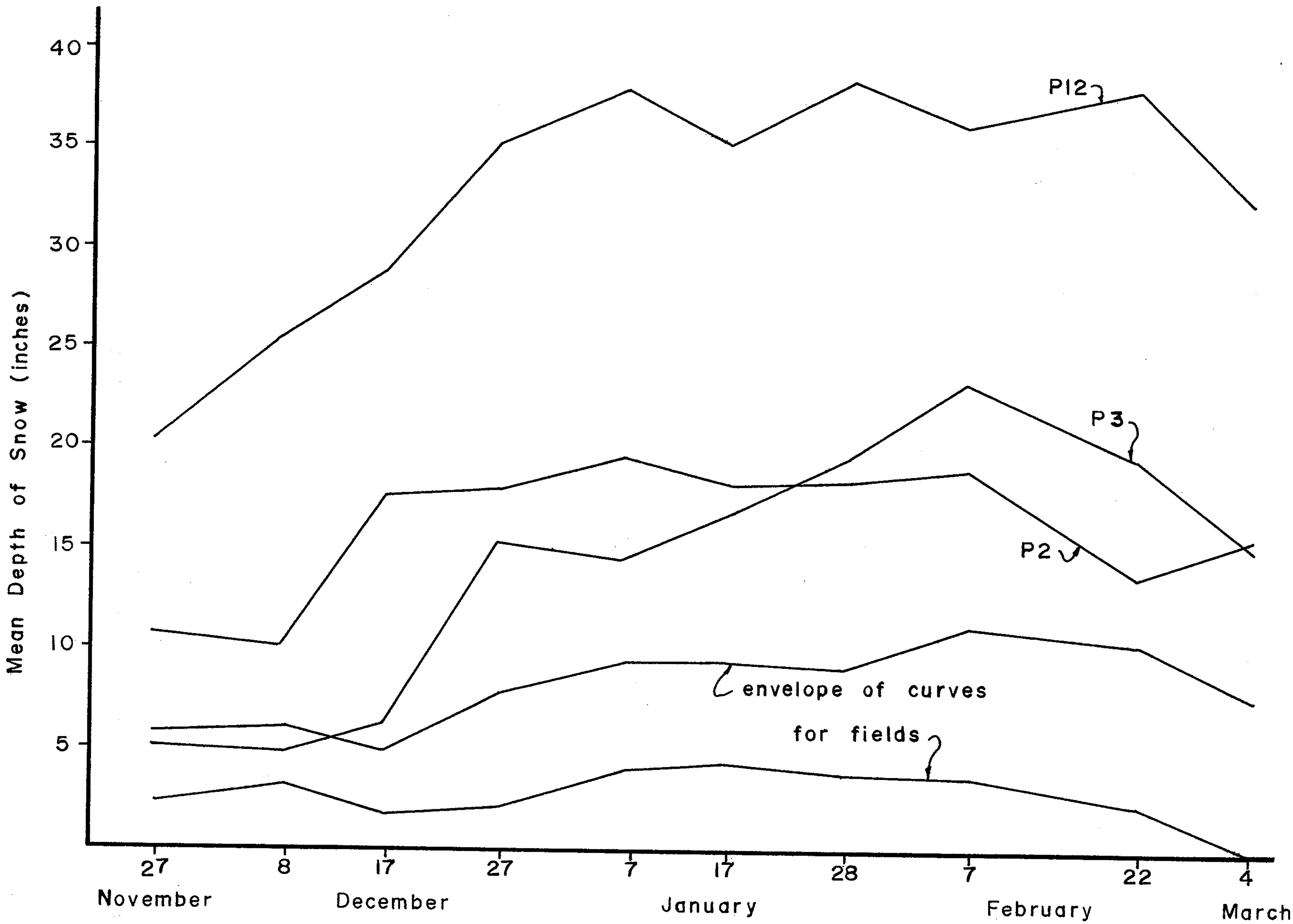


FIGURE 5.1. Variations in Mean Depth of Snow at St. Norbert, November 27, 1972 to March 4, 1973.

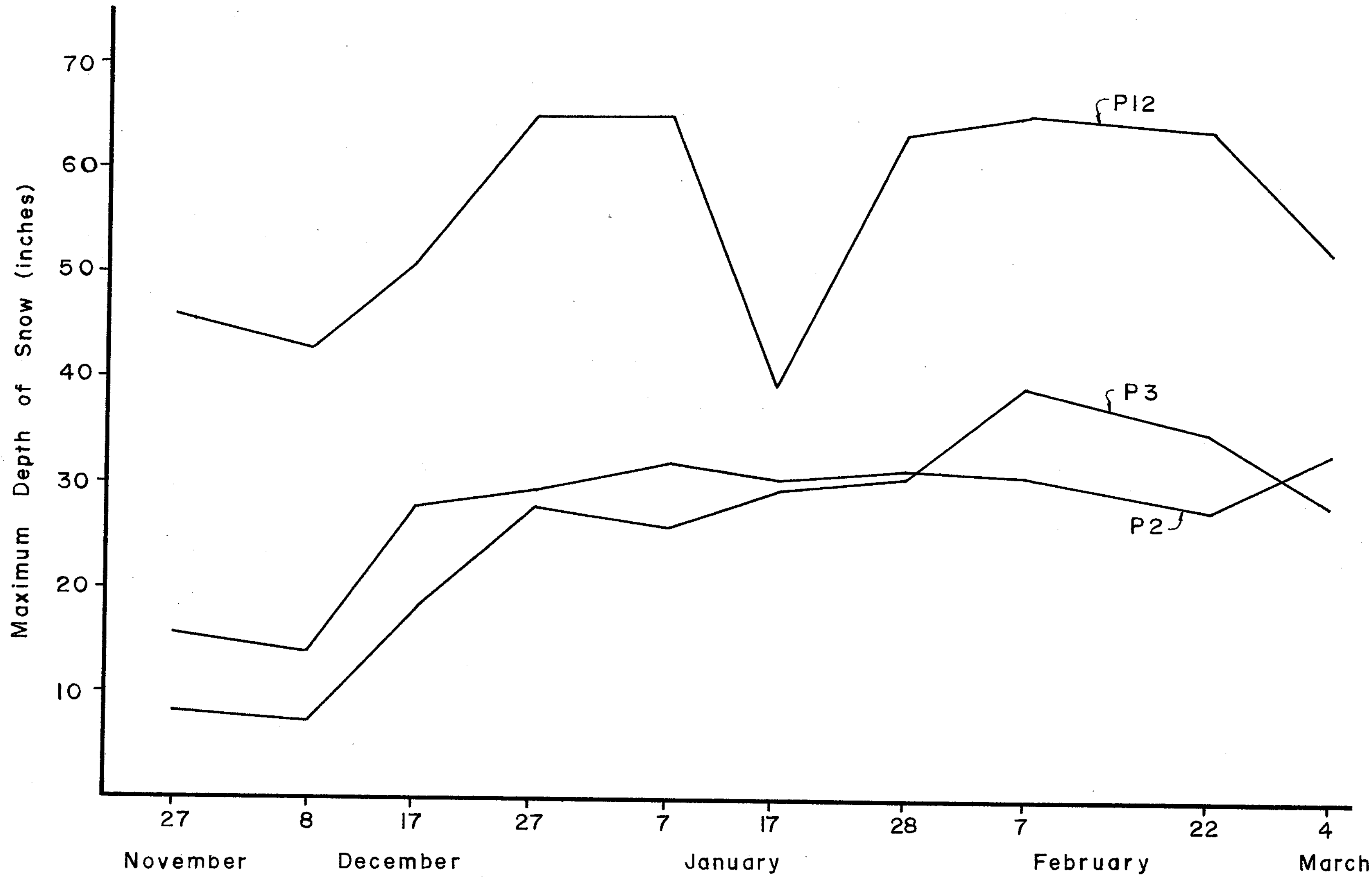


FIGURE 5.2. Variations in Maximum Depth of Snow for Channels P2, P3 and P12, November 27, 1972 to March 4, 1973, St. Norbert.

In middle and late winter it would appear that some channels become filled while others continue to accumulate snow and perhaps never reach equilibrium conditions as a result of wind effects, channel morphology and orientation. One similarity noted, however, was a tendency for the snow surface in the channels to be slightly concave (Figures 5.3, 5.4 and 5.5).

In general the agricultural fields accumulated snow at a relatively slow, uniform rate throughout the winter, responding to surface roughness, changes in snowfall and the occurrence of snow-eroding winds. From the data collected it was apparent that no single factor was dominant. To evaluate this would require much more detailed sampling, probably on a daily basis, as well as detailed meteorological data at each site.

Site	Maximum Depth of Snow (inches)		Date
	Potential	Actually Recorded	
P2	44	32.0	Jan.7
P3	43	39.5	Feb.7
P12	69	65.0	Dec.27

TABLE 5.5. Potential and maximum recorded depth of snow and corresponding dates, St. Norbert.

Contributing Areas

Stichling and Blackwell (1958) developed drainage basin concepts which were intended to more accurately reflect runoff under varying rainfall conditions. Gross drainage area is that plane area enclosed within a divide which would contribute runoff to a stream in extremely wet years while the wet drainage area is that portion of the basin

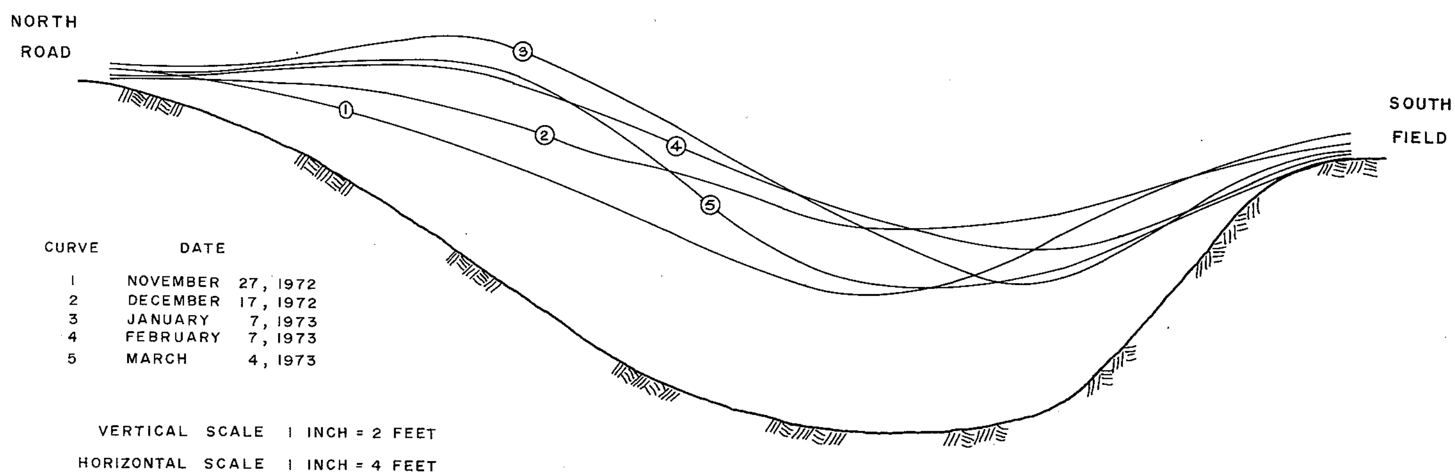


FIGURE 5.3 SNOW ACCUMULATION IN CHANNEL P2, NOVEMBER 27, 1972 TO MARCH 4, 1973

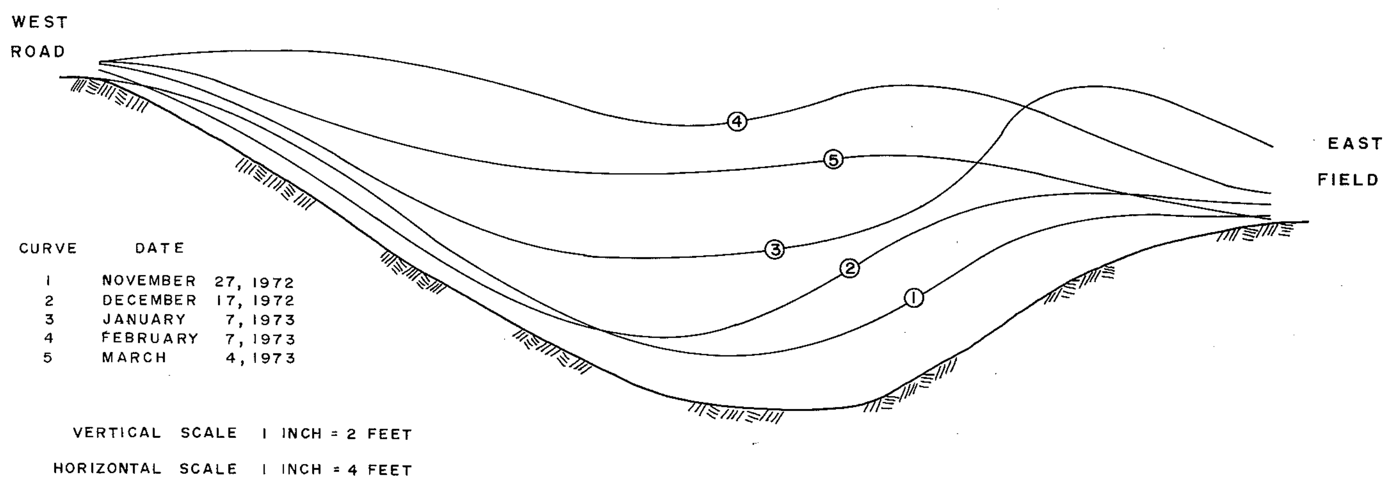


FIGURE 5.4 SNOW ACCUMULATION IN CHANNEL P3, NOVEMBER 27, 1972 TO MARCH 4, 1973

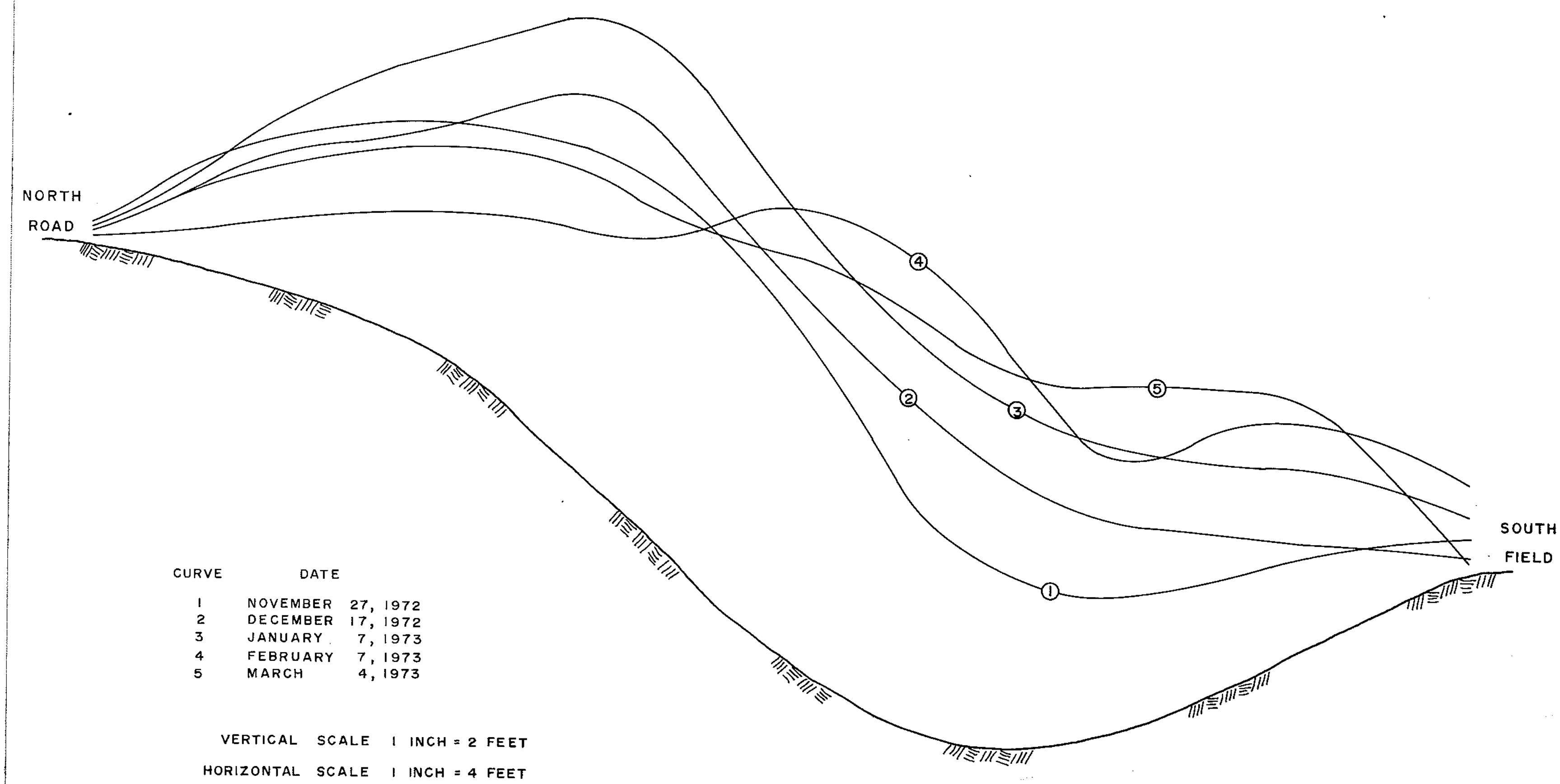


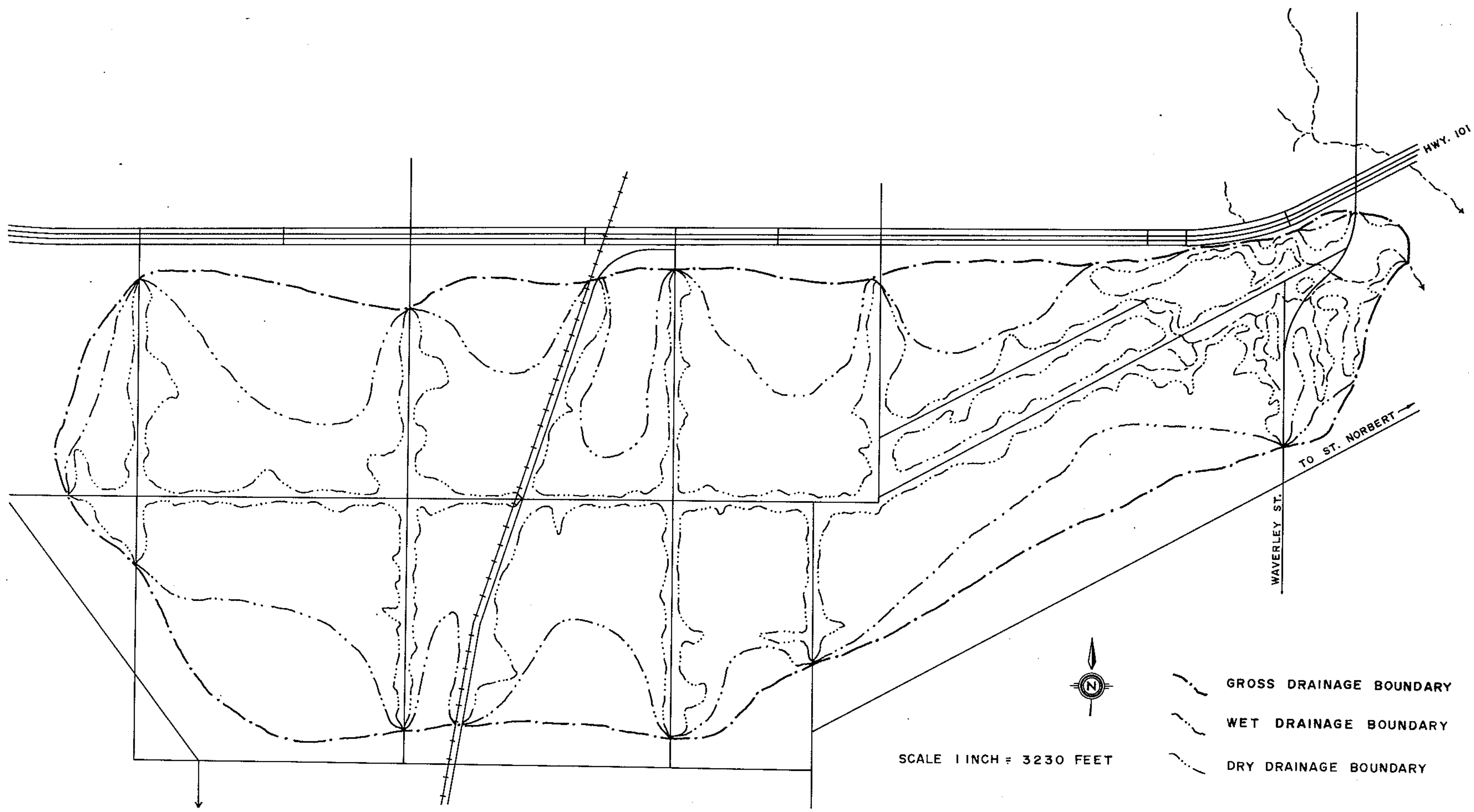
FIGURE 5.5 SNOW ACCUMULATION IN CHANNEL P12, NOVEMBER 27, 1972 TO MARCH 4, 1973

contributing runoff under conditions of much above normal rainfall (1:50 event). Dry drainage areas are those areas that would be expected to contribute flow from much below normal rainfall (1:2 event). Lastly, areas of internal drainage or ponding are referred to as dead drainage.

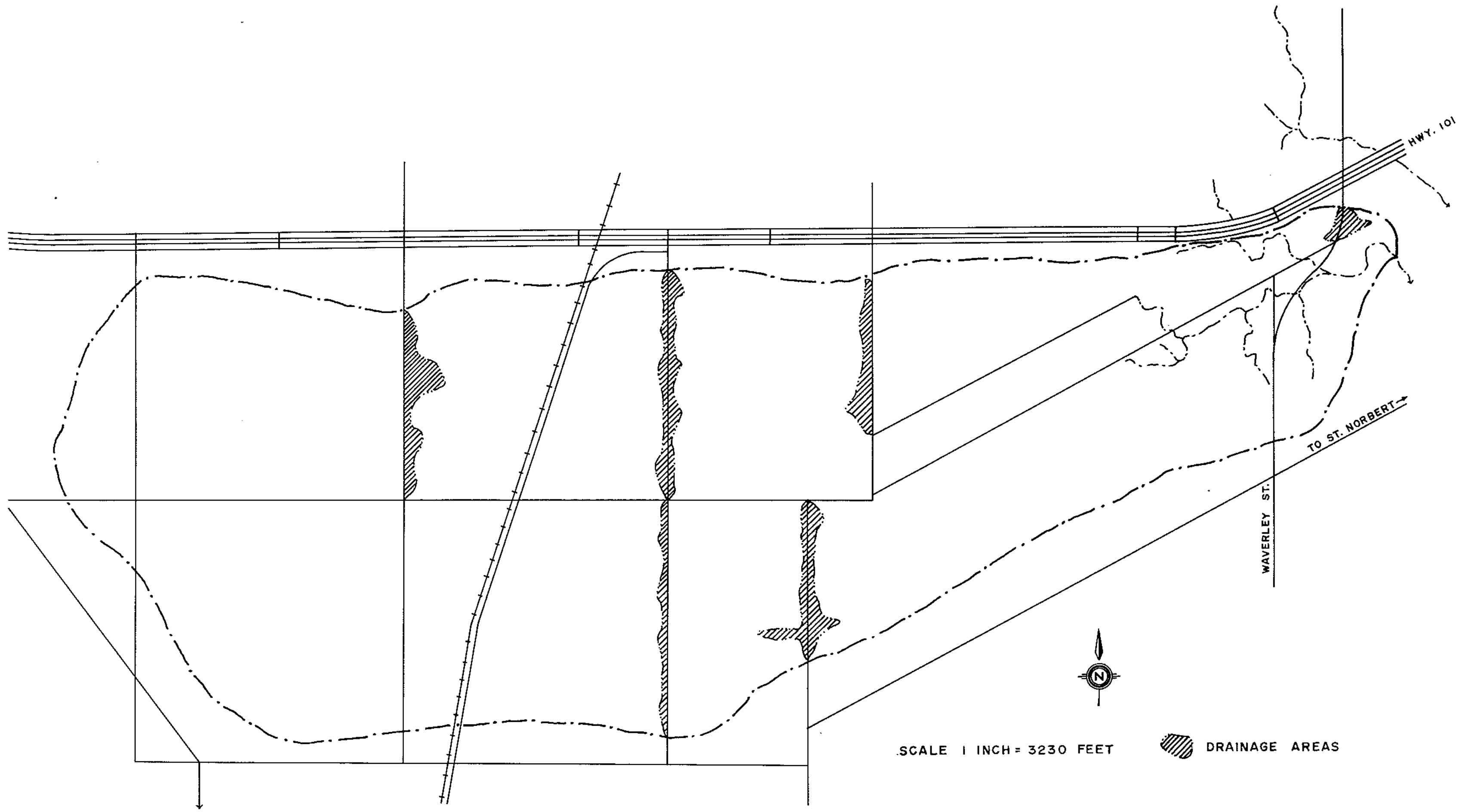
Although these drainage basin concepts were developed for areas of "gently undulating to strongly rolling morainic topography with numerous undrained or partially drained depressions and marshy areas" under rainfall/runoff conditions, it is proposed herein that these concepts have applicability to snowpack/snowmelt conditions.

The wet and dry drainage boundaries are defined in a similar manner except that the 1:50 and 1:2 rainfall events become snowpack conditions. Delineation of the gross drainage divide is usually accomplished by joining the heights of land on topographic maps. Due to the low relief in the study basin, this had to be supplemented by surveying conflicting areas. Aerial photographs taken on April 13, 1966 effectively show late melt conditions and indicate surface water ponding and are, thus, useful for determining areas of dead drainage. The dry drainage boundaries are relatively easily determined since in most cases the drainage divides coincide with channel banks as well as connected swales and shelterbelts. Maps 5.1 and 5.2 delineate the various drainage areas and channels in the study basin with the respective gross, wet and dry drainage areas being 4268 acres (100%), 2995 acres (70%) and 976 acres (23%). (Table 5.6)

The 1972-73 winter snowfall of 25.7 inches was much below the long-term mean annual snowfall recorded at the Winnipeg International Airport



MAP 5.1 DELINEATION OF GROSS, WET AND DRY DRAINAGE AREAS, ST. NORBERT



MAP 5.2 DRY DRAINAGE AREAS NOT CONTRIBUTING TO SNOWMELT RUNOFF

Drainage Area	Area (acres)	% of Basin
Gross	4268	100
Wet	2995	70
Total Dry (include all channels)	976	23
Potential Channel Area	109	3
Contributing Channel Area	74	2
Dry (Not cont. to runoff)	173	4
Extra-Channel Dry Contrib. to Runoff	729	18

TABLE 5.6. Study Basin Drainage Areas, St. Norbert.

of 51.3 inches. This would indicate that snowmelt should occur primarily from channel accumulation or the dry drainage area with relatively minor contributions from agricultural fields.

The volume of snowmelt runoff was 193.2 acre-feet which was equivalent to 0.54 inches applied over the entire drainage basin (8.4×10^6 cubic feet). Since this value is much below any observed value of snow water equivalent as of March 4, 1973, it is apparent that the entire gross drainage basin could not have contributed to the runoff process. Analysis of the potential volumes of runoff from drainage channels and road-side ditches indicates runoff quantities in the order of 5.2×10^6 cubic feet (119.4 acre-feet). A more realistic value of runoff would be slightly less than this as several channels were not designed for drainage but were originally borrow areas for the roads. Runoff from designed drains was equivalent to 3.0×10^6 cubic feet (68.9 acre-feet) which represents an underestimate since there would be some spillover from borrow ditches when these are partly filled with runoff water.

The dry drainage area apart from the channels and contributing to runoff is approximately 729 acres. Since time did not permit intensive sampling in these areas, it is necessary to estimate the additional volume of potential runoff from this region. To account for the deficit between channel runoff and total measured runoff volume of approximately 4.0×10^6 cubic feet (91.9 acre-feet), an average water content of 0.13 inches applied over this extra-channel dry drainage area would suffice.

It can be observed from Table 4.4 that as of March 4, 1973 most agricultural fields retained snow water equivalents in this order of magnitude. In conclusion, therefore, it would appear that by far the largest proportion of spring runoff from the study basin during the 1973 snowmelt could have originated in what has been termed the dry drainage area.

CHAPTER VI

CONCLUSIONS

Measurement of basin snowpack in prairie environments is difficult because of the heterogeneous character of snow accumulation. Problems arise in selecting sample points as well as in the choice of instrumentation. At present, multiple-point snow survey courses appear to offer the best alternative as these facilitate sampling many points with comparative efficiency and economy. However, more research could be expended in this area. Questions concerning the number of points and their spacing need to be answered. The orientation of each snow course should be examined to determine the relative importance on snow depth and water equivalent of prevailing winter wind direction and wind direction accompanying high velocity winds. Ideally this should be expanded to include the effects of varying vegetation.

The selection of the appropriate snow sampler is not as complex. In mountainous areas the small diameter Mount Rose sampler is common as it is lightweight and easy to drive through the deep snowpacks encountered. The large diameter samplers, such as the M.S.C. and Adirondack types, are designed for use in shallow prairie snowpacks as they sample a larger cross-sectional area per sample, thus reducing the error inherent in shallow depths. However, problems in driving the large diameter sampler through the ice lenses and heavy crusts common to prairie regions, as well as difficulties in retrieving a complete core, reduce the utility of this instrument for prairie conditions. It is suggested that the Mount Rose sampler be used whenever many sites are to be monitored in a short time period. The sampler used in this research recorded water equivalents to an accuracy of 0.5 inches over a working temperature range of -10^{o} F to 31^{o} F and snow depths were accurate to within 0.25 inches. Extension of these findings to similar samplers was not attempted.

In agricultural areas devoid of much relief and with very low natural drainage densities, source regions of snowmelt runoff are determined by snowpack and meteorological conditions. It has been shown that under much below normal snowfall and under normally brisk prairie winds, snow tends to accumulate in natural and artificial depressions at the expense of the flatter, more exposed areas. Runoff volumes can be estimated by sampling these depressions. It is suspected that as snowfall increases, depressions become filled so that their upper surface is near the level of the surrounding fields. Once this occurs, snow accumulation should be more uniform. However, research should continue in this area over numerous winters to determine the maximum snowpack expected in channels. This would involve an analysis of depression morphology (perhaps some function of width/depth ratio, side slopes, etc.), vegetative roughness adjacent to or in the depression, orientation with respect to surface winds and other meteorological parameters that may determine snow mobility, such as air temperature, age of snow surface and grain shape.

To estimate runoff volumes it is recommended that the snow course index sites operated by agencies such as the Water Control and Conservation Branch of the Manitoba Department of Mines and Natural

Resources be supplemented by the following procedure:

(a) a preliminary check should be made on snow accumulation in selected natural and man-improved drainage-ways in conjunction with reported snowfall for the area before any intensive sampling is performed in the Spring;

(b) if these channels contain a maximized snowpack, then existing field index sites should be sampled since total runoff will be a combination of channel runoff and field runoff;

(c) if these channels contain less than a maximum snowpack, then fields need not be sampled. Runoff from agricultural fields will be negligible.

In summary, this thesis has examined the measurement of basin snowpack in Prairie environments and has identified areas of snowpack accumulation that contribute directly to runoff for one prairie drainage basin. Such information should improve the reliability of indexing the heterogeneous snowpack as an input to flood prediction models. It should also prove useful in: (1) studying geomorphic processes which require identifying areas of Spring runoff; (2) studying vegetation where either snow cover insulation or Spring soil moisture recharge are important; and (3) studying the variable depth of frost penetration in Prairie soils.

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APPENDIX

GENERAL INFORMATION CONCERNING
SNOW SURVEYING IN MANITOBA

I. History

Started in Manitoba in February, 1951.

II. Reasons for Snow Surveys

To determine snow water content available for municipal supply and recreation purposes and to provide data in regard to flood control and flood forecasting.

III. Number of Measurements per Course

Average 3 to 6 samplings per course.

IV. Marking

Courses usually designated by number with reference to nearest town.

V. Location

(a) Located by river basins and nearby towns in patches of bush.

(b) In open areas in bush protected from high winds the area must be large enough that snow may fall to the ground without being intercepted.

(c) Open, wind-swept locations must be chosen with particular care.

VI. How Reliable Measurements are Obtained

(a) Snow course must be sufficiently accessible to ensure continuity of surveys.

(b) Measurements must be made at a sufficient number of points to ensure that the average of the measurements on the course will not be unduly affected by drifting or wind-swept snow. The topography and presence or absence of forest cover account for wide variations in the selection of measurement points on covers.

(c) If snow falls on an area large enough that snow may fall to the surface without being intercepted and in a location protected from high winds such that the snow falls and lies uniformly over this area, comparatively few measurements made either as a group in one space or separately in several adjacent spaces will yield the desired record.

(d) If an open space is large and of a shape that might permit the snow to drift within it the only sure plan to follow is to make a series of measurements along lines that form a cross or an "L" or as otherwise so arranged that the average of measurements will represent the depth of snow cover within the area.

(e) If protection from wind is altogether lacking and the course must be in the open, the measurements should be taken over an area of at least one-half square mile.

(f) In open prairie regions without forest or bush cover great areas of cultivated land become completely bare due to wind action and/or evaporation of the snow cover. Where these conditions are encountered an estimate should be made for general information of the percentage of the representative area that is bare of snow and measurements made on a snow course in the middle of a large unplowed tract of land such as grassed area where it is estimated that the depth of snow cover is a good average for the representative area.

(g) Surveys should be made on a sufficient number of courses properly located on each drainage basin to cover the variability of storms over the area.

VII. Number of Times Measured per Year

Measurements should be made at least twice, one in February and one in March.

VIII. Transportation

Usually by automobile or aeroplane and then on snow shoes around the snow course.

IX. Number and Frequency of Reports

About two or three interim reports per year with one report issued during the second week in each of the months of February, March. A final summary report to be issued early in the month of April each year.

X. Number of Copies of Report

About three to six copies depending on the demand for this data. Approximately fifty copies of snow survey maps prepared from snow survey data are distributed after each survey.

XI. Number of Forecasts per Year.

Probably not more than two forecasts.

XII. Method of Forecasting

Correlation depth of snow water with runoff and precipitation corrections applied.

XIII. Snow Sampler to be Used

Samplings to be made with a 2.90 inch inside diameter aluminum tube about 48 inches long with a 21-inch beam scale graduated in pounds and ounces for weighing purposes. The factor for the 2.90 inch inside diameter tube is 3.8. To determine the equivalent water depth in inches on the area divide the weight of snow in ounces by the tube factor 3.8. Under special conditions samplings may also be made with a Stevens tube. The type of sampler used must be noted in the field book.

XIV. Code

The following code is used to describe the crust conditions:

A - No crust

B - Light Crust

C - Crust strong enough to support a man on snow shoes.

April 10, 1962 Water Control and Conservation Branch.

CIR. - 3566
OBS. - 305
10 Nov 61

METEOROLOGICAL BRANCH - DEPARTMENT OF TRANSPORT - CANADA

A GUIDE TO SELECTION OF SNOW SURVEY COURSES

1. Introduction

1.1 Much of the success of the snow survey programme being undertaken by the Meteorological Branch, will rest with those selecting the observation sites. The snow survey sites must be representative of the surrounding area, easily accessible, free from excessive wind drifting, and in locations where permanence of the site, and thus continuity of record, can be reasonably assured.

1.2 These general principles and those indicated in section 2 apply to selection of sites for both 10-point type A courses, and 5-point type B courses. Some distinctions between site requirements for the two types are noted in sections 3 and 4 of this guide.

2. Site Selection - General Principles

2.1 The best site for a snow survey course is, in general, the best site for a precipitation gauge. The type of site which has been found to yield most consistent and reliable results is "an opening in the forest surrounded by hills for protection from high winds, and sloped sufficiently to permit runoff of water beneath the snow pack". ("Snow Hydrology", U.S. Corps of Engineers).

2.2 However, this ideal type of site is often not available, particularly at airports and on the Prairies and in the Arctic. In these cases, the course should sample the areas of both heavy and light snow accumulations, and should be away from snow fencing, buildings, and other obstructions which cause "abnormal" winds and consequently abnormal drifting of snow.

2.3 A number of practical matters should be kept in mind when selecting a snow course site. First of all the observation points should not be located in areas where a small rivulet runs or where water becomes ponded after a rainstorm or during snow-melt periods. Secondly, sharp irregularities in the ground level should be avoided, and observation points kept away from boulders, fallen logs, underbrush or shrubs. It is also important to select sites remote from road and runway snow removal and snow dumping activities.

3. Length, Shape and Extent of Courses

3.1 Type A

Courses at type "A" stations should be 900 ft. in length along a straight line with 10 sampling locations at 100 ft. intervals. Both the first and last sampling points must be clearly marked by posts, or markers on trees, fences, etc. Intermediate points may be indicated by such markers or by giving concise directions and distances from markers or natural objects. If it is impossible to obtain a 900 ft. straight line course of suitable characteristics, a "T"-shaped, "L"-shaped or "+"-shaped course could be accepted, provided the hundred foot distance between sampling points is maintained. Type A courses must be readily accessible on foot or skis or by vehicle and should be within 3 miles of the observer's building.

3.2 Type B

Only five sampling points are required for this type of course. They should be along a straight line 400 ft. in length, with 100 ft. intervals between sampling points. If a site suitable for a straight line course is not available, L, T or + shaped courses are permissible.

Such courses should be located within easy walking distance of the building in which the observers work.

4. Particular Aspect of Site Selection

4.1 Type "A"

At stations of this type, where measurements are made every other week rather than weekly, efforts should be made to obtain course sites as nearly ideal as possible. In areas where bushland or forest forms a substantial portion of the vegetative cover of the region, courses should be selected with a representative number of points in a small clearing at the edge of a bush. For example if 60% of the area surrounding a station is forested, 6 of the 10 snow course points should be somewhat protected by trees from wind action.

4.2 Type "B"

Snow course locations at Type B stations will normally be closer to the regular instrument enclosure than at type A stations, as observations are to be taken at weekly intervals. However, many instrument enclosure areas will be unsuitable as they tend to be affected by buildings, near areas where snow removal operations take place, and close to snow fences which disturb natural snow deposition. Many airport areas do have good snow survey sites, in locations off the runways and away from buildings and snow removal work. Airport authorities will usually make such sites available for snow surveys. If such sites are near the regular instrument enclosure, they should be selected in preference to more remote sites. However, care should be taken to locate a course which complies with the general and specific principles outlined above and is within reasonable walking distance of the observers' building.

5. <u>Making and Mapping the Course</u>

5.1 After a suitable site is selected, the observing points should be located and numbered. This may involve the installation of numbered stakes to mark the sampling points or the suitable marking of trees, fence posts, telephone poles, etc. The marker need not be precisely at the sampling point, but the observer could be instructed to take point 3, say, 50 ft. east of a certain marked tree, for example.

5.2 Sketch maps of each course must be prepared showing the location of each of the 5 or 10 sampling points, the vegetation of the area, the type of marker for each observing point, and giving the topography of the land at the course site. Copies of this sketch map will be used by observers in taking samples along the course, and by the meteorologists interpreting the observational data.

5.3 In addition, the snow survey course site should be marked on a regular topographic map of the region, which will show the surrounding influences on wind and snow deposition at the course site. Two such maps will be required, one for retention in the regional office and one for Meteorological Branch Headquarters.