PRAIRIE PROVINCES WATER BOARD

WATER DEFICIENCY PATTERNS IN THE PRAIRIE PROVINCES

by A.H. Laycock

Compiled for the P.P.W.B.
by the Hydrology Division, P.F.R.A.,
Regina, Saskatchewan.

February 1964

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Motherwell Bldg.,
Regina, Saskatchewan,
February 1964.

Mr. M.J. Fitzgerald, Chairman,
Prairie Provinces Water Board,
Regina, Saskatchewan.

Dear Mr. Fitzgerald:

Transmitted herewith is Prairie Provinces Water Board Report #8 entitled "Water Deficiency Patterns in the Prairie Provinces."

This report was prepared to partially fulfill one of the duties of the Board as set out in Section 4(a) of the Water Board Agreement which states, "----to collate and analyze the data now available relating to the water and associated resources of interprovincial streams with respect to their utilization for irrigation--------."

This investigation was undertaken by the Hydrology Division of P.F.R.A. (Canada - Agriculture) for the Prairie Provinces Water Board. The study was made and the report written by Dr. A.H. Laycock, Associate Professor of Geography, University of Alberta. Professor Laycock has already published a preliminary paper on this matter entitled, "Drought Patterns in the Canadian Prairies" which he presented to the International Association of Scientific Hydrology in Helsinki in 1960. This report is not complete. It has been published in this form due to heavy demand for the information. However, Dr. Laycock plans to continue studying the implications of these drought and surplus patterns: -----to use his own words--

> "The enclosed report with its accompanying maps showing Water Deficiency Patterns in the Prairie Provinces is a preliminary part of a longer report on Water Surplus and Deficiency Patterns in the Prairie Provinces. The additional chapters on water surpluses and study applications and the appendicies will be completed early this summer. Meanwhile, it is hoped that these chapters and maps will be of interest and value to their users and that useful comments and suggestions may be submitted so that the final report may be improved."

Acknowledgement should be made to the Meteorological Branch, Department of Transport, for supplying most of the data, and to G.W. Robertson, Canada - Agriculture (Plant Research Institute) for extensive computational assistance and useful comments.

Yours very truly,

E. F. Durrant

E.F. Durrant,
Engineering Secretary,
Prairie Provinces Water Board.

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I.

INTRODUCTION

The purpose of this study is to map the major patterns of drought and moisture surplus in the Prairie Provinces. Procedures developed during and since World War II by Thornthwaite (1948, 1955, 1957)*, Lowry and Johnson (1941), Blaney and Criddle (1952) and others enable us to define these patterns more closely than has previously been possible. In addition, the meteorological data employed are more recent and complete in coverage than those used by previous observers. The data of the 575 Prairie stations listed in the Canadian Monthly Record with one or more complete years of record in the period 1921-1950** have been used in most studies and subsequent data have been employed in some. Only 91 of the above stations had over 20 years of record in the base period and there were relatively few data for some regions but the major patterns appear to be well established, particularly for the "settled" regions.

The maps are largely self-explanatory and only brief descriptions of mapping procedures and significant patterns are included. Most of the maps can be applied in different ways but these uses are only suggested in this report.

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* See bibliography

** The period 1921-1950 is used as a base period by the Canadian Meteorological Branch for comparative studies - e.g. see "Temperature and Precipitation Normals for Canadian Weather Stations Based on the Period 1921-50" by the Climatological Division of the Branch. Cir.3208 Cli.19, June, 1959, 33p.

II.

PREVIOUS STUDIES

The earliest studies of the Prairies include many references to drought in what is now Southern Saskatchewan and South-Eastern Alberta (Palliser, 1863; Hind, 1864; Macoun, 1883, etc.). Most of these were based on observations of vegetative cover and local drainage patterns. Records of temperature and precipitation became available for a small number of widely scattered stations in the 1880's and droughts were soon defined as periods without rain or with rainfall well below normal for specific periods.

Most settlement in the Prairies took place with little regard for previously defined precipitation or drought patterns. After various periods of trial and error farming, farmers in many areas abandoned their farms or let their cropland revert to grass because severe droughts occurred too frequently for their type and scale of farming to be successful. Most of these areas were shown to have low and variable precipitation in numerous concurrent and subsequent studies by various authorities (e.g. Stupart 1905, Bracken 1921, Koeppe 1931, Connor 1933, Hope 1938, Thomson and Connor 1949, Jacobson 1952, Currie 1953, Longley 1953, Thomas 1953, Kendrew and Currie 1955, and others). Many of the patterns of precipitation deficiency were explained by these and other authorities (e.g. various publications of the Meteorological Branch, articles in the Monthly Weather Review, Borchert 1950, Villmow 1956 etc.). Numerous studies of adjoining areas in the United States were also useful in defining and explaining drought patterns (e.g. publications of the U.S. Depts. of Agriculture, Commerce and Interior and State Departments of Agriculture). Additional information was available in various reports concerning adaptations of land use to limited moisture supplies (e.g. Canadian and U.S. Dept. of Agriculture studies etc.), explanations of crop production patterns (e.g. Searle Grain Co. Research Dept., Canada and Provincial Dept. of Agriculture studies etc.) and Soil Survey reports. Numerous special and local studies by the Experimental Farms Service, Meteorological Branch, P.F.R.A., and various individuals are also helpful in defining and explaining regional patterns. (See Bibliography)

Drought patterns may be indicated to some degree by patterns of the natural vegetative cover. These are not as definitive as we might wish because plants may vary appreciably in density and vigor as well as in species composition and we know relatively little about the original cover in many areas. Farming practices, past fires and variations in grazing intensities by buffalo and livestock have resulted in significant changes in cover not directly related to drought patterns. Present plant cover that appears to be natural (e.g. along road allowances) has often had greater protection from fire and grazing, and greater moisture receipt (i.e. from snow that has drifted from adjoining fields) than the cover that was originally present. It is probable that many plants, particularly trees, have been influenced in their distribution to a great degree by intense droughts thus it is hard to define average drought and other patterns. We can suggest many climatic patterns if we know the nature of the vegetative cover but if we wish to define patterns more closely we must turn to the comparatively detailed long term meteorological records that are now available.

Other indicators of deficient moisture supply such as runoff or streamflow patterns may be useful, but runoff is generally seasonal (e.g. snow-melt) or dependent upon heavy rains of long duration, and the intensity of drought is not closely related. Evaporation studies may indicate where water losses from free water can be large and how these vary seasonally, but this information need not apply to land surfaces.

Definitions of drought in terms of length of period without rain or variations of precipitation from "normal" are inadequate for many purposes. It is apparent that growth response to a period of two weeks without rain after heavy rains may be very different from that in a dry period of two weeks separated from previous dry periods by only light showers. Similarly, the effect of two weeks of rainless hot windy weather with low relative humidity may be very different from that of two weeks of cool humid weather with little wind. Drought, in this paper, is expressed in terms of moisture deficiency as outlined in the following section on "The Water Balance".

Numerous studies of runoff and streamflow have been conducted in the Prairies (e.g. P.P.W.B. 1960). In most of these, there has been relatively little reference to local runoff into depressions which rarely if ever reaches major streams. Some of the exceptions are Stichling and Blackwell (1957) and Laycock (1959). It is very hard to measure this local runoff and apply the results to larger areas because it varies so greatly in amount with differences in soil texture, slope, vegetative cover, land use, moisture in storage, nature of frozen ground etc. in addition to precipitation intensity and duration, amount and rate of snow melt, evaporation and transpiration and other climatic variables. However, if gradients relating to climate can be established, local variations can then be noted and a greatly improved picture of regional patterns can be developed.

III.
THE WATER BALANCE

In the last few decades there has been an increasing realization that drought could not be adequately defined in terms of deficiency and variability of rainfall alone. Such definitions fail to take into account the amount of water that is needed and the amount of soil moisture that might be available for use during the growing season.

A more useful definition would describe it as a condition in which the available water supply is exceeded by the amount that is needed for evaporation and transpiration if optimum growth is to be obtained. This moisture deficit is expressed in inches in this region and, though most frequently calculated for the full growing season, may be obtained for any period. The available water supply is that which is obtained from precipitation and can be used by plants during the growing season (i.e. precipitation less surface runoff and percolation to beyond root depth, but including moisture storage that has accumulated previous to the growing season). The amount of water needed for evaporation and transpiration if optimum growth is to be obtained (potential evapotranspiration or PE) is primarily a function of climate because it is assumed that soil moisture supply is never limiting. The amount of solar energy and resultant air temperature is accordingly far more important than the kind of vegetative cover, soil type and texture, soil moisture storage capacity and land use in the determination of potential evapotranspiration.

Potential evapotranspiration has been measured in many parts of the world but it is impractical for us to measure it in all areas of the Prairies. It is far better, for our purposes, to employ climatic parameters, such as temperature and length of day, that are indicative of potential evapotranspiration.

This is possible now that Thornthwaite and others have established empirical procedures that have been widely tested and shown to be valid. The great advantage in our use of these procedures is that we are now able to use temperature and precipitation data that have been widely obtained in the Prairies for many years, in our water balance studies.

The water balance for a year has been summarized by Mather (1959) as follows:

> When the potential evapotranspiration is compared with the precipitation, and allowance is made for the storage of water in the ground and its subsequent use, periods of moisture deficiency and excess are clearly revealed, and an understanding of the relative moistness or aridity of a climate is obtained. If the amount of precipitation is always greater than the evapotranspiration, the soil will remain full of water, and a water surplus will occur. On the other hand, if precipitation is always less than the potential evapotranspiration or water need, moisture will be limited and a moisture deficit will exist. Under normal conditions both of these conditions will occur during the course of a year or several years at a place so that a comparison of the potential evapotranspiration with the precipitation will show both a wet or a cold season in which water need is less than the available precipitation and a dry or hot season in which the water need exceeds the precipitation. Under such circumstances there usually occurs a period of full soil moisture storage when precipitation is greater than the moisture demand and a moisture surplus accumulates; a drying period, when the moisture in the soil is used by the plants, the soil moisture storage is diminished, and a moisture deficit occurs; and a re-moistening season, when precipitation exceeds water use and the soil moisture storage is replenished. The values of moisture surplus and deficiency as well as of the other factors of the water balance can be computed by means of a simple water-balance bookkeeping procedure.

The Thornthwaite procedures (1948) for Swift Current, Saskatchewan, are shown below in tabular form for a representative period of four years.

Water balance at Swift Current Saskatchewan 1946, 1947,1948 & 1949
(4.0" moisture storage capacity).

1946

	J	F	M	A	M	J	J	A	S	O	N	D	Year
Temperature °F	15	14	34	47	49	59	69	62	53	38	19	11	
Potential Evap.	0	0	0.3	2.1	2.7	4.2	5.9	4.3	2.6	0.6	0	0	22.7
Precipitation	0.5	0.3	0.1	0.3	0.7	2.5	2.4	3.0	1.4	1.2	2.1	1.4	15.9
Ppt.- P.E.	0.5	0.3	-0.2	-1.8	-2.0	-1.7	-3.5	-1.3	-1.2	0.6	2.1	1.4	
Storage (1.8*)	2.3	2.6	2.4	0.6	0	0	0	0	0	0.6	2.7	4.0	
Surplus	0	0	0	0	0	0	0	0	0	0	0	0.1	0.1
Deficit	0	0	0	0	1.4	1.7	3.5	1.3	1.2	0	0	0	9.1

1947

	J	F	M	A	M	J	J	A	S	O	N	D	Year
Temperature °F	12	5	16	39	48	56	70	64	52	47	20	17	
Potential Evap.	0	0	0	1.0	2.5	3.9	6.0	4.6	2.5	1.7	0	0	22.2
Precipitation	1.4	0.8	0.7	1.2	1.1	3.2	0.9	1.9	1.9	0.7	1.4	0.9	16.1
Ppt. - P.E.	1.4	0.8	0.7	0.2	-1.4	-0.7	-5.1	-2.7	-0.6	-1.0	1.4	0.9	
Storage (4.0*)	4.0	4.0	4.0	4.0	2.6	1.9	0	0	0	0	1.4	2.3	
Surplus	1.4	0.8	0.7	0.2	0	0	0	0	0	0	0	0	3.1
Deficit	0	0	0	0	0	0	3.2	2.7	0.6	1.0	0	0	7.5

1948

	J	F	M	A	M	J	J	A	S	O	N	D	Year
Temperature °F	15	5	15	34	53	61	65	66	59	45	27	7	
Potential Evap.	0	0	0	0.3	3.2	4.4	5.1	4.8	3.2	1.4	0	0	22.4
Precipitation	0.8	1.6	0.6	2.0	0.7	1.8	3.1	0.9	0.0	0.0	0.8	1.0	13.3
Ppt. - P.E.	0.8	1.6	0.6	1.7	-2.5	-2.6	-2.0	-3.9	-3.2	-1.4	0.8	1.0	
Storage (2.3*)	3.1	4.0	4.0	4.0	1.5	0	0	0	0	0	0.8	1.8	
Surplus		0.7	0.6	1.7	0	0	0	0	0	0	0	0	3.0
Deficit	0	0	0	0	0	1.1	2.0	3.9	3.2	1.4			11.6

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* Soil moisture in storage at the start of the year.

1949

	J	F	M	A	M	J	J	A	S	O	N	D	Year
Temperature °F	1	2	26	49	55	60	66	68	55	39	39	5	
Potential Evap.	0	0	0	2.1	3.4	4.4	5.2	5.2	2.7	0.6	0.6	0	24.2
Precipitation	0.7	0.3	0.5	0.2	1.3	1.5	2.1	1.2	0.6	1.4	0.2	1.2	11.2
Ppt. - P.E.	0.7	0.3	0.5	-1.9	-2.1	-2.9	-3.1	-4.0	-2.1	0.8	-0.4	1.2	
Storage (1.8*)	2.5	2.8	3.3	1.4	0	0	0	0	0	0.8	0.4	1.6	
Surplus	0	0	0	0	0	0	0	0	0	0	0	0	0
Deficit	0	0	0	0	0.7	2.9	3.1	4.0	2.1	0	0	0	12.8

The usual water balance equation "Precipitation equals Evapotranspiration (Potential Evapotranspiration minus Deficit) plus Surplus plus or minus Storage Charge" provides a summary for each year:

1946 -------------- 15.9" equals (22.7" - 9.1") + 0.1" + 2.2",

1947 -------------- 16.1" equals (22.2" - 7.5") + 3.1" - 1.7",

1948 -------------- 13.3" equals (22.4" - 11.6") + 3.0" - 0.5", and

1949 -------------- 11.2" equals (24.2" - 12.8") + 0" - 0.2". **

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* Soil moisture in storage at the start of the year.

** The Deficit and Surplus patterns of these years might be placed in perspective by reference to maps in chapters IV and VI. The average annual surplus for the period 1921-1950 for Swift Current was 0.6 inches and the range was from 0 (in 20 years) to 4.5 inches (in 1927). The average annual deficit was 8.5 inches and the range was from 1.5 inches (in 1942) to 16.2 inches (in 1937). Average precipitation for the year is 14.9 inches, and by months it is Jan. 0.8, Feb. 0.6, Mar. 0.6, Apr. 0.9, May 1.7, June 3.0, July 2.1, Aug. 1.8, Sept. 1.3, Oct. 0.8, Nov. 0.7 and Dec. 0.7. Some observers might wish to use other than calendar year periods but the average values would not change.

Data for a series of years illustrate features of water surplus and deficit that cannot readily be shown in single or average years. In 1946 the early dry spring resulted in rapid use of the limited moisture reserve. The deficit by the end of July was 6.6 inches. Precipitation in the last three months of the year was great enough to more than fill soil moisture storage to capacity (upon melting in the following spring). In 1947, spring runoff from snow melt was moderately high. Good moisture reserves plus above normal rainfall resulted in below normal seasonal deficits. In 1948, spring runoff from snowmelt and April rain was again moderately high and soil moisture reserves lasted well into the summer (the deficit by the end of July was only 3.1 inches). The late summer was very dry and storage was not filled to capacity by the following spring. In 1949 runoff occurred only in areas with limited infiltration and storage capacities and the summer deficit was large. Soil moisture recharge was light in the fall, largely because November was warm and dry.

The procedures illustrated above (described by Thornthwaite 1948) have been modified in more recent years (1955 and 1957) in several ways. Greater storage capacities are usually assumed and the water loss from storage is at less than the potential rate as the soil dries. Water surpluses are converted to streamflow with allowance for detention storage in the form of snow and ice and in the regolith and rock beyond root depth. These are quite reasonable and logical modifications but they have not been introduced into this study for several reasons: (1) The procedures are more time consuming than those used; (2) A significant part of the data processing had been done before the 1957 tables became available; (3) The Potential Evapotranspiration values, which are basic, remained unchanged in the new procedure and there appears to be very little difference in the deficit and surplus patterns resulting from the use of the more recent procedure in the Prairie region; (4) The summer rains in the Prairies tend to be frequent but light and studies by other authorities (e.g. Holmes and Robertson 1959) indicate that this addition to surface moisture is used at or near potential rates rather than at the slower rates suggested in the modification; (5) The information provided in this study is to be used in part in irrigation planning and a changing rate of storage water use is less needed than it might be if major storage depletion were to take place; and (6) Much of the Prairie streamflow is obtained from surface runoff (meltwater and intense rains) and the general patterns of streamflow involving percolation to beyond root depth are only partly applicable in this region.

Numerous authorities have studied the water balance and aspects of it in the last several decades. The procedures of several of these will be discussed briefly in Chapter V (e.g. Lowry and Johnson 1941, Blaney and Criddle 1952). Some of the procedures of others, e.g. Penman (1948), and Turc (1953 and as modified by Mohrmann and Kessler 1959), tend to be sufficiently complex that the necessary data are not available for more than a few stations or involve conversions which make them as empirical as those discussed. Still other procedures, though simple, provide only rough indices of drought. Many of these have been employed in check studies and there appears to be little reason for major revision of the patterns mapped.

Local studies of water surplus and deficiency patterns and of streamflow and crop yields etc. generally confirm the patterns established through use of the Thornthwaite procedures. Their value is greatly enhanced when related to these patterns, for then they can be placed in time and space perspective.

IV.

WATER DEFICIT PATTERNS IN THE PRAIRIE PROVINCES - THORNTHWAITE PROCEDURES*

It has been noted previously that water deficit is the amount by which the supply of water available for evaporation and transpiration is exceeded by plant needs. Since most of the precipitation is available (runoff is small), and water needs are indicated by calculations of potential evapotranspiration, some of the general patterns of water deficit can be suggested by comparison of precipitation and potential evapotranspiration patterns.

Average Precipitation 1921-1950** (Figure 1)

Average precipitation is lightest in South-Eastern Alberta and South-Western Saskatchewan, to the north and south of the Cypress Hills, where less than 12 inches is received per year. Precipitation increases gradually to the east of this area to over 20 inches in South-Eastern Manitoba. North of the area of lightest precipitation, increases to over 16 inches are indicated but smaller amounts are received still farther to the north. To the west of the "dry belt" precipitation increases slowly in the plains, more rapidly in the foothills, and very rapidly in mountain areas and annual totals of between 50 and 100 inches are received on the higher mountains on the continental divide.

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* This descriptive review is supplemented by Appendix A, a discussion of some of the technical problems relating to map development and analysis.

** Based on "Temperature and Precipitation Normals for Canadian Weather Stations Based on the Period 1921-1950" by the Climatology Division, Meteorological Branch, Department of Transport of Canada. Cir. 3208 Cli 19, 3 June, 1959, Ottawa. Allowances have been made for topographic variations. See Appendix A.

Only some of the local variations in precipitation are noted. above average amounts are received in hilly areas and below average amounts are generally received in valleys. Some hill, moraine, and escarpment areas within the plains may receive 5 or more inches more than adjoining lowlands. Some valley areas with rough terrain and forest cover, however, probably receive greater precipitation than adjoining featureless plains. The variations in the plains regions are generally small but those of mountain areas may be very large. Some mountain valleys are almost as dry as the drier parts of the plains while higher areas nearby receive up to 50 inches more precipitation per year. Many local variations are not indicated on the map because of scale and data limitations.

It is assumed that the recorded data are correct for all stations and that station data are representative of precipitation in surrounding areas. Some allowances have been made for topography but these have been conservative.* This map is believed to be much more accurate than most that have been published previously (e.g. plate 25, Atlas of Canada, 1957). Despite this, it is suggested that improvements in precipitation measurement (particularly snowfall) can do more than improvements in techniques and procedures to correct the surplus and deficit patterns mapped in this study.

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* More recent maps by McKay 1960, Muttit 1960 and others show other local variations but Figure I has not been modified because subsequent maps in this paper were based upon it. Fortunately, the local variations indicated above are minor for settled areas. See Appendix A.

Average Potential Evapotranspiration 1921-1950 (Figure 2)

This map shows how much water would be evaporated and transpired if the surface was completely covered with vegetation and there was sufficient moisture in the soil at all times for the use of this vegetation. This expression of heat available for plant growth, in terms of inches of water required, enables us to conduct water balance studies.* It is assumed that the water is available at precisely the time of need thus, in practice, larger amounts of precipitation would be required if seasonal deficits were to be avoided because there is no allowance for surface runoff or percolation beyond root depth.

The major patterns show decreases from south to north with some reflections of elevation in the west, and proximity to Hudson Bay in the north-east. The areas with low precipitation have relatively high evapotranspiration potentials, in part because less of the solar energy is used to evaporate water and more is available for surface heating than in more humid areas. Other factors are also important, e.g. more solar radiation is received at the surface because of the smaller amounts of water vapour and cloud in the atmosphere.

Many local variations are present within the general patterns mapped.** For example, south facing slopes have significantly

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* Calculations of Potential Evapotranspiration are also used in showing the comparative amounts of heat available for growth in different regions, and in scheduling crops to provide for balanced harvest operations (e.g. at Seabrook Farms, N.J.).

** See Appendix A.

greater evapotranspiration potentials than north facing slopes, and there are variations with changes in vegetation type and cultural practice.

Average Deficit 1921-1950 (4 inches storage capacity) (Figure 3 and Figure 4-b)

One of the major problems in mapping moisture deficit patterns in the Prairies is that the water supply available for plant use varies so appreciably in small areas because of variations in soil moisture retention storage capacity and in the capacity of plants to utilize the stored moisture. It is conceivable that detailed maps of moisture storage capacities could be prepared, but such maps are not yet available. Some impressions of the local patterns might be obtained if information on storage capacity variations with soil texture etc. (as in Appendix B) is applied to the soil maps available.

It is possible for us to determine approximate local deficiency patterns if we draw up maps for each of a number of storage capacities and apply the one that is appropriate for local soil and growth conditions. The values selected for computation are 1/2", 1", 2", 4", 6", 8" and 12".

Maps based on a 4" storage capacity are reasonable for showing average conditions and might be applied for loam soils and for crops that have moderately full root development--e.g. most cereal grains.

The average deficit patterns in the Prairies may be related to the precipitation and potential evapotranspiration (P.E.) patterns. The driest areas are in Southeastern Alberta and Southwestern Saskatchewan where precipitation is low and P.E. is high. Deficiencies here average up to 12 inches per year. Deficiencies are smaller to the east, west and north averaging 4 to 6" in the more humid agricultural areas and 0 - 4" in the more humid forested areas. Deficiencies are moderately large in northern parts of Alberta but are not as large as in areas with equivalent precipitation in the south because evapotranspiration is low. If we were to calculate deficits using average monthly temperature and precipitation data we would be able to establish patterns of drought intensity that are not greatly in error in the drier areas (e.g. see Sanderson, 1948). Unfortunately, deficits based on average monthly data are not average deficits. If certain months had deficits in all years, we would find that deficits based on average monthly temperature and precipitation data would be the same as average deficits based on calculations of all years of the period. Since many of the months have deficits in some years, surpluses in others and storage recharge or withdrawal in still other years, we must complete calculations for all years if we are to determine averages of surpluses and deficits. When this is done, we find that both surpluses and deficits are larger than those based on average temperature and precipitation.* In making our calculations for all years of the period, we have obtained abundant information for establishing many different frequency-intensity and other deficit patterns. The more detailed studies are essential if we are to obtain a more adequate understanding of

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* Surpluses and Deficits for Swift Current for 1946-1949 inclusive would have been 0.4" and 8.2" respectively if based on average temperature and precipitation for the period. If we refer to chapter III we find that if calculated for each year, they averaged 1.6" and 10.3" respectively.

moisture deficits in non-irrigated areas and potential water needs in irrigable and irrigated areas.

Maximum Deficit 1921-1950 (4inches storage) (Figure 5-a)

It should not be assumed that the more humid regions are free from intense drought. Droughts are of greater intensity in the normally dry regions but the humid regions also suffer from severe moisture deficits in some years. There are many other variables (e.g. in the timing and duration of the drought) that are important, but growth will be very limited if annual deficits of over 8 to 10 inches are experienced.

The demand for irrigation water is over 16 inches in the drier regions in the driest years--plus allowances for conveyance and other losses. Supplemental irrigation facilities might usefully supply from 8 to 16 inches of water in the drier years in most other agricultural regions in the Prairies if water were available at low cost.

Minimum Deficit 1921-1950 (4 inches storage) (Figure 5-b)

In some years, precipitation is so abundant and well distributed that moisture deficiencies may be nil in almost all parts of the Prairies. If extra storage allowance were to be made (e.g. 12 inches), and longer periods of record were available, many of the stations recording drought in their wettest years would show no deficiency. Most of these stations have some runoff in some years.

The occasional year with little or no moisture deficiency will have excellent crops without irrigation and many farmers base their hopes and too much of their planning on the moisture conditions of these years. Irrigation requirements are very limited and little of the available water is utilized.

Median Deficit 1921-1950 (4 inches storage) (Figure 4-c)

For some purposes data on median deficits are more useful than those on average deficits (they are not greatly affected by abnormally large or small values and show the value for 50 percent of the time. Averages are generally used in this study but it is of interest that median values are very similar (compare maps 4c and 3). The differences are almost always under 0.5 inches and are frequently 0. In the drier areas the median value is slightly larger because the infrequent moist years affect it less than they do the average. In some of the more humid areas (e.g. the Southern Alberta Foothills) the average value is the larger because very dry years are infrequent.

Moisture Deficit - Lower Quartile 1921-1950 (1/4 of the years have this deficiency or less) (4 inches storage) (Figure 5-c)

Perhaps the most useful information on drought is contained in maps of frequency-intensity patterns. For example, a farmer wants to know what the chances are that a severe drought will not occur in the current year, and government agencies want to know how much water is needed in different proportions of the years for irrigation. Planning can be based to a large degree on the past record if this is expressed in terms of frequency and intensity.

Large deficits are experienced in the drier areas in at least 3/4 of the years and one might conclude that certain crops and farming practices would not be feasible. Summerfallow frequencies, plant species and varieties, the scale of farming operations and other variables should be affected in planning land use in especially the drier areas.

The deficits are very small in large parts of the Prairies in enough years that high yields may be obtained and most of the expenses of farming can be recovered.

The water demand in irrigation projects in the drier areas is shown to be quite large in at least 3/4 of the years. The success of irrigation will probably be greatest in these areas, in part because farmers are not encouraged by the record to hope for rain.

Moisture Deficit - Upper Quartile 1921-1950 (1/4 of the years have this deficit or more) (4 inches storage) (Figure 5-d)

Most of the farming areas of the Prairies have deficits of over 8 inches in the driest quarter of the years. West Central Alberta is one of the few areas with deficits of below 6 inches in these years and yields are comparatively dependable (the moisture supply is the only variable considered here--other factors such as frost, hail, fall rain, etc. are of great importance on the cooler humid margins). In much of the Prairie, yields will be very low in most of these years and the success of farming depends primarily upon the yields of the better years (see the previous map).

Irrigation water needs are large in these years and irrigation projects tend to be utilized almost to the limit of irrigable acreages and/or water supply. Supplemental irrigation could greatly benefit crop production in most areas. Local water surpluses are not usually very large in the spring of most of these dry years but there is some potential in the use of these surpluses in many years.

Deficit 1927 (4 inches storage) (Figure 7-a)

The deficit patterns have been mapped for all years of the period 1921-1950. There is a strong tendency for drought patterns of individual years to resemble the average patterns mapped previously but there are numerous exceptions and variations in individual years. Forecasting for any one year is very risky but forecasts for a series of years can be quite reliable. Four years, 1927, 1936, 1944 and 1950 have been selected to illustrate some of the variations. A comparison of each with the average patterns (Figures 3 and 4) will show the contrasts.

In 1927, one of the wettest years in the Prairies, the dry belt could not be identified as such. Medicine Hat, one of the driest locations in most years, had a deficit of only 0.4 inches. In contrast, the Peace River region was moderately dry.

The deficit patterns of 1927 were probably attributable to a greater than normal flow of tropical Maritime air into the Prairies from the Gulf of Mexico, and to greater cyclonic activity than normal along southern Prairie storm tracks (see Appendix A).

Deficit 1936 (4 inches storage) (Figure 7-b)

In 1936, the dry belt was very dry and greatly enlarged. The southern parts of the Prairies were particularly dry but some northern areas (e.g. the Peace River region) were wetter than normal. Southwestern Saskatchewan and Southeastern Alberta were very dry again in 1937 and the combination of successive very dry years resulted in excessively low moisture reserves, damage to grasses, trees etc. and widespread crop failure.

It is apparent that severe droughts can affect broad regions in any one year and that the demand for the limited supplies of irrigation water can be very large in particular years. Only rarely is there severe drought in one part of the region in need of irrigation and minor drought in another.

The deficit patterns of 1936 may be attributed to an almost total absence of moist Maritime tropical air in the region--normally the most significant source of moisture in the southeastern parts of the Prairies. Cyclonic activity was very limited along southern tracks but above normal uplift of Pacific air occurred in the northwestern regions.

Deficit 1944 (4 inches storage) (Figure 7-c)

In 1944, Southern Manitoba and Saskatchewan and Central Alberta were relatively moist. The "Dry Belt" was a bit to the west of normal and there was a dry extension to the northeast. In addition the Peace River country was dry.

The storm tracks were not as well distributed as "normal" but there was at least a normal degree of cyclonic activity. The Pacific sources of moisture were most important in the west and tropical Maritime in the southeast--a fairly typical pattern.

Deficit 1950 (4 inches storage) (Figure 7-d)

In 1950, most eastern and far northern areas were moist but Central and Southern Alberta were moderately dry. In this, as in most years some drought was experienced in almost all regions but the intensities varied regionally.

The moisture deficit patterns mapped and described previously are those of the full growing season. Many crops do not utilize the full growing season in their various stages of growth to maturity. It is thus of some value for us to determine the deficiencies for the period of growth of specific crops. Since the data have been calculated by months, some generalization is necessary. The first of the crops discussed is alfalfa and the months of May to September inclusive are used in calculating growing season deficiencies.

Average Deficit 1921-1950 (1/2 inch storage capacity) (Figure 4-a)

Coarse textured sandy soils have very limited capacities for moisture retention storage (see Appendix B). If these capacities are approximately 1/2 inch for given crops, the patterns shown in this map might be applied locally rather than the patterns developed for other storage values. Plants with very limited capacity to develop roots and utilize stored moisture from more than very limited soil volumes might suffer the degree of drought indicated on this map.

It will be noted, upon inspection of this map, that droughts in Southern Manitoba are not much less severe than those of Southwestern Saskatchewan for soils with very low storage capacities. The patterns shown are very nearly those of P.E. less precipitation during the growing season. This would suggest that a significant part of the production advantage of Southern Manitoba lies in its greater soil moisture storage capacities plus the greater filling of these capacities before the growing season begins.

If we assume that fire hazards in grassland and forest areas vary largely with the degree of the organic matter present, this map might be used to show some annual hazard patterns. Dead organic matter that is well exposed to drying will tend to have limited moisture holding capacities and will burn readily when this moisture has evaporated. Live plants will generally have access to larger moisture storage, and the patterns of drying and intense fire damage will be more like those on later maps (e.g. 12" storage capacity). Frequency-intensity, and monthly patterns are also significant.

Average Deficit 1921-1950 (12 inch storage capacity) (Figure 4-d)

Fine textured clays and clay loams have large capacities for moisture retention storage (see Appendix B). If alfalfa or other crops with deep and extensive rooting habits are grown in these soils, the moisture deficiency within the growing season will tend to be small if storage capacities are well filled at the start of the season.

The moisture storage capacities are more nearly filled in most years in the more humid areas of Southern Manitoba, Northeastern Saskatchewan and West Central Alberta than in the drier parts of Southeastern Alberta and Southwestern Saskatchewan. This is almost as important as the difference in growing season precipitation in explaining regional differences in deficit and it is the major reason why there is a greater decrease in drought intensity from dry to humid regions than is apparent in the 1/2 inch storage maps.

There is little change in drought intensity with additional moisture storage capacity above 4 inches because non-growing season contributions to storage are small in most years in most parts of the Prairies. This would indicate that there is little difference in productive capacity between medium textured loams and clays-- from the moisture supplies of the current year. Since many crops do not utilize all the moisture of the full growing season, and summerfallowing is widespread, the extra storage capacity of clays is more fully utilized and the productivity advantage is greater than is indicated here. Some of these qualifications are noted later.

The three maps of average deficit (3, 4a, and 4d) indicate that irrigated crops in the drier regions require approximately 4 inches more water in sandy soil areas than in areas with clay loams. In addition they show that supplemental irrigation might be utilized to a much greater degree on sandy than on clay soils and for shallow than deep rooted plants in the more humid regions.

Additional maps showing patterns for 1, 2, 6 and 8 inches storage have been drawn up but are not included because they are as one might expect for the intermediate values between those that have been discussed.

Percentage of Years with Over 8 Inches Deficit 1921-1950 (1/2 inch storage) (Figure 8-b)

The frequency-intensity patterns of moisture deficit vary significantly with soil moisture storage capacity. If available retention storage capacity is only 1/2 inch (e.g. sandy soils or crops with very limited root development) the proportion of years with severe drought (e.g. over 8 inches deficit) will be very high in most parts of the

Prairies. The regional variations are still significant however: for example, the sandy soils near Ponoka, Devon and Grande Prairie in Alberta might be utilized with less drought, or supplemental water need, than similar soils between Saskatoon and Outlook, to the east of Brandon, or to the north of Maple Creek.

Percentage of Years with Over 8 Inches Deficit 1921-1950 (4 inches storage) (Figure 8-a)

The frequency of years with intense drought is a bit lower in the dry regions and much lower in the more humid regions if storage capacities are 4 inches rather than 1/2 inch (the previous map). The difference can be attributed largely to the larger non-growing season contributions to water storage.

The drought frequency in the drier areas (e.g. the areas within the 75 % isoline) is sufficiently great that dry farming is marginal on soils with only moderate moisture storage capacities. The severe droughts occur much less frequently in areas to the northwest, north and east, and the need for summerfallowing in rotation programs is greatly reduced.

Percentage of Years with Over 8 Inches Deficit 1921-1950 (12 inches storage) (Figure 8-c)

The areas with clays and clay loams that are utilized in the production of crops with deeper rooting habits (e.g. alfalfa) have smaller potential moisture deficits than those with lesser storage capacities. The differences are minor (nil in most years, moderate in some) in the drier regions but crops in the more humid regions benefit significantly from this extra storage capacity and use.

The irrigation water needs are approximately the same as in areas of lighter soil in the drier regions. There is less need for supplementary irrigation on the heavy soils in the humid regions however.

It is probable that the greater crop successes in Manitoba than Southwestern Saskatchewan can be attributed in part to the wider distribution of heavy soils with excellent moisture retention storage capacities.

Many natural vegetative cover patterns can be attributed to severe drought patterns. For example, trees are excluded from large parts of the "Parkland" area, not by moisture deficiencies in average years but by a combination of drought and fire in the drier years. Similar relationships in grassland cover patterns, forest fire patterns etc. can be established. A number of land use relationships may also be noted. (See Chapter 7).

Percentage of Years with No Deficit 1921-1950 (12 inches storage) (Figure 8-d)

The proportion of years with optimum moisture supplies from current precipitation and large storage capacities (e.g. clays with alfalfa), is quite small in the drier part of the Prairies (over 1/3 of the stations within the 10 % isoline had 0 values but they are so scattered that we might conclude that any station could have a sufficiently wet year in a 30 year period that no deficit would be present). This proportion increases rapidly in the most humid regions but most of the farms of the Prairies have some drought in most years, even with the best moisture storage conditions. It is of interest that droughts of some degree are quite frequent in the Peace River country.

It could be suggested that some irrigation waters could be used by crops in almost all years in most parts of the Prairies. Many of these areas and years have deficits of such a low order that irrigation might not be warranted. However, small water projects might utilize spring surpluses to advantage in many years at relatively low cost.

Average Deficit for Alfalfa: May-September 1921-1950 (1/2, 4, 8 and 12 inches storage) (Figures 10-a, 10-b, 10-c, 10-d)

The average deficits for the period May-September are very similar to those of the full year for the same storage values (e.g. maps 3, 4a and 4d). There are differences especially in the southwestern regions where small deficits in October and November are not unusual and others may occur in April of some years.

The storage values selected are approximately those of coarse sand, sandy loams, medium loams and clay loams or clays for alfalfa growth. It is doubtful that alfalfa would be grown on the coarse sands because of the intensities of droughts in all areas. The deficits are appreciably smaller in humid regions where storage capacities are larger but the change with increasing storage capacity in the drier regions is not great for over 4 inches capacity. Only the most humid regions have large use of large storage capacities in many of the years unless summerfallowing is employed.

The irrigation requirements vary greatly in amount (as indicated) and in frequency. Crops on the sandy soils would require water in such large amounts and so frequently that water must be abundant and delivery must be by sprinklers. Crops on clay soils would require much less water in infrequent applications and there would be a danger of over-irrigating and water-logging the soil in wet seasons.

Average Deficit for Wheat: June-August 1921-1950 (1/2, 2, 4, and 8 inches storage) (Figures 11-a, 11-b, 11-c, 11-d)

The period June-August is used in this map series as the period of wheat growth. The deficit for the lightest soils is about 1 - 2 inches smaller than for alfalfa in the wetter regions and 2 - 4 inches smaller in the drier regions. This is approximately the order of moisture deficiency in May and September.

The difference between the alfalfa and wheat deficit patterns decrease with added storage, especially in the more humid regions. Slightly different soils are involved because alfalfa has a greater capacity to utilize moisture from deeper soil levels. It is doubtful that much over 8 inches storage is available for wheat in even the finest soils because of the more limited rooting habit of wheat. The limitations of summerfallowing as a means of moisture conservation in humid areas are thus indicated.

The irrigation water requirements of wheat are smaller than those of alfalfa but not as much smaller as we might expect with the shorter growing season. Evaporation continues in the other months and only part of the annual precipitation enters into storage.

Average Deficit in May 1921-1950 (1/2 inch storage) (Figure 12-a)

The deficit patterns for wheat based on single storage values and the season of June-August may be refined, particularly in southwestern areas, if several additional modifications in procedure are made. The season possibly should be May, June and July--final ripening and harvesting may take place in August but the condition of the crop will have been determined by then and drought then may not mean much.

The germinating seed and seedling have very limited access to soil moisture in May--a moisture storage capacity of 1/2 inch may be most valid. The seedling will suffer drought if it cannot reach the moisture beyond its roots. The amount of deficit in May may be indicated reasonably closely by a map based on such a storage value . In irrigated areas this deficit may not be overcome because irrigating for small requirements in spring may not be feasible and the crop yields may suffer as a result, even though abundant moisture is supplied at a later date.

Average Deficit in June 1921-1950 (2 inches storage) (Figure 12-b)

The wheat plant has a greater but still limited capacity to reach soil moisture supplies in June. A 2 inch storage capacity may be a reasonable base for mapping deficit patterns in this month. The area of drought is still a broad one but the dry belt pattern is becoming apparent.

Average Deficit in July 1921-1950 (6 inches storage) (Figure 12-c)

In July the wheat plant has a well developed root system and it is able to utilize moisture from a much larger volume of soil. A moisture storage base of 6 inches is perhaps the most useful but this is potentially available only in the finer soils. The dry belt patterns are now well established.

Average Deficit - May, June and July 1921-1950 (1/2, 2 and 6 inches storage) (Figure 12-d)

The moisture deficit patterns for wheat in these three months are possibly the most useful of the patterns suggested but local research studies should help to confirm or correct the assumptions used.

It is certainly true that the values suggested are more valid than those for the full growing season (Figures 4 and 5).

V.

WATER DEFICIT PATTERNS IN THE PRAIRIE PROVINCES
LOWRY JOHNSON: BLANEY & CRIDDLE

The Thornthwaite procedures used in obtaining the data mapped in Part IV are empirical and, although widely tested, are not necessarily the most correct for local conditions. Two other procedures that have been discussed previously (Part III and Appendix A) have been applied for a number of Prairie stations and the maps can now be reviewed. The number-letter sequence used is that of the maps.

Consumptive Use: May-September 1921-1950 (Lowry & Johnson) (Figure 13-a)

The "Comsumptive Use" of Lowry Johnson is very similar in concept to the "Potential Evapotranspiration" (Figure 2) of Thornthwaite. It will be noted if the two maps are compared that the patterns and the values are very similar. The Thornthwaite values are very slightly larger in this comparison but the difference is largely the P.E. of April, October, and November. The Lowry Johnson values are actually very slightly higher for the corresponding periods. Lowry Johnson procedures have not been applied for stations in the Alberta mountain and foothill areas or in Northern Saskatchewan and Manitoba and the isoline values for these areas have not been included on the map. It is probable that they would be very similar to those based on Thornthwaite procedures.

Moisture Deficit 1921-1950 (Lowry Johnson) (Figure 13-b)

The moisture deficit values of this map exceed those of the Thornthwaite "average" deficit (4 inches storage--Figure 4-c) by a significant amount in almost all areas. This is probably because there is little or no allowance for moisture storage at the start of the season. The areas in Western United States in which the procedure is widely used (Bureau of Reclamation) have very little soil moisture at the start of the growing season.

Moisture Deficit 1921-1950 (Lowry Johnson) (Less storage on May 1st--4 inches capacity) (Figure 14)

The storage values of May 1st - the start of the growing season - are those based on Thornthwaite procedures. If these are subtracted from the moisture deficit of the previous map, average deficit patterns very similar to those of Figure 4-c are established. Gradients are steepened slightly because the humid areas have similar values and the drier areas have slightly greater values.

The water demand in irrigation is slightly greater than that indicated in Thornthwaite-based maps but the patterns are generally the same.

It would appear that there is little conflict between the results of these procedures if some allowance is made for moisture storage.

Consumptive Use--Alfalfa: May-September 1921-1950 (Blaney & Criddle) (Figure 15-a)

The "Consumptive Use" of Blaney and Criddle may also be compared with the P.E. of Thornthwaite. There is a greater difference between these than between the Lowry Johnson consumptive use and Thornthwaite's P.E. Perhaps the major reason is that the Blaney and Criddle procedures were developed in the southern irrigated areas of Western United States. The consumptive use patterns farther north in the U.S. could be accommodated in this empirical procedure only if fairly large allowances were made for increasing summer day lengths with increasing latitude. It would appear that these allowances, when applied to Canadian regions where day length in summer increases very rapidly to the north, are a bit high in the Southern Prairies and very high in the North. It is unreasonable to suggest that Fort Vermilion in the Northern Peace River country should have a greater seasonal capacity for crop growth (heat adequate to require 24.9 inches of water per year) than areas in Southern Saskatchewan (Midale 24.4, Whitewood 24.2 etc.). If allowance is made for possible error in a north-south direction because of this factor, it will be seen that isoline orientations are very similar to those of the maps based on Thornthwaite and Lowry Johnson procedures.

Consumptive Use--Wheat: June-August 1921-1950 (Blaney & Criddle) (Figure 15-b)

In the Blaney and Criddle procedures, a lower consumption factor is employed for wheat than for alfalfa in the same period of growth. It is assumed that wheat will consume water less rapidly than alfalfa. The rate of use and the period are both smaller thus there is an appreciably smaller consumptive use than that indicated on the previous map. Once again, however, the latitudinal allowance would appear to be excessive. Except for this, regional patterns are comparable to those of maps based on Thornthwaite and Lowry Johnson procedures.

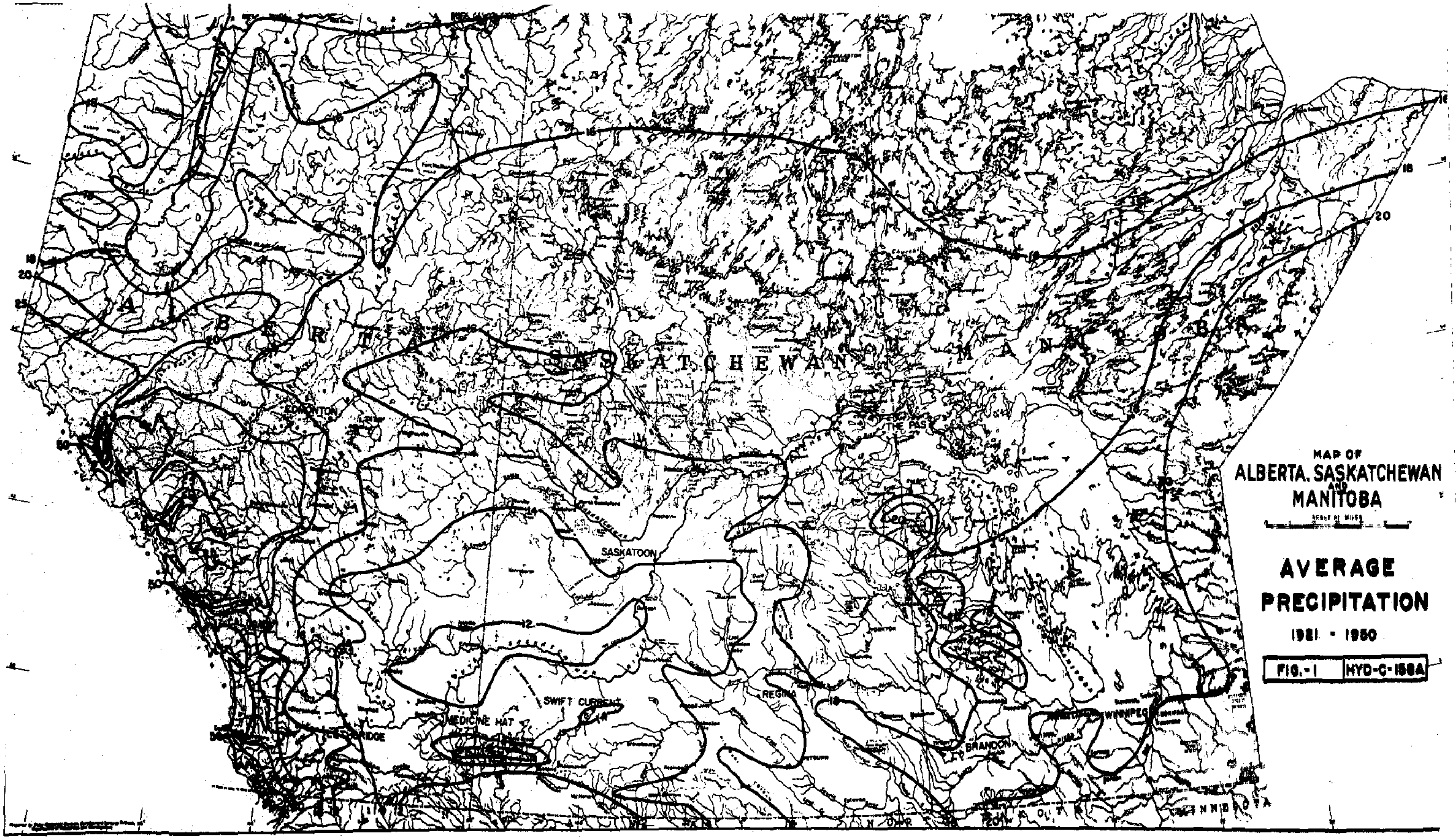
Average Moisture Deficit for Alfalfa: May-September 1921-1950 (Blaney & Criddle) (Less storage on May 1st--4 inches capacity) (Figure 16-a)

The moisture deficit for alfalfa, based on Blaney and Criddle procedures is significantly higher than that based on Thornthwaite procedures (Figure 10-b). An allowance for storage on May 1st has been subtracted but the results are still 4 to 6 inches in excess of those of Figure 10-b. The major patterns are similar on these maps though the values differ. Local studies made to establish local values could be adapted for comparative purposes to either map.

Average Moisture Deficit for Wheat: June-August 1921-1950 (Blaney & Criddle) (Less storage on June 1st--4 inches capacity) (Figure 16-b)

The moisture deficit patterns for wheat are very similar in value and pattern to those on a map employing Thornthwaite procedures (Figure 11-c). The moisture storage allowances of the Thornthwaite procedures are again used and this contributes to the degree of similarity.

It would appear that the major patterns of water need and moisture deficit are very similar when different procedures are used. This would tend to indicate that these patterns are valid though some of the values might be modified slightly by regional studies. Other procedures are available, but since the same variables are used, there is little reason to expect major differences in pattern even if some of the values might differ slightly. It would probably be best for us to apply the results of local studies to revise the values suggested, rather than conduct additional general studies using other procedures. The patterns developed appear to be valid when compared with patterns of crop yields, local research studies, water demands, etc. and it should be possible to apply the results of local studies to other parts of the Prairies more reliably than previously, now that these maps are available.

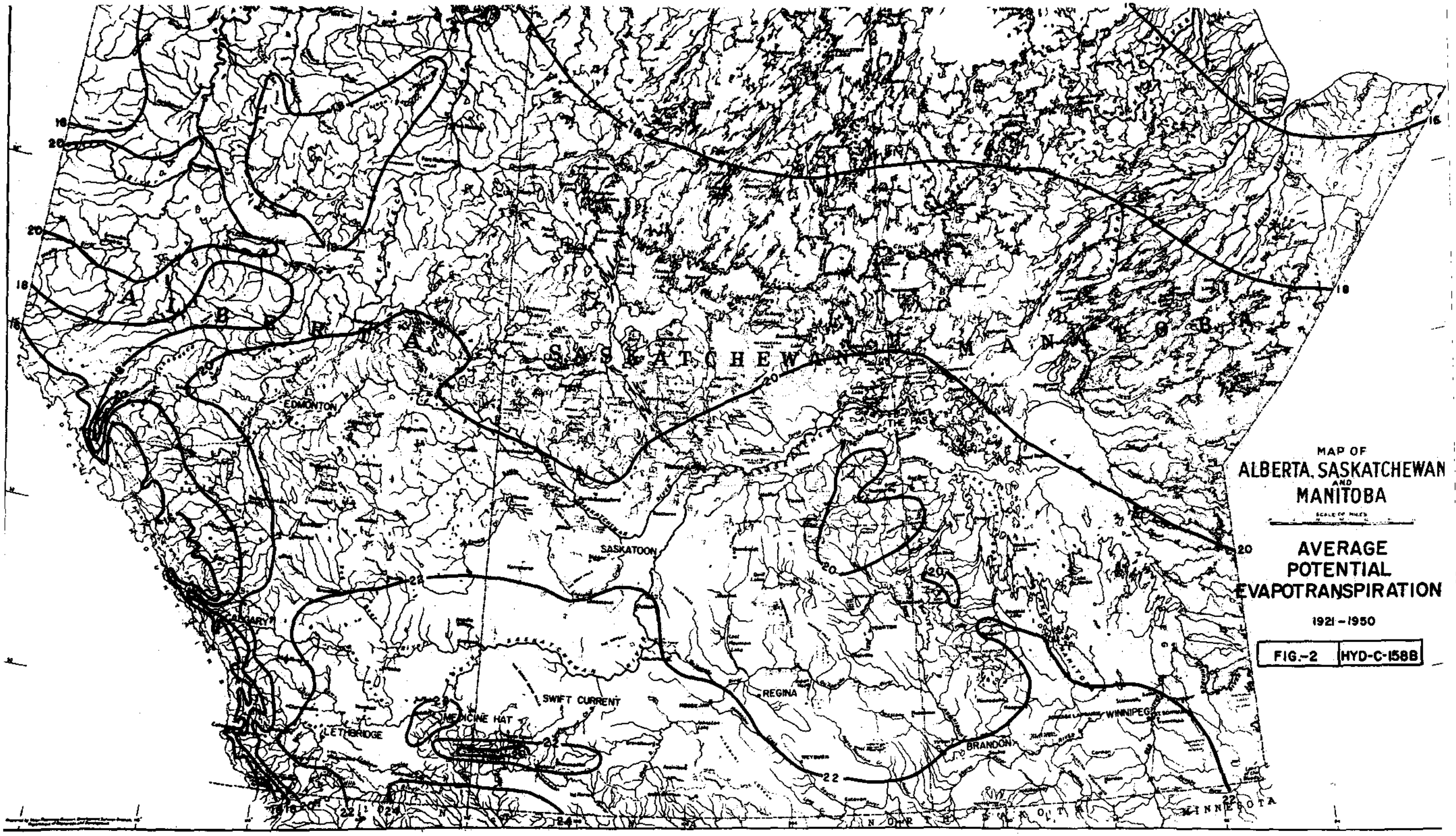


MAP OF
ALBERTA, SASKATCHEWAN
AND
MANITOBA

SCALE IN MILES

AVERAGE
PRECIPITATION
1921 - 1950

FIG.-1 HYD-C-158A



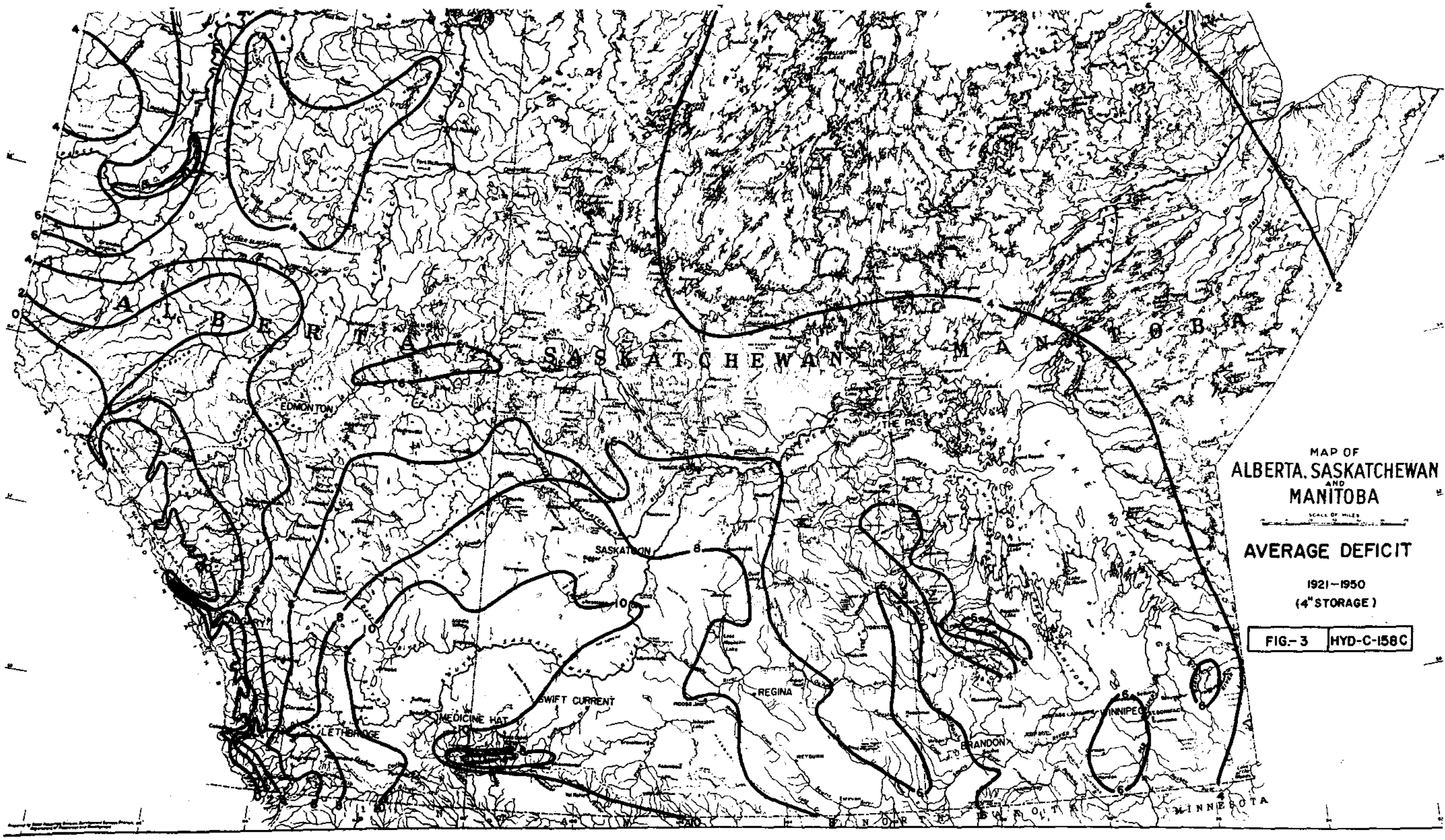
MAP OF
ALBERTA, SASKATCHEWAN
AND
MANITOBA

SCALE OF MILES

AVERAGE
POTENTIAL
EVAPOTRANSPIRATION

1921 – 1950

FIG.–2 HYD-C-158B



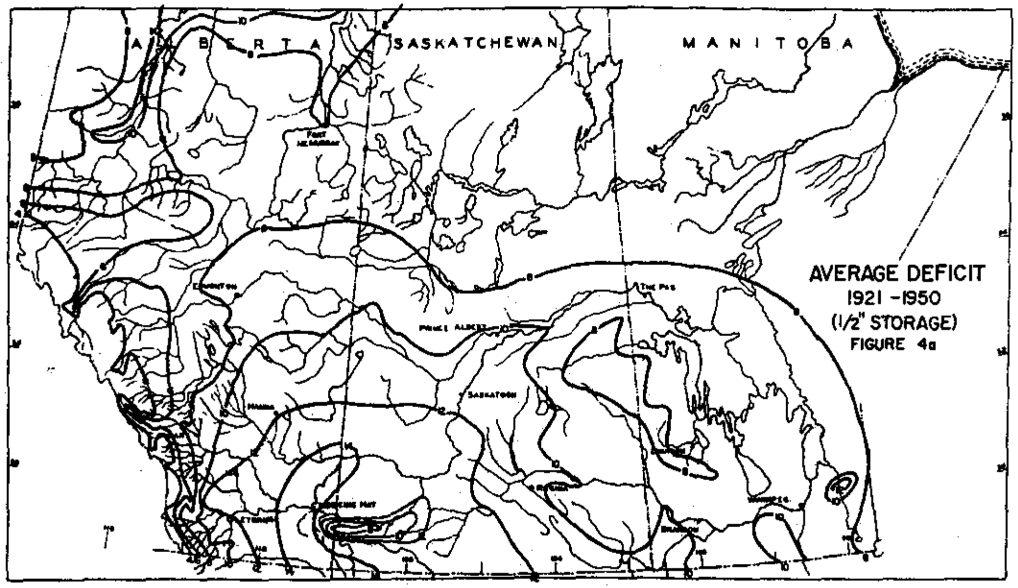
MAP OF
ALBERTA, SASKATCHEWAN
AND
MANITOBA

SCALE OF MILES

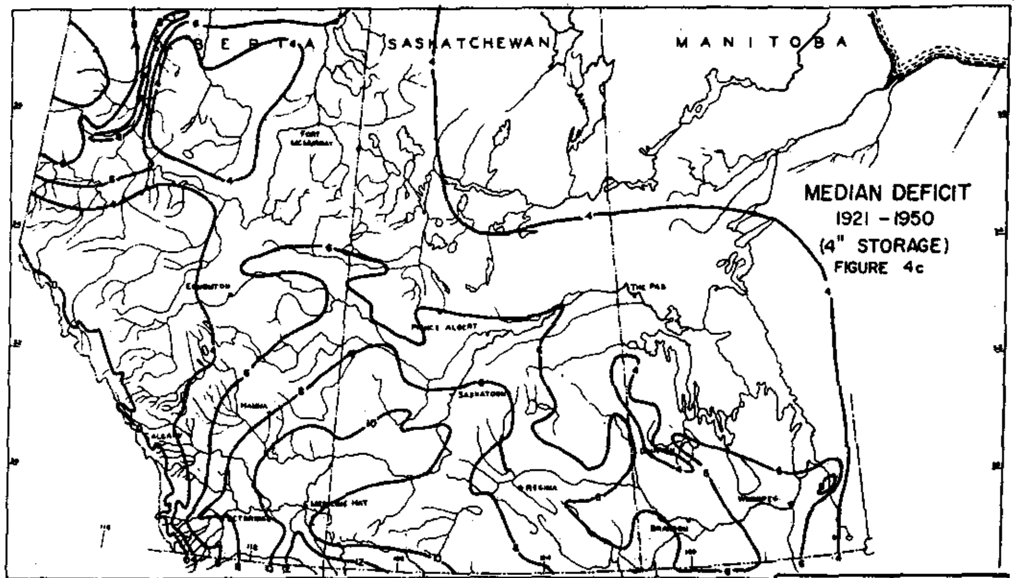
AVERAGE DEFICIT

1921–1950
(4" STORAGE)

FIG.– 3 HYD-C-158C

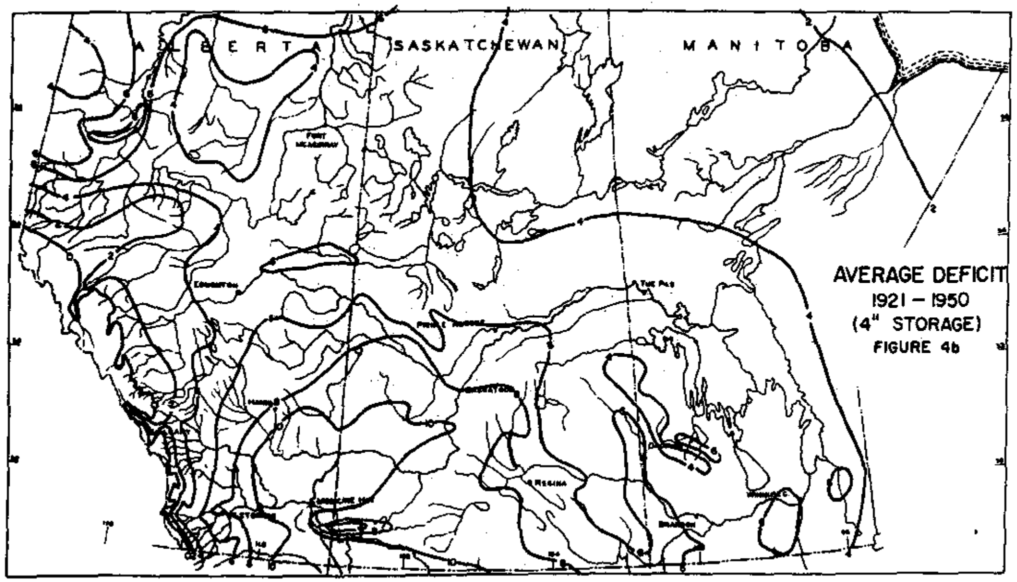


AVERAGE DEFICIT
1921 -1950
(1/2" STORAGE)
FIGURE 4a

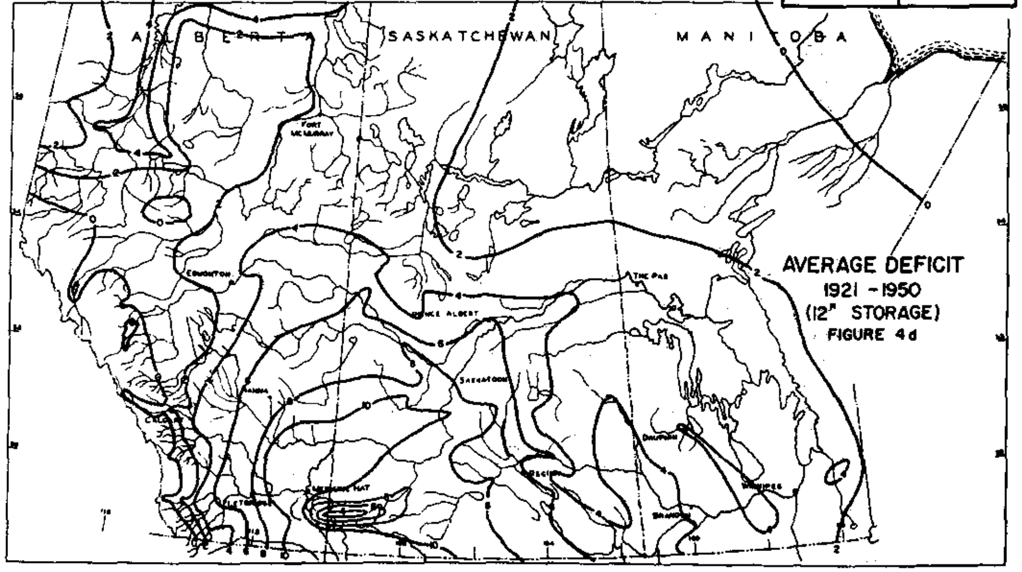


MEDIAN DEFICIT
1921 - 1950
(4" STORAGE)
FIGURE 4c

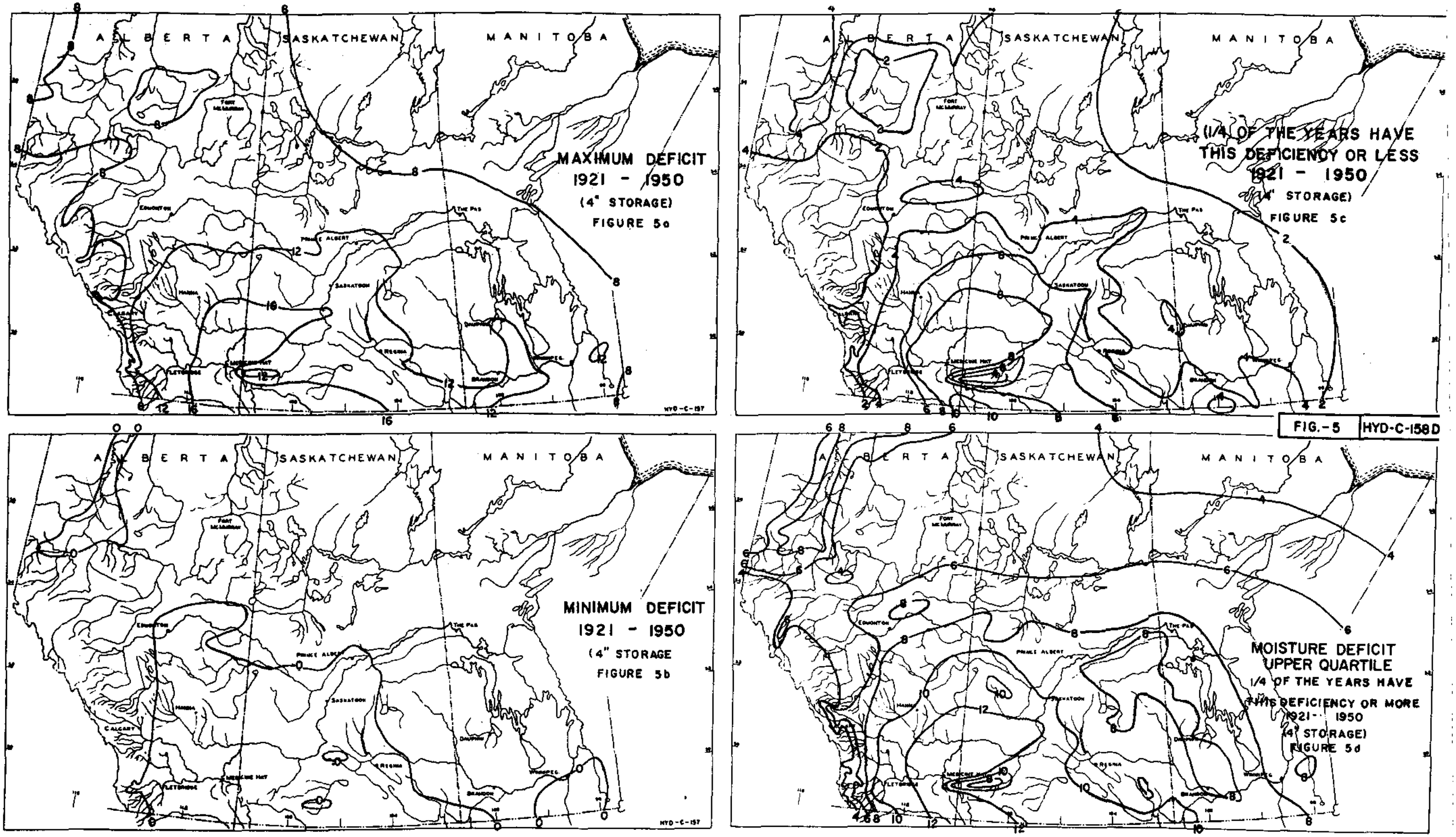
FIG- 4 HYD-C-158R



AVERAGE DEFICIT
1921 – 1950
(4" STORAGE)
FIGURE 4b



AVERAGE DEFICIT
1921 -1950
(12" STORAGE)
FIGURE 4d



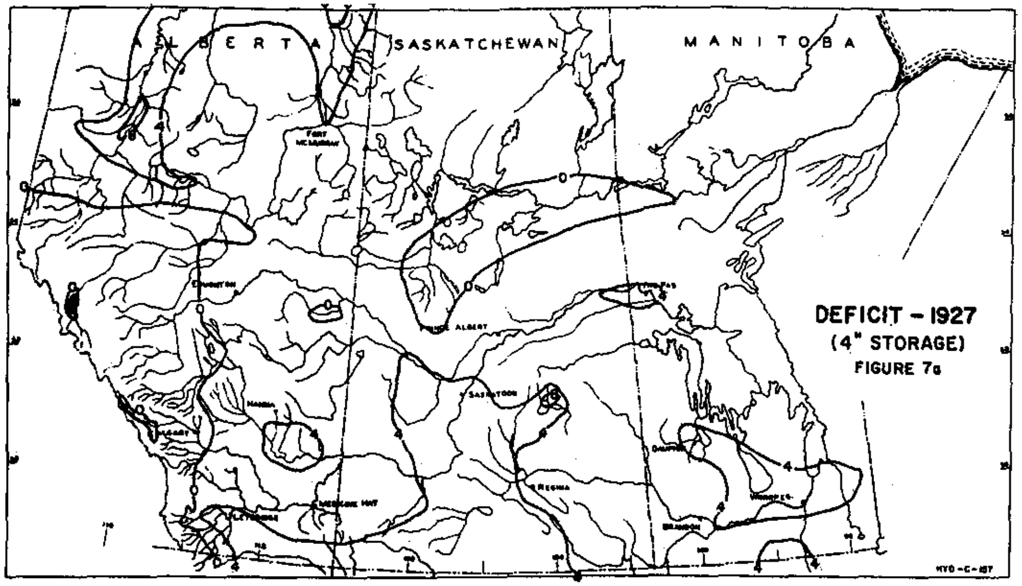
MAXIMUM DEFICIT 1921 - 1950 (4" STORAGE) FIGURE 5a

MINIMUM DEFICIT 1921 - 1950 (4" STORAGE FIGURE 5b

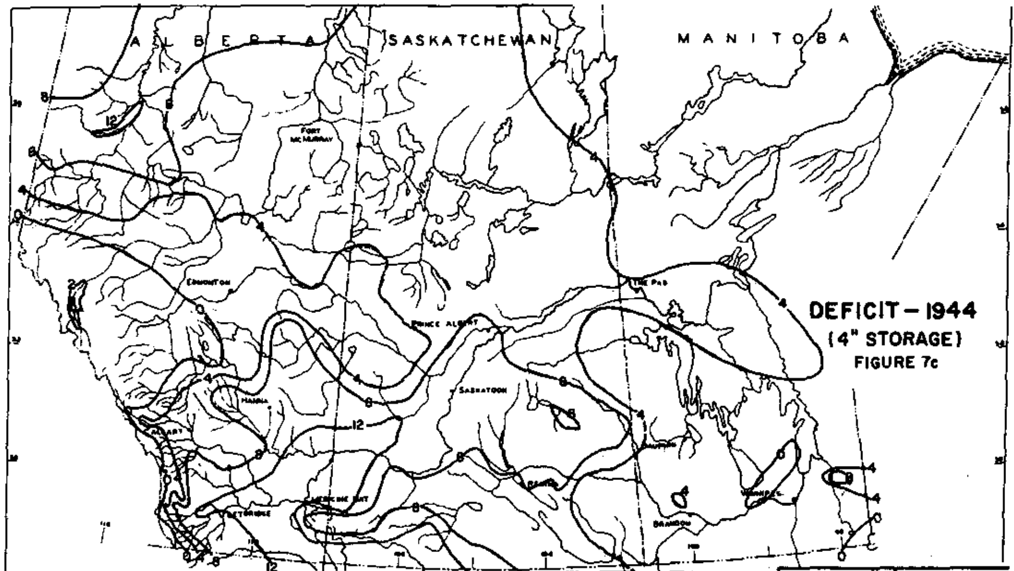
(1/4 OF THE YEARS HAVE THIS DEFICIENCY OR LESS 1921 - 1950 (4" STORAGE) FIGURE 5c

MOISTURE DEFICIT UPPER QUARTILE 1/4 OF THE YEARS HAVE THIS DEFICIENCY OR MORE 1921- 1950 (4" STORAGE) FIGURE 5d

FIG.-5 HYD-C-158D

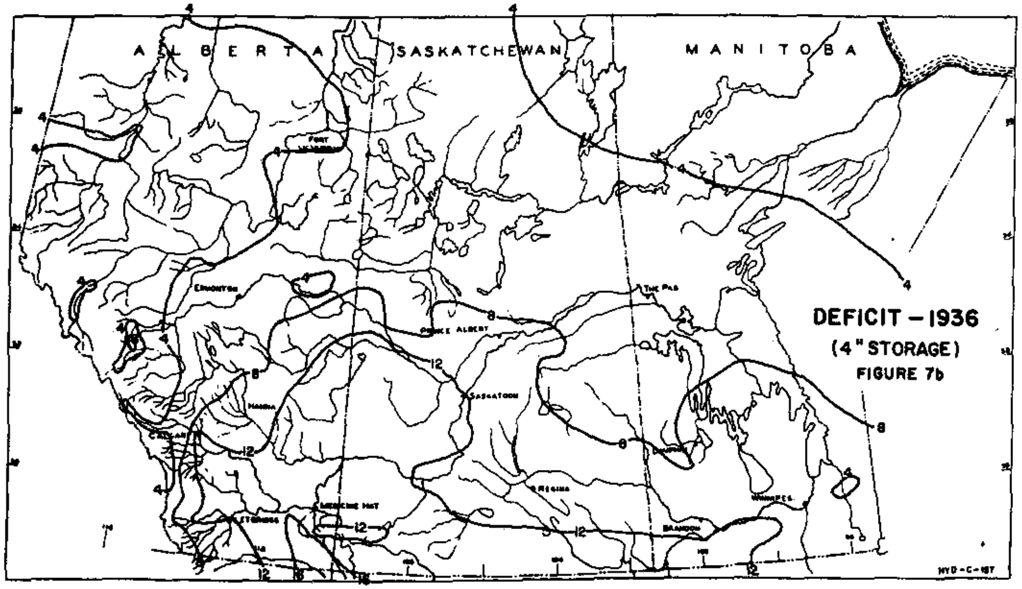


DEFICIT - 1927
(4" STORAGE)
FIGURE 7a

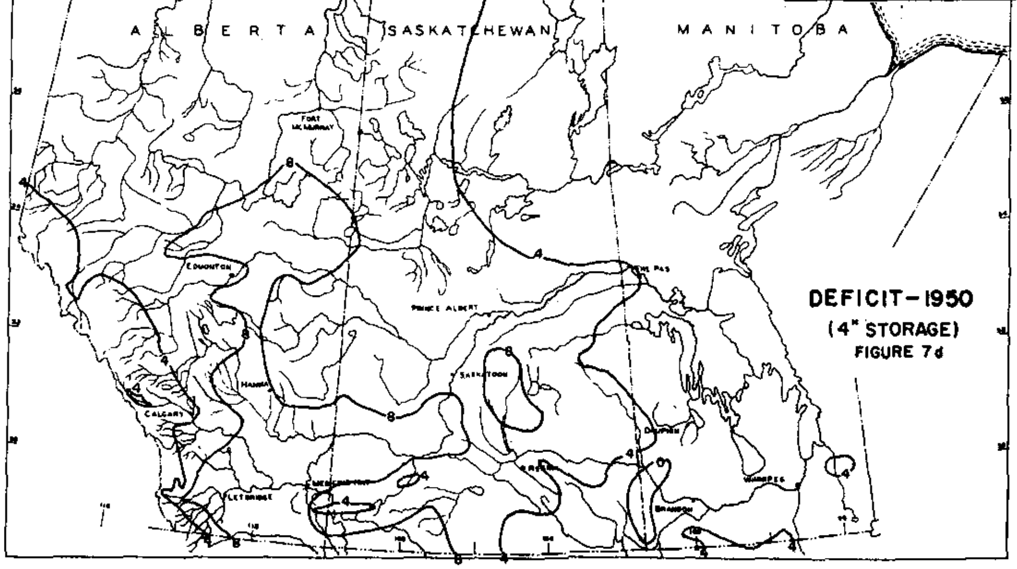


DEFICIT - 1944
(4" STORAGE)
FIGURE 7c

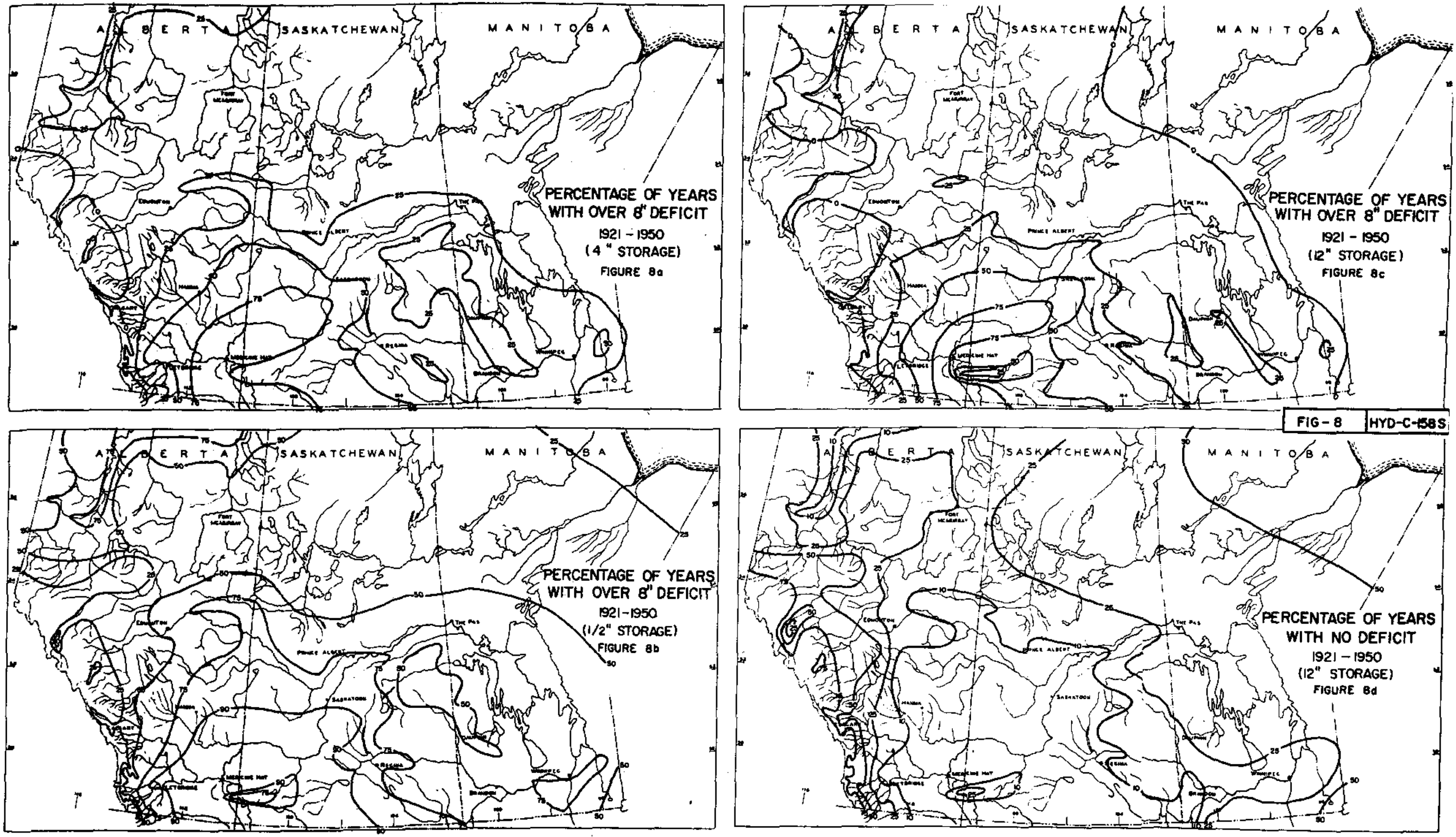
FIG.-7 HYD-C-158F



DEFICIT - 1936
(4" STORAGE)
FIGURE 7b



DEFICIT - 1950
(4" STORAGE)
FIGURE 7d



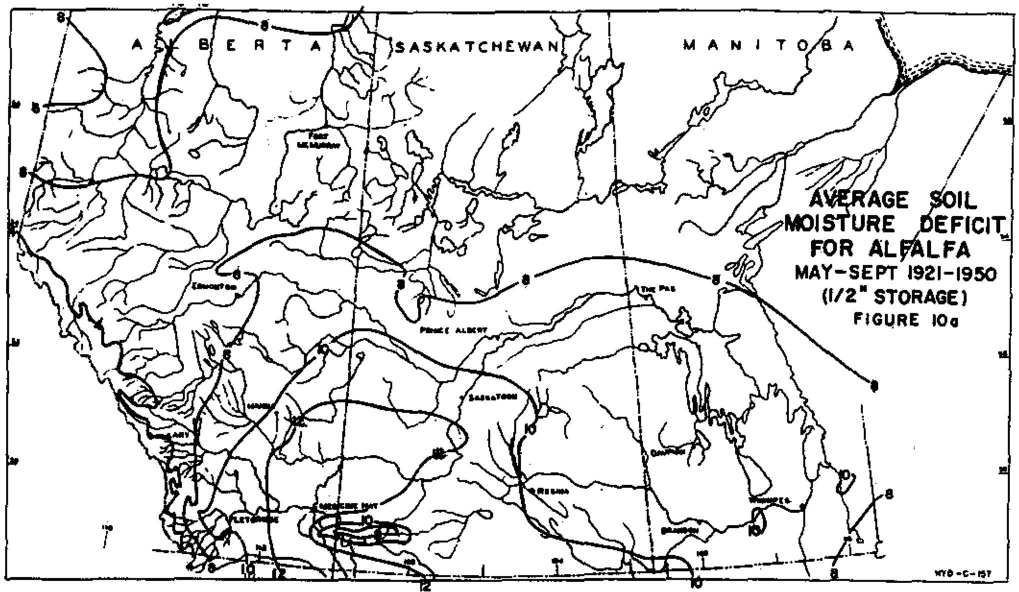
PERCENTAGE OF YEARS WITH OVER 8" DEFICIT
1921 - 1950
(4" STORAGE)
FIGURE 8a

PERCENTAGE OF YEARS WITH OVER 8" DEFICIT
1921 - 1950
(12" STORAGE)
FIGURE 8c

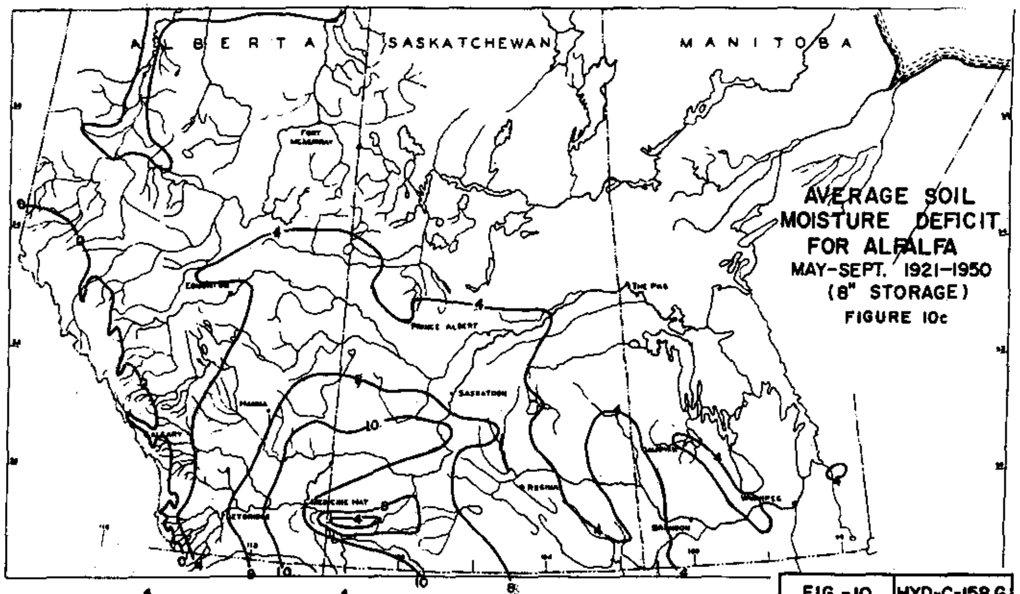
PERCENTAGE OF YEARS WITH OVER 8" DEFICIT
1921-1950
(1/2" STORAGE)
FIGURE 8b

PERCENTAGE OF YEARS WITH NO DEFICIT
1921 - 1950
(12" STORAGE)
FIGURE 8d

FIG - 8 HYD-C-158S

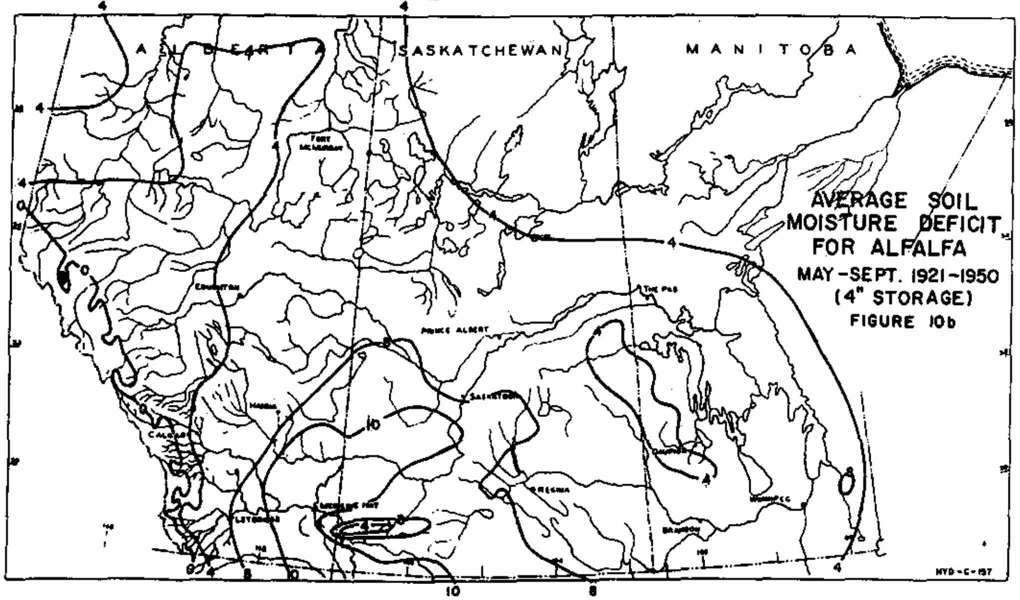


AVERAGE SOIL MOISTURE DEFICIT FOR ALFALFA
MAY-SEPT 1921-1950
(1/2" STORAGE)
FIGURE 10a

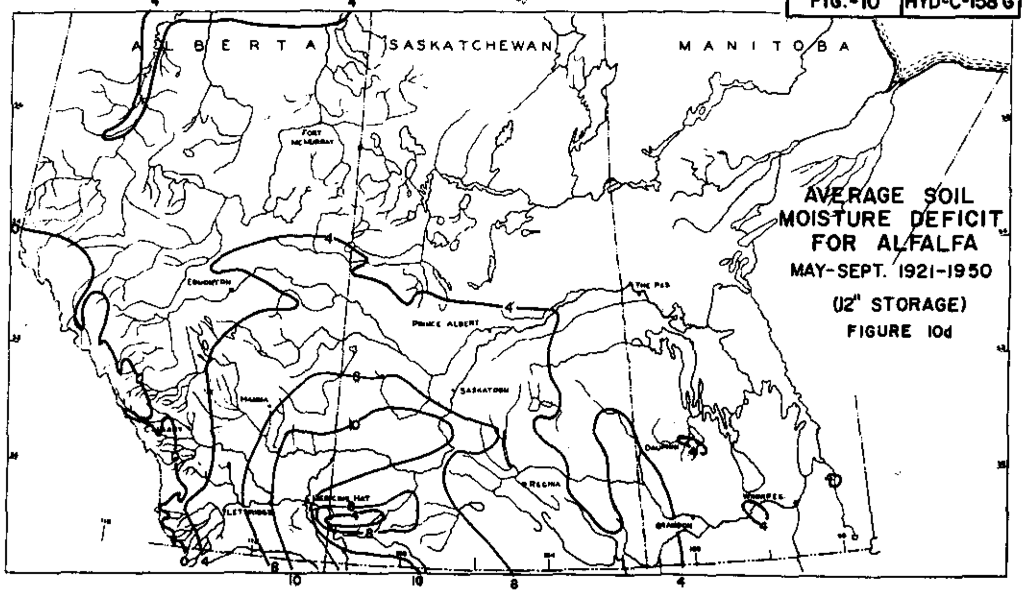


AVERAGE SOIL MOISTURE DEFICIT FOR ALFALFA
MAY-SEPT. 1921-1950
(8" STORAGE)
FIGURE 10c

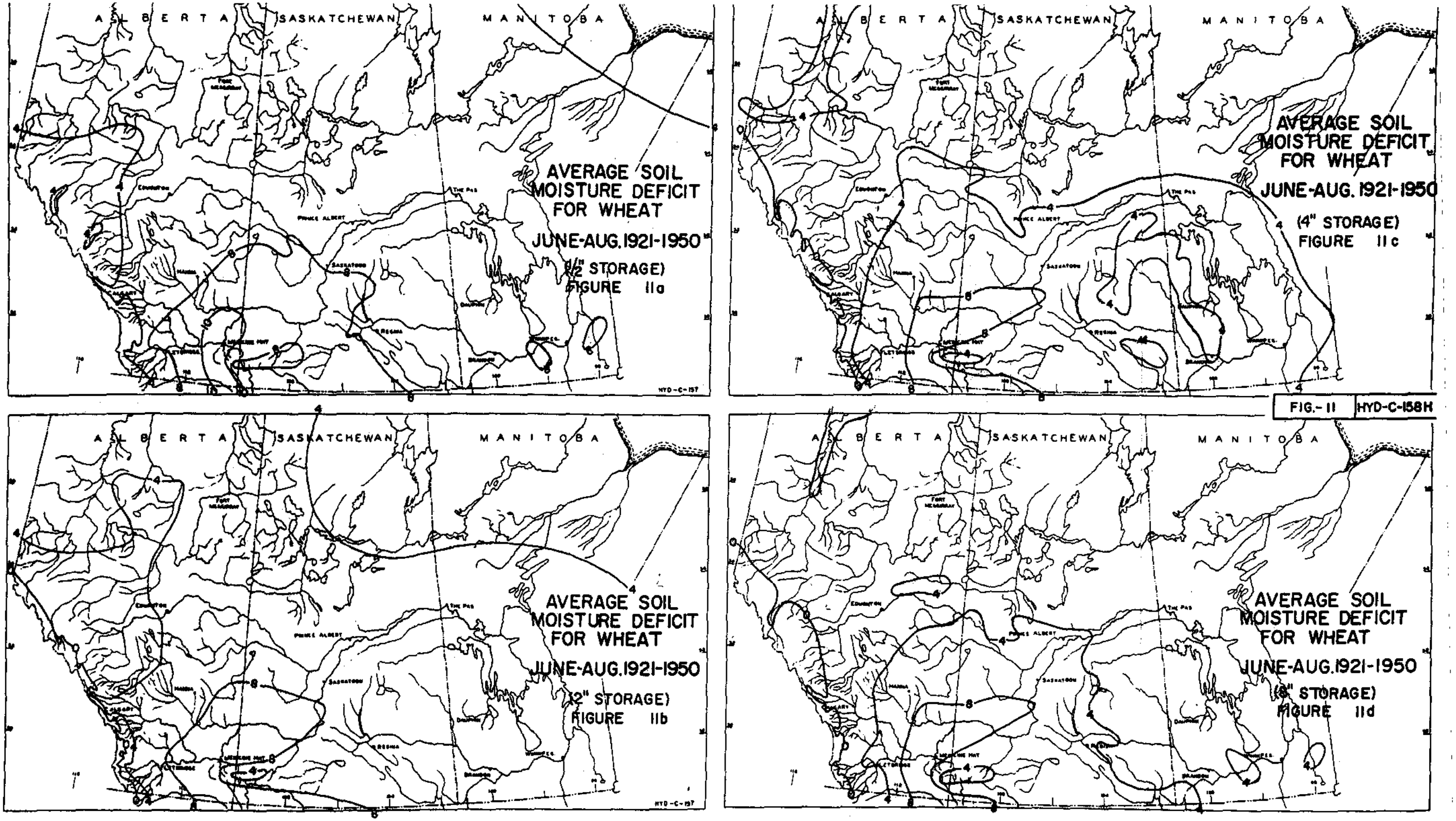
FIG.-10 HYD-C-158 G



AVERAGE SOIL MOISTURE DEFICIT FOR ALFALFA
MAY-SEPT. 1921-1950
(4" STORAGE)
FIGURE 10b



AVERAGE SOIL MOISTURE DEFICIT FOR ALFALFA
MAY-SEPT. 1921-1950
(12" STORAGE)
FIGURE 10d



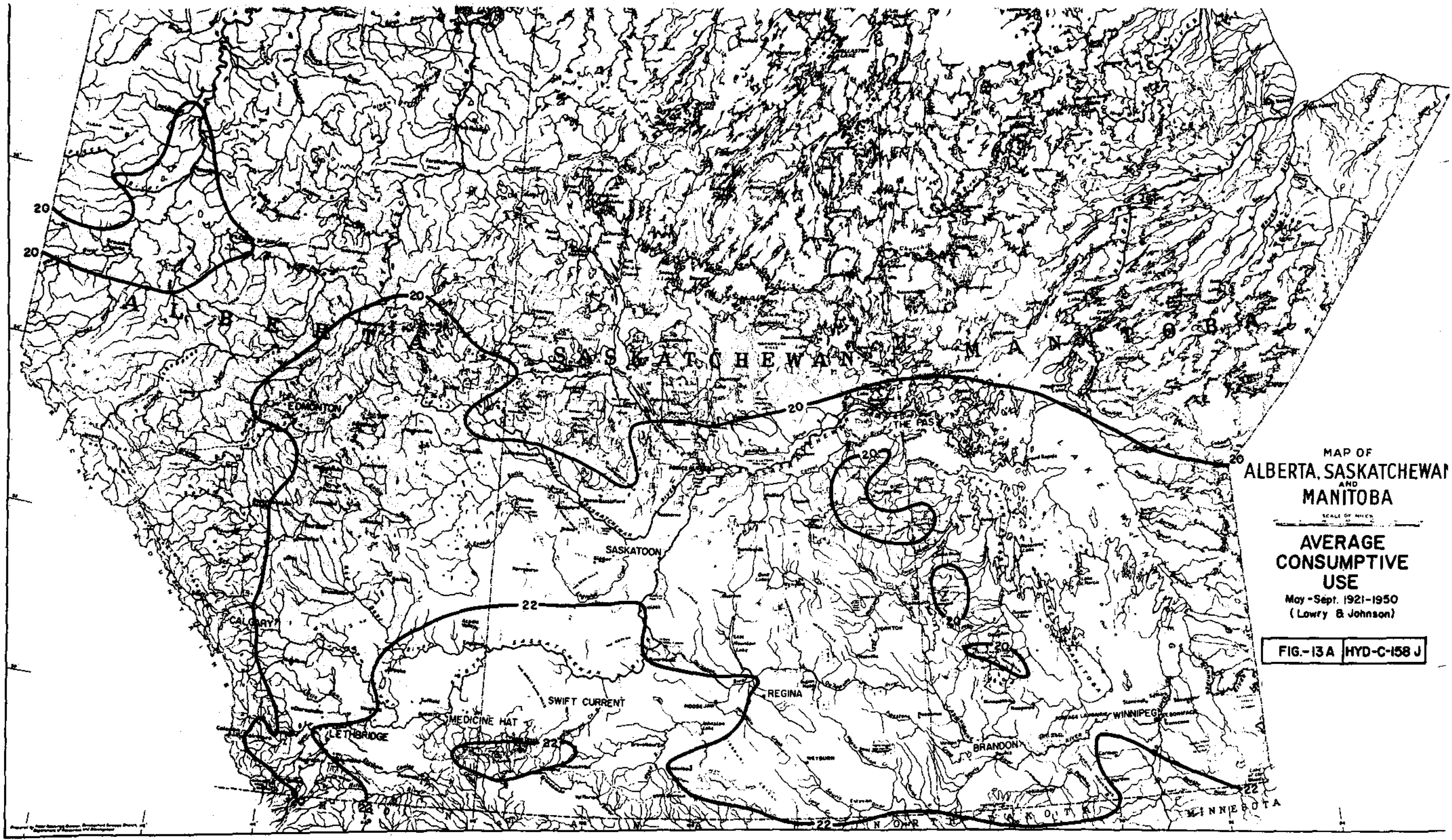
AVERAGE SOIL MOISTURE DEFICIT FOR WHEAT JUNE-AUG. 1921-1950 (1/2" STORAGE) FIGURE 11a

AVERAGE SOIL MOISTURE DEFICIT FOR WHEAT JUNE-AUG. 1921-1950 (4" STORAGE) FIGURE 11c

AVERAGE SOIL MOISTURE DEFICIT FOR WHEAT JUNE-AUG. 1921-1950 (2" STORAGE) FIGURE 11b

AVERAGE SOIL MOISTURE DEFICIT FOR WHEAT JUNE-AUG. 1921-1950 (8" STORAGE) FIGURE 11d

FIG.- 11 HYD-C-158H



MAP OF
ALBERTA, SASKATCHEWAN
AND
MANITOBA

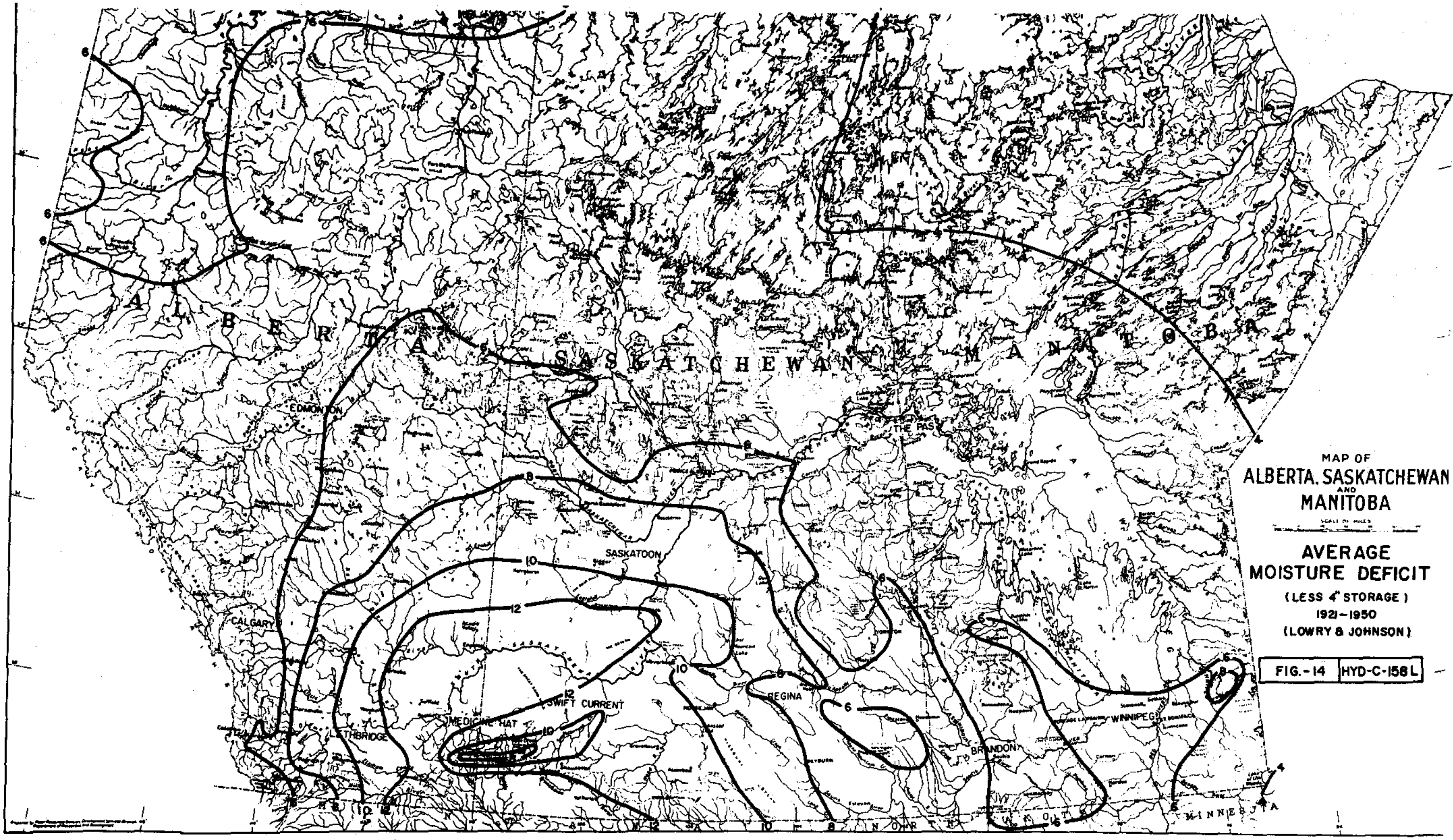
AVERAGE
CONSUMPTIVE
USE
May-Sept. 1921-1950
(Lowry & Johnson)

FIG.-13A | HYD-C-158 J

MAP OF
ALBERTA, SASKATCHEWAN
AND
MANITOBA

AVERAGE
MOISTURE DEFICIT
1921 - 1950
(Lowry & Johnson)

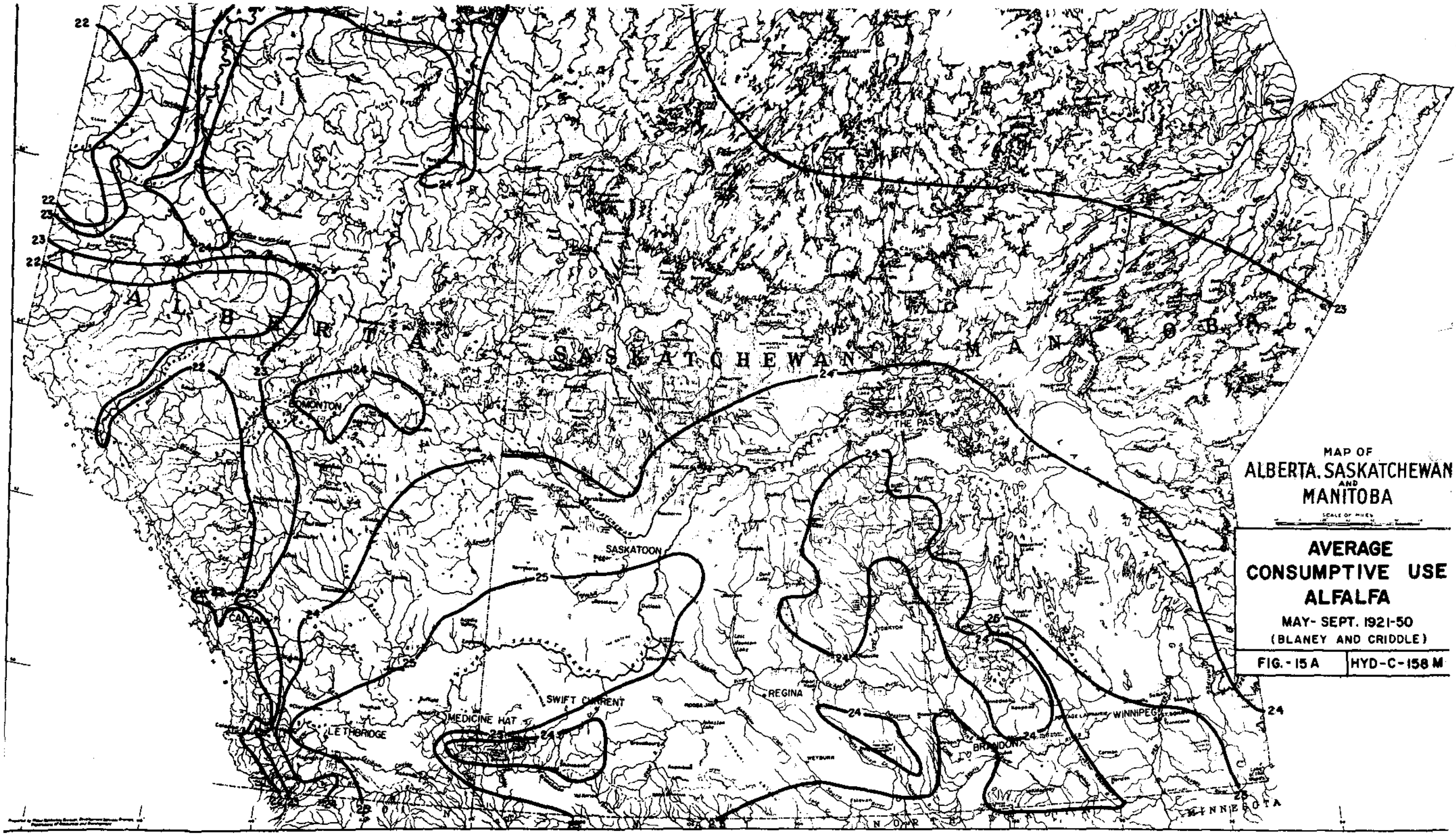
FIG.-13 B HYD-C-158 K



MAP OF
ALBERTA, SASKATCHEWAN
AND
MANITOBA

AVERAGE
MOISTURE DEFICIT
(LESS 4" STORAGE)
1921–1950
(LOWRY & JOHNSON)

FIG. - 14 HYD-C-158L



MAP OF
ALBERTA, SASKATCHEWAN
AND
MANITOBA

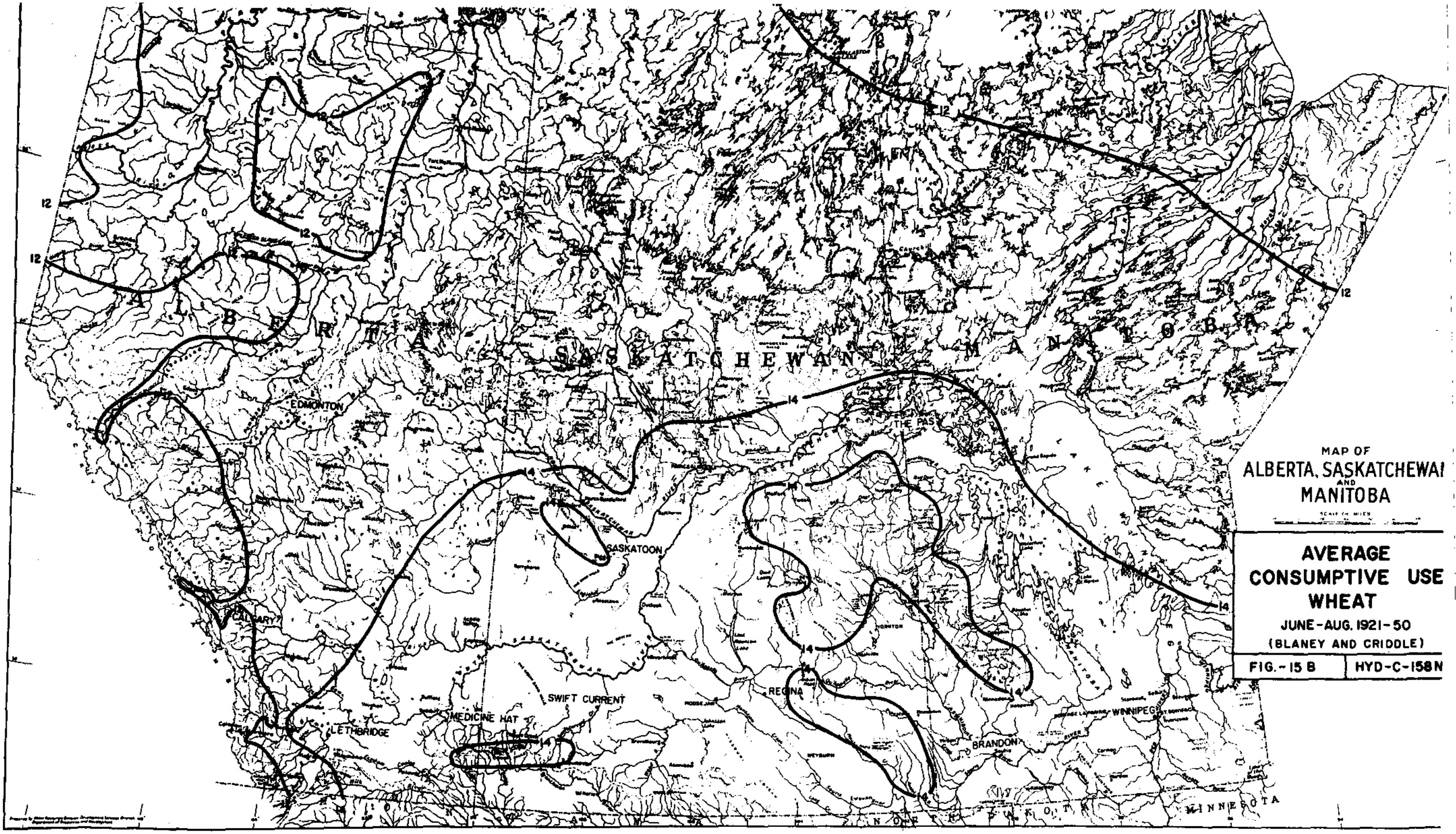
SCALE OF MILES

AVERAGE CONSUMPTIVE USE ALFALFA

MAY-SEPT. 1921-50
(BLANEY AND CRIDDLE)

FIG. - 15 A

HYD-C-158 M

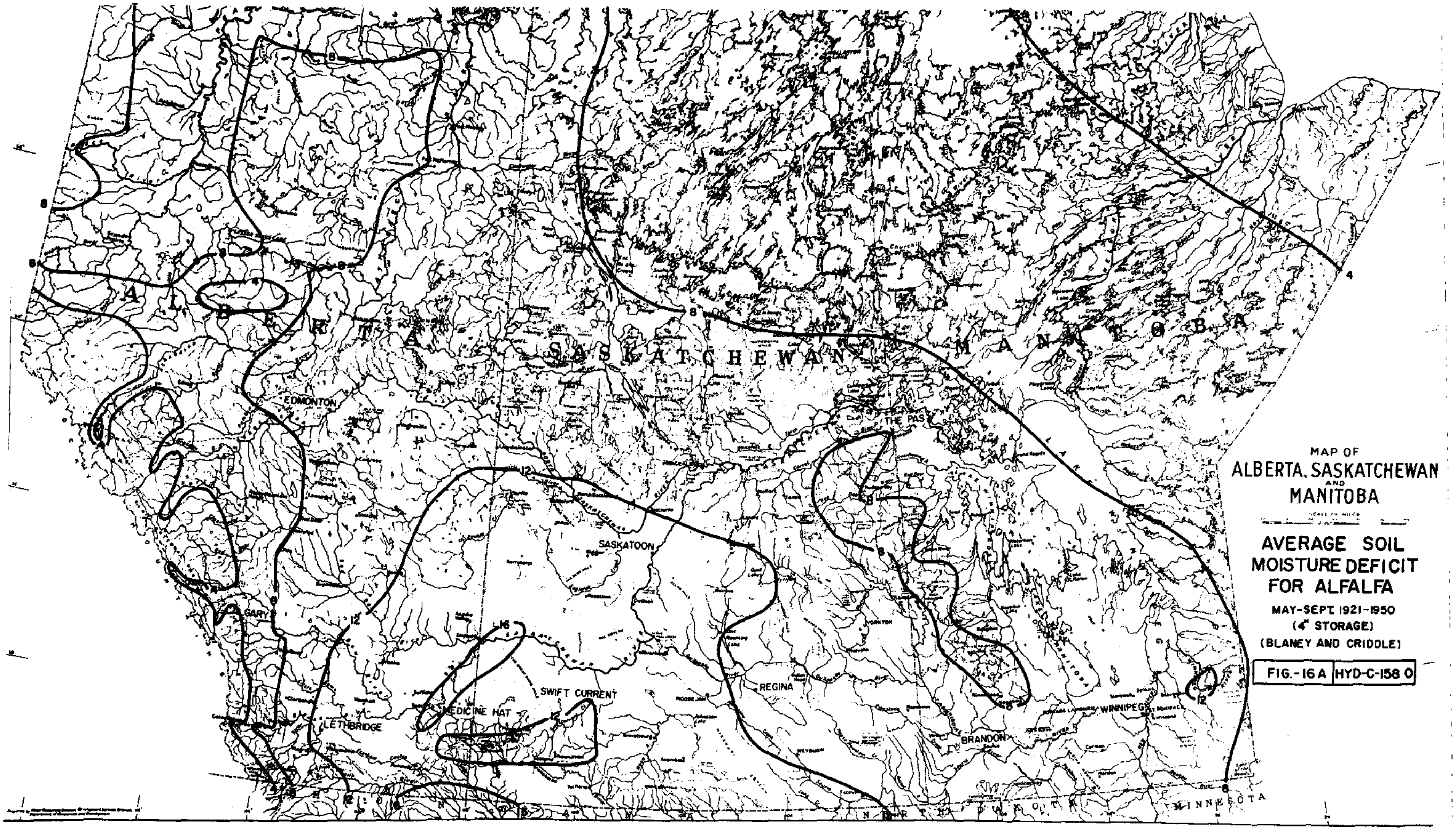


MAP OF
ALBERTA, SASKATCHEWAI
AND
MANITOBA

AVERAGE CONSUMPTIVE USE WHEAT

JUNE-AUG. 1921-50
(BLANEY AND CRIDDLE)

FIG.-15 B HYD-C-158N

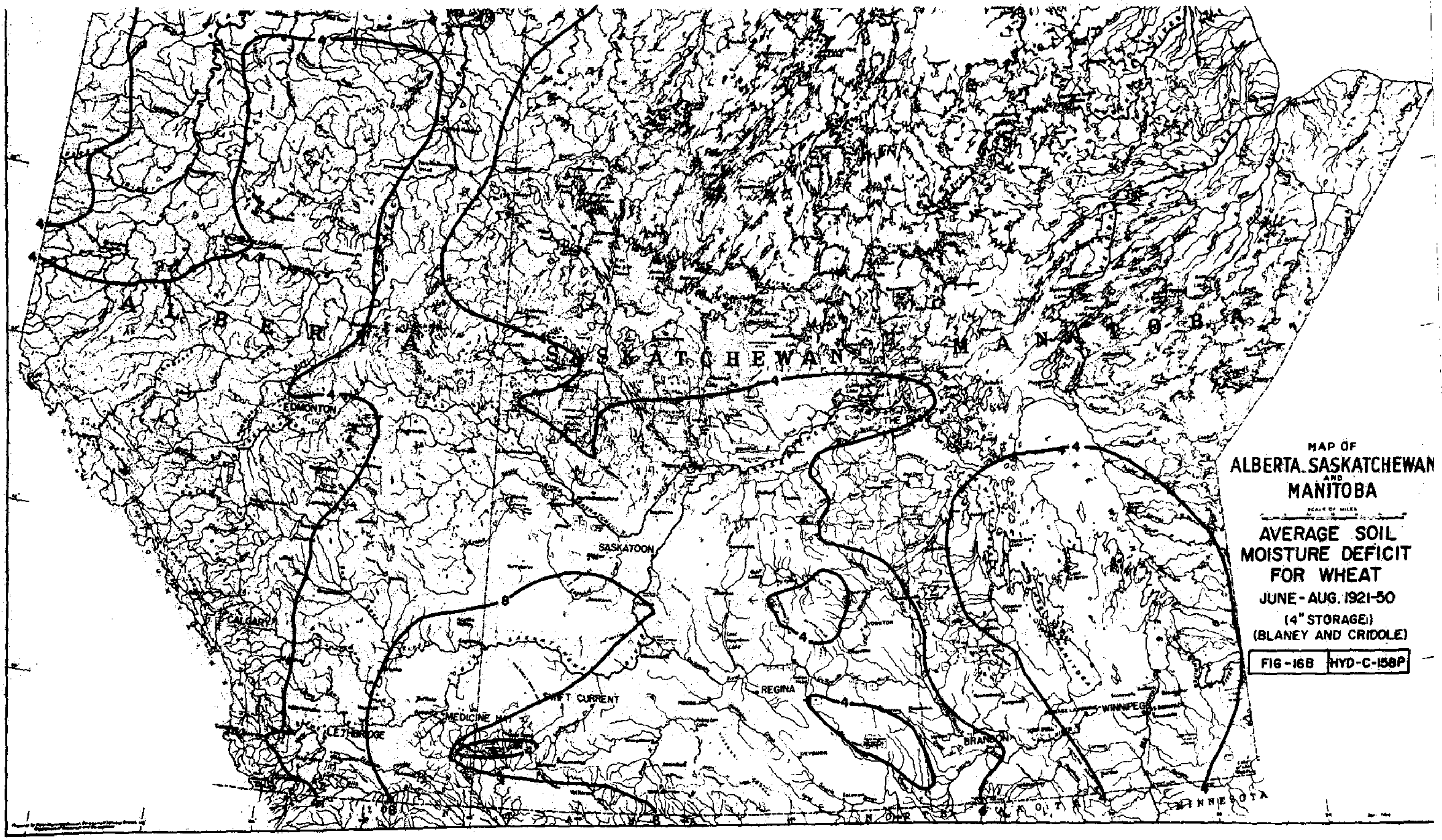


MAP OF
ALBERTA, SASKATCHEWAN
AND
MANITOBA

AVERAGE SOIL MOISTURE DEFICIT FOR ALFALFA

MAY-SEPT. 1921-1950
(4" STORAGE)
(BLANEY AND CRIDDLE)

FIG.-16A HYD-C-158 0



MAP OF
ALBERTA, SASKATCHEWAN
AND
MANITOBA

AVERAGE SOIL MOISTURE DEFICIT FOR WHEAT
JUNE - AUG. 1921-50
(4" STORAGE)
(BLANEY AND CRIDDLE)

FIG - 168 HYD-C-158P