PRAIRIE PROVINCES WATER BOARD

WATER DEFICIENCY AND SURPLUS PATTERNS

IN THE PRAIRIE PROVINCES

---

by A. H. Laycock

March, 1967

Compiled for the Prairie Provinces
Water Board by the Hydrology Division,
Prairie Farm Rehabilitation Administration
Regina, Saskatchewan

REPORT NO. 13

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PRAIRIE PROVINCES WATER BOARD

401 Motherwell Building
Regina, Saskatchewan
March 7, 1967

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

Dear Mr. Fitzgerald:

Transmitted herewith is Prairie Provinces Water Board Report No. 13, entitled "Water Deficiency and Surplus 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---."

The study was made and the report written by Dr. A. H. Laycock, Associate Professor of Geography, University of Alberta.

Yours very truly

J.G.S. McMorine

J. G. S. McMorine
Acting Engineering Secretary
Prairie Provinces Water Board

ACKNOWLEDGEMENTS

Many people have contributed directly and indirectly to this study and their contributions are gratefully acknowledged. The study was initiated when Mr. William Berry, then Engineering Secretary of the Prairie Provinces Water Board, suggested that work that had been done with Thornthwaite procedures in the Rocky Mountain and Foothill area for P.P.W.B. Report No. 6 should be extended to include the plains areas. This work was continued and expanded under his successor, Mr. Fred Durrant, who offered numerous suggestions concerning the study and applications of it. It has now been completed under his successor, Mr. C. Booy. Each has been more than patient in waiting for different aspects of research to be completed and reported upon.

Assistants who must be thanked for their conscientious processing of data and for plotting basic and derived data on base maps include Donald Buchanan, Francis Capp, John Cole, Clifford Cunningham, Samuel Doz, Eugene Eisert, Helen Eisert, Joan Eisert, Roy Fletcher, Margaret Fridel, Jopie Heringa, Ernest Homeniuk, Charles Hutton, Ditmar Kaul, Udo Kaul, John Marshall, Ursula Mueller, Michael Mullen, Eleanor Nordlund, Victor Nordlund, Andrew Purdy, Marion Pylypchuk, Sally Rankin, Doris Taggart and Derald Willows. The suggestions, supervisory assistance and heavy time contributions of Doris Taggart, Donald Buchanan, Helen Eisert, Victor Nordlund and Ron Fletcher were particularly helpful.

PART I. WATER DEFICIT PATTERNS

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. 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 and a number of uses are briefly discussed. All of the maps contain broadly generalized patterns and it should be understood that many local variations are present. Some of these can be defined more clearly with the available station data but major refinement must await the accumulation of better basic data and local testing of procedures in water balance studies.

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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 1921-1950" by the Climatological Division of the Branch, Cir. 3208 Cli. 19, June, 1959, 33 pp.

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 1860; Macoun 1882, 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. Departments 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. Department of Agriculture studies etc.), explanations of crop production patterns (e.g. Searle Grain Co. Research Department, Canada and Provincial Department of Agriculture studies etc.) and Soil Survey reports. Numerous special and local studies by the Experimental Farms Service, Meteorological Branch, Prairie Farm Rehabilitation Administration 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 vigour 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, and 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. Prairie Provinces Water Board 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 (1958) 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	
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 VII. 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 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 PROCEDURE*

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** (Fig. 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, Canada Department of Transport, 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 five 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 region 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 1961, Muttit 1962 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 (Fig. 2)

This map shows how much water would be evaporated and transpired if the surface were completely covered with vegetation and there were 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 northeast. 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 greater evapotranspiration

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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.

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

Average Deficit 1921-1950 (4" storage capacity) (Fig. 3)

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) were 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 $\frac{1}{2}$, 1, 2, 4, 6, 8 and 12 inches.

Maps based on a 4 inch 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 South Eastern Alberta and South Western 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 inches in the more humid agricultural areas and 0 to 4 inches 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 moisture deficits in non-irrigated areas and potential water needs in irrigable and irrigated areas.

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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.

Maximum Deficit 1921-1950 (4" storage capacity) (Fig. 7)

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" storage capacity) (Fig. 8)

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" storage capacity) (Fig. 5)

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 great interest that median values are very similar (compare maps 5 and 3). The differences are almost always under 0.5 inches and are frequently zero. 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 (¼ of the years have this deficiency or less) (4" storage capacity) (Fig. 9)

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 three quarters 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 so 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 three quarters 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 (¼ of the years have this deficit or more) (4" storage capacity) (Fig. 10)

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" storage capacity) (Fig. 11)

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 (Figs. 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" storage capacity) (Fig. 12)

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. South Western Saskatchewan and South Eastern Alberta were very dry again in 1937 and the combination of successive 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" storage capacity) (Fig. 13)

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" storage capacity) (Fig. 14)

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 ($\frac{1}{2}$" storage capacity) (Fig. 4)

Coarse-textured sandy soils have very limited capacities for moisture retention storage (see Appendix B). If these capacities are approximately $\frac{1}{2}$ 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 South Western 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" storage capacity) (Fig. 6)

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, North Eastern Saskatchewan and West Central Alberta than in the drier parts of South Eastern Alberta and South Western 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 ½ inch storage maps.

The irrigation water needs are approximately the same as in the 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 South Western 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 VIII).

Percentage of years with no Deficit 1921-1950 (12" storage capacity) (Fig. 18)

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 one third of the stations within the 10% isoline had zero 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 ($\frac{1}{2}$", 4", 8" and 12" storage capacity) (Figs. 19, 20, 21 and 22)

The average deficits for the period May-September are very similar to those of the full year for the same storage values (e.g. Figs. 3, 4 and 6). 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 ($\frac{1}{2}$", 2", 4" and 8" storage capacity) (Figs. 23, 24, 25 and 26)

The period June-August is used in this map series as the period of wheat growth. The deficiy for the lightest soils is about 1 to 2 inches smaller than for alfalfa in the wetter regions and 2 to 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 decreases 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 summer-fallowing 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 ($\frac{1}{2}$" storage capacity) (Fig. 27)

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 may not mean much.

The germinating seed and seedling have very limited access to soil moisture in May and a moisture storage capacity of $\frac{1}{2}$ 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" storage capacity) (Fig. 28)

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" storage capacity) (Fig. 29)

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 in May, June and July, 1921-1950 ($\frac{1}{2}$", 2" and 6" storage capacity) (Fig. 30)

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 (Figs. 3, 4 and 6).

V. WATER DEFICIT PATTERNS IN THE PRAIRIE PROVINCES

LOWRY-JOHNSON, BLANEY-CRIDDLE PROCEDURES

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

Average Consumptive Use: May-September, 1921-1950 (Lowry-Johnson) (Fig. 31)

The "Consumptive Use" of Lowry-Johnson is very similar in concept to the "Potential Evapotranspiration" (Fig. 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.

Average Moisture Deficit 1921-1950 (Lowry-Johnson) (Fig. 32)

The moisture deficit values of this map exceed those of the Thornthwaite "average" deficit (4 inches storage, Fig. 3) 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.

Average Moisture Deficit 1921-1950 (Lowry-Johnson) (Less storage on May 1, 4" storage capacity) (Fig. 33)

The storage values of May 1, 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 Fig. 3 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.

Average Consumptive Use, Alfalfa: May-September, 1921-1950 (Blaney-Criddle) (Fig. 34)

The "Consumptive Use" of Blaney-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-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.

Average Consumptive Use, Wheat: June-August, 1921-1950 (Blaney-Criddle) (Fig. 35)

In the Blaney-Criddle procedure, 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 and 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 Soil Moisture Deficit for Alfalfa: May-September, 1921-1950 (Blaney-Criddle) (Less storage on May 1, 4" storage capacity) (Fig. 36)

The moisture deficit for alfalfa, based on the Blaney-Criddle procedure is significantly higher than that based on the Thornthwaite procedure (Fig. 20). An allowance for storage on May 1 has been subtracted but the results are still 4 to 6 inches in excess of those of Fig. 20. 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 Soil Moisture Deficit for Wheat: June- August, 1921-1950 (Blaney-Criddle) (Less storage on June 1, 4" storage capacity) (Fig. 37)

The moisture deficit patterns for wheat are very similar in value and pattern to those on a map employing the Thornthwaite procedure (Fig. 25). The moisture storage allowances of the Thornthwaite procedure 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 better 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.

PART II. WATER SURPLUS PATTERNS

VI. INTRODUCTION

The information on the water deficiency patterns that has been mapped and described in Part I of this study becomes more significant and useful if water surpluses occur in areas with deficiencies and information on both can be related and evaluated. Similarly, a study of water surpluses gains importance from the fact that deficiencies are experienced because added uses for these surpluses are indicated.

Part II of this report is thus a review of water surplus patterns in the Prairie Provinces, and a discussion of some of the ways by which the surplus and deficiency patterns can be related to each other and to the growing demands for water uses in the Prairie Provinces. A reference list and supplementary appendices complete the report.

Many of the patterns, problems and associations that are described and discussed have been recognized and much has been written and done about them. It is hoped that, with the different procedures employed in this study, surplus and deficiency patterns will have been more closely defined and the use relationships discussed will lead to further studies and applications.

VII. WATER SURPLUS PATTERNS IN THE PRAIRIE PROVINCES

When we process precipitation and temperature data according to Thornthwaite procedures in order to determine water deficiency patterns we are left with a residual category called "water surplus".* This term is sometimes confused with or used synonymously with "runoff" and "streamflow." In semi-arid and sub-humid regions particularly, differences between them may be significant and should be recognized. The water surplus is that water which percolates at levels beyond root depth or moves in surface flow toward streams and depressions after soil-moisture storage capacities have been recharged to a specified level, e.g. $\frac{1}{2}$, 1, 2, 4, 6, 8 or 12 inches (see Appendix B). In practice, surface runoff may take place in areas of fine-textured or tightly-frozen soil during intense rains or periods of snow melting before recharge to these levels has been completed. The term "runoff", used singly, denotes both surface and subsurface flow. This is usually greater than measured streamflow by the amount of such water that has been evaporated from water surfaces, including that from local depressions, and that has been transpired by phreatophytes. Streamflow is that which is or might be measured in streams and rivers.

In theory, we might obtain as much information as we need about surface and subsurface water supplies from the measurement of stream and groundwater flow. In practice we do obtain a great amount of information from such measurements but major gaps are present. The data are inadequate for most areas and have been accumulated for only short periods of time for many stations. We do not know how representative they are in either time or

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* See Chapter III

place because of the many variables involved; climatic, topographic, biotic, pedologic, etc. A thorough understanding of water supply patterns may be gained only if all of these are considered. If climatic parameters can be used, many runoff relationship patterns may be developed because measurements of temperature and precipitation are more widely available and cover larger time periods than measurements of other variables. In addition, local variations due to biotic, pedologic, topographic, and other factors may then be separated and identified. The Thornthwaite procedures are perhaps the most useful in illustrating the effects of the major climatic variables (precipitation and evapotranspiration) upon regional surplus patterns. If reasonable allowances are made for the differences between "surplus," runoff and measured streamflow patterns, we may establish each in general and suggest local variations if we consider local storage and water use patterns.*

The general patterns of water surplus in the Prairie Provinces have been mapped and may be reviewed as water deficit patterns were reviewed in Chapter IV.

Average Surplus, 1921-1950 (4" storage capacity) (Fig. 38)

If we assume that there is no runoff until 4 inches soil-moisture storage has been recharged and that all water in excess of this is surplus in all parts of the Prairies, we will have a standard base for comparing water surpluses of different areas. Allowances for some of the

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* See Appendix A and Chapter VIII.

variations are noted in later map descriptions, but it is remarkable how closely the patterns shown conform to patterns of average streamflow if allowance is also made for local evaporation and phreatophyte losses.*

The average surplus patterns in the Prairies may be related to the precipitation, potential evapotranspiration, and deficit patterns noted in Chapter IV. The areas with the smallest surpluses are the lower-lying plains and valleys of South Eastern Alberta and South Western Saskatchewan where precipitation is low, potential evapotranspiration is high and deficits are large. All stations had at least one year with a surplus, thus there is no zero isoline such as one might find if average temperature and precipitation records were used in the calculations.** The area with less than 1 inch surplus extends farther to the north than might be anticipated from reference to the water deficit patterns noted previously. This is due largely to the fact that most of the summer precipitation, which is a large proportion of the total, is evaporated or transpired and runoff is accordingly small.

Surpluses average over 4 inches in Eastern Manitoba, the foothill and mountain regions of Alberta, and in a few hill areas within the plains, e.g. Cypress and Swan Hills. Some areas near the continental divide in the mountains where precipitation is high and evapotranspiration is low, have yields of over 40". Some mountain valleys, especially at a lower

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* See the section on groundwater in Chapter VIII.

** As reported by M. Sanderson 1948, see Chapter III. Lyman Chapman has also used this simplified procedure in his ARDA Agro-Climatology map series (1965).

elevation and some distance from the divide, have little or no surplus. These local patterns, which cannot be shown fully on a map of this scale, are mapped in greater detail elsewhere.*

It is apparent that a large part of the surface water supplies in the plains must be obtained from streams that rise in the mountain and foothill areas in the west, and in the Shield areas to the north and east. The surpluses of the drier regions are nevertheless very significant because they occur in areas of seasonal deficit and should thus be studied closely so that they may be managed effectively.

Maximum Surplus, 1921-1950 (4" storage capacity) (Fig. 39)

The maximum surpluses of the 30-year period occurred in different years in different areas. They were produced, in combination or in part, by above-normal fall rain that recharged soil-moisture storage, heavy winter snow, a cold winter and late cool spring with little evaporation loss, heavy rain in spring and early summer, and occasional intense local storms in summer. Flooding occurred because channels formed in years of lesser surpluses were unable to hold the larger supplies. In the drier regions the problems were accentuated because many areas that normally had runoff into local depressions had overflow into adjoining basins and added to the problems of the latter.** The maximum surpluses are important for their flushing value, stagnant and alkaline ponds are freshened and calcium carbonate concentrations in soils are reduced or moved to lower levels. It is of interest that deficits also occurred in many of the years in which

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* Laycock 1957

** See Stichling and Blackwell 1958 and Laycock 1959.

maximum or near maximum surpluses were experienced. Moisture in soil, reservoir, lake and groundwater storage may last well into the following year, or years.

Minimum Surplus, 1921-1950 (4" storage capacity) (Fig. 40)

Almost all parts of the settled prairies experienced at least one year in the 30-year period in which there was no water surplus. In the driest areas over two-thirds of the years do not have surpluses after a recharge of 4 inches of soil-moisture storage (see Appendix B). It is apparent that if runoff is to occur in these areas in the dry years it must come from intense flash storms on soils with limited infiltration capacity, rapid snowmelt with runoff before complete soil-moisture recharge to 4 inches, areas with soils of less than 4 inches storage capacity and groundwater carryover from wetter years.

The very limited and undependable local surface water supply of the major agricultural areas of the prairies is indicated. In contrast the minimum surplus of mountain areas in the west is well over 30 inches in some of the ice fields along the divide.

Surplus, 1927 (4" storage capacity) (Fig. 41)

In 1927 many parts of the southern plains had larger surpluses than in any other year of the 30-year period. Many areas farther north had relatively small surpluses, e.g. Peace River to Watrous, and moderate deficiencies (Fig. 11). Local variations are more striking for a single year than for a long period and these help to explain why local floods may not be reflected in outstanding streamflow for major basins.

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* The years 1927 and 1936 have been selected to show an exceptionally wet and an exceptionally dry year in the southern plains. Other areas, e.g. the Peace River, had dissimilar patterns in these years. Maps of other years of the period 1921-1956 exhibit many other local and regional variations.

Surplus, 1936 (4" storage capacity) (Fig. 42)

The severe drought of 1936 (Fig. 12) in the southern plains is only partly reflected in surplus patterns. Many stations still had small surpluses in spring before the drought period began, and others had surpluses from the local intense showers that are such a striking feature of prairie precipitation. Heavy general rains are particularly lacking in the drier years. Improvements in soil-moisture storage, and in the use of surface runoff in spring through the development of dugouts, stock-watering dams, and small irrigation projects can help to reduce the effects of drought in most years. Stubble-mulch tillage, the use of snow fences and shelterbelts, basin listing, snow plowing, etc. can help to reduce the loss of moisture by snow blowing and may contribute to local areas having net receipts of moisture from adjoining areas.

Median Surplus, 1921-1950 (4" storage capacity) (Fig. 43)

Median values of zero surplus are present in the drier areas but average values (Fig. 38) are approached in the more humid regions where surpluses are present in most if not all years. The very small surplus available in half of the years in much of the settled prairie is such that limitations in use must be anticipated. Groundwater supplies are sometimes claimed to hold great promise but these cannot be used for long at a rate greater than that at which local recharge takes place. Recharge can be only a part of the surplus indicated in this map series because runoff into local depressions and streams also occurs.

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* The years 1927 and 1936 have been selected to show an exceptionally wet and an exceptionally dry year in the southern plains. Other areas, e.g. the Peace River, had dissimilar patterns in these years. Maps of other years of the period 1921-1956 exhibit many other local and regional variations.

Moisture Surplus, Upper Quartile 1921-1950 (4" storage capacity) (Fig. 44)

The planning of water resource use is made easier if frequency-intensity patterns of supply are known. If the wetter one-quarter of the years have surpluses of the amount shown, or more, some planning for the use of these surpluses may be done. These are the years in which most of the groundwater recharge, freshening of brackish sloughs by overflow to streams, and most flooding takes place. Culvert and bridge design, drainage-ditch specifications, etc. will vary from place to place to some degree according to the patterns shown here and in Fig. 39. Obviously other patterns illustrated in this series and local factors must also be considered.

Moisture Surplus, Lower Quartile 1921-1950 (4" storage capacity) (Fig. 45)

The driest quarter of the years have this surplus or less. If water supplied for dugouts, stockwatering dams, community water supplies, etc. must be adequate for at least three-quarters of the years (supplementary supplies must be found for not more than one-quarter of the years), the values shown indicate that a very large part of the prairie has very inadequate amounts. It is apparent that local supplies must come from areas with low infiltration or storage capacities, or that artificial or natural concentration of the available water must occur, e.g. through the drifting of snow into shelterbelts or wooded depressions, etc. The surplus from an area with normal storage is inadequate for most local uses, but this is desirable in terms of crop growth because crops should use all of the available moisture.

Average Surplus, 1921-1950 (12" storage capacity) (Fig. 46)

The average (4 inch) storage capacity maps show only that surplus which is available after 4 inches of storage capacity has been recharged. The finer-textured soils under crops with deep-rooting habits have greater soil-moisture storage and use. If the useable capacity* is 12 inches, no surplus is available in a large part of the prairie, roughly from Edmonton to Brandon. Surpluses following the full recharge and limited withdrawal in a series of wet years have occurred occasionally in more humid agricultural areas. Larger surpluses, occurring every year, are available in mountain areas. Contributions to runoff and streamflow are unlikely in most wooded areas in the plains unless moisture concentration has taken place, e.g. from drifting snow, groundwater, etc.

Average Surplus, 1921-1950 (½" storage capacity) (Fig. 47)

Many areas with coarse-textured soils are present in the prairies. If we consider the surplus patterns of a sand with only a ½ inch of available moisture (a non-agricultural soil if we think in terms of a full year, but quite possibly representative of a soil in spring when seedlings have limited root development, see Appendix B), we can illustrate the greater surpluses of these areas. Average surpluses of over 2 inches occur in the driest parts of the plains, e.g. in the Great Sand Hills north of the Cypress Hills. These are sufficient to provide a significant streamflow when streams in areas of better soil-moisture storage nearby are dry. Similarly, the contribution to streamflow in the sand hills between Brandon and Portage la Prairie is more than double that of neighbouring clay plains. Groundwater recharge is particularly large in sand-plain

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* See Appendix B.

areas and this detention storage contributes to a much less variable streamflow than is present in clay-plain areas.

The large runoff of the Canadian Shield is due in large part to the limited moisture storage of many of the surface materials. Bare-rock areas have well under ½ inch storage capacity and a very large proportion of the precipitation runs off. This is partly balanced by the evaporation from the extensive water and marsh surfaces, but the larger lakes are cold and evaporation is not very large. Bare-rock areas in the mountains also have limited storage and large runoff. Water surpluses of 40 to 50 inches and more are locally available.

Moisture Surplus, Upper Quartile 1921-1950 (½" storage capacity) (Fig. 48)

In the wettest quarter of the years the water surpluses of sandy-soil areas approach 4 inches in the driest parts of the prairies. Groundwater recharge in these areas is very significant and streams rising in sand plains may flow for long periods following this recharge. Shield and mountain areas have major surpluses for streamflow. Flash flooding is uncommon in most of these regions because of detention storage in sand, mountain detritus, widespread lakes and marshes, and the deferred melting of much of the snow present. Local exceptions are present in mountain areas.

Moisture Surplus, Lower Quartile 1921-1950 (½" storage capacity) (Fig. 49)

The surpluses of areas with limited detention storage are still very significant in the drier quarter of the year. Three-quarters of the years had surpluses of over 1.2 inches in the driest areas to the north and south of the Cypress Hills, and few zero values were recorded for the driest years. The greater dependency of these surpluses is due in large part to early recharge of moisture-storage capacities in winter; much of the rest of winter precipitation is then surplus. Some evaporation that takes place in winter is now adequately recognized.*

Seasonal Water Surpluses, 1921-1950**
(Figs. 50, 51, 52, 53, 54, 55, 56, 57, 58 and 59)

In September of most years evapotranspiration exceeds precipitation and water surpluses are almost wholly absent in the Prairie Provinces. In moist years, when precipitation exceeds evapotranspiration, the excess moisture is usually contributed to soil-moisture recharge because little, if any, moisture remains in reserve after the summer period.

In October precipitation most commonly exceeds evapotranspiration and most of this moisture enters into soil-moisture storage. Some is detained upon the surface as snow which may last until spring before contributing to soil-moisture recharge or runoff.** Areas with very limited storage capacities, e.g. coarse sands, shallow soils, and bare rock largely in the mountains and Shield, usually have small surpluses in October.

In November to February precipitation quite generally exceeds evapotranspiration, but the difference is still now adequate upon melting in spring to recharge soil-moisture storage to 4 inches in the southwestern parts of

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* See Appendix A.

** Although a number of maps have been drawn up, only 10 have been selected to show some of the patterns described.

Saskatchewan and South Eastern Alberta. The evaporation and sublimation of a part of this moisture is normal in these areas.* The surpluses elsewhere are largely detained upon the surface as snow and are not reflected in streamflow in winter months.

In March, precipitation still exceeds evapotranspiration in most areas in most years. As noted in Fig. 50 (March surplus, ½ inch storage) the surplus in areas of limited moisture storage capacity is over ½ inch in almost all areas. To this might be added a part of the surplus of previous months which is available as snowmelt runoff. In the drier parts of the plains most of the annual runoff occurs in March and April. Fig. 51 (March Surplus, 4 inches storage) has much lower values in the drier parts of the prairies because soil-moisture storage capacities are usually not yet refilled to the 4 inch level. In the wetter areas this is less frequently true and the isoline patterns are comparable to those of the previous map.

In April, May and June (Figs. 52, 53 and 54) the average surpluses become smaller as average evapotranspiration increases more rapidly than average precipitation. Moisture in storage is depleted and rains must be increasingly heavy if surpluses are to occur.

Moisture in storage at the end of April (Fig. 55) is slightly less than at the end of March in the more humid regions (it was then at or very near the 4 inch capacity level). In the drier southcentral plains areas moisture levels do not reach 4 inches in over half of the years, thus the average at the start of spring seeding is well below this amount.

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* See Appendix A

Although the average surpluses decline from March and April into May and June, streamflow increases to higher levels in the latter months in all but the drier areas. This is due to late springs and delayed melting of snow (particularly in the higher mountain and northern Shield areas), detention of surpluses in soil, groundwater and channel storage for delayed release, and occasionally to the occurrence of heavy rains when little reserve storage capacity is available.

In the wetter springs when evapotranspiration withdrawals are small and heavy rains occur, quite large surpluses are locally available in March, April, May and June (Figs. 56, 57, 58 and 59). The maximum surpluses (in a few cases the only surpluses of the 30-year period) vary greatly from one station to the next, particularly in late spring and early summer when thunderstorms are common. In March heavy snowfall is occasionally received in the more western and eastern areas. The lesser snowfall of the central plains is greater than is revealed by this map, however, because that which contributes to soil-moisture recharge is not surplus. In April the heavy snowfall of some years in the foothills and western plains margin contributes to large surpluses. In late May and June humid air from the Gulf of Mexico may release large amounts of moisture as far west as the foothills and front ranges of the Rockies. If prior moisture reserves are high, major surpluses are produced. In May the effect of heavy rains in 1927 in the southern plains is strikingly apparent. Longer periods of record would reduce local variations, e.g. the low maxima of northcentral plains areas. An extension of the period into the 1950's would reflect the heavy precipitation of April 1952 in the Cypress Hills, June 1953 in the southern foothills, August 1954 in the central foothills, and May 1955 in South-Central Saskatchewan.

In July and August surpluses are very infrequent in most parts of the Prairie Provinces including the mountain and Shield areas that have moderate moisture storage capacities. Streamflow continues at a declining rate, largely from detention storage because evapotranspiration exceeds precipitation almost everywhere and in almost all years. The occasional heavy rain usually contributes more to soil-moisture recharge than to runoff. In areas of limited storage capacity, surpluses occur more frequently. The average based on monthly data is still usually zero, but that based on daily data is occasionally large.*

Seasonal surpluses in areas with 12 inches storage, e.g. deep but penetrable fine-textured soils and alfalfa or tree cover, are absent in a large part of the prairies (Fig. 46) and occur in the winter and spring of occasional years, usually at the end of a series of wet years, in the remaining plains areas. In the wetter mountain-forest areas the heavy precipitation is adequate for soil-moisture recharge and a surplus in every year. In the drier mountain and foothill forests, surpluses occur in some years, but deficits are also common (Fig. 6). Shield areas also have undependable yields from areas with large withdrawal of moisture from storage, yet areas with limited soil-moisture storage are so much more widespread that the effects upon streamflow are noticeable only in small basins on the southern and western margins.

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* See Appendix A.

VIII. APPLICATIONS OF WATER BALANCE STUDIES

1. Introduction

A discussion of the uses of individual maps of water-surplus and deficit patterns becomes repetitious when a number of different maps may be employed for particular needs, e.g. for irrigation scheduling or flood limitation programmes. In addition, alternative maps may be employed for specific needs and reference to such a use in the discussion of any one map may seem arbitrary and exclusive. Much of the discussion of how the maps in this study might be employed has accordingly been postponed until this chapter.

The obtaining and dissemination of information concerning water resources are among the major objectives of many agencies including the International Hydrologic Decade, national and provincial resources conferences, research councils and foundations, federal and provincial government departments and agencies, and educational institutions. The need for improved basic and derived data is becoming increasingly apparent.

The major objective in this study has been educational in the broad sense of the term. We wish to obtain a better understanding of water supply and water deficit patterns and, with the use of procedures developed by Thornthwaite and others, we are able to use widely available data in relating the component parts of the water-balance equation to each other.* With the basic information on potential evapotranspiration, water surplus

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* See Chapter III

and water deficiency obtained in this study we can also suggest relationships of each to water demand. These demand aspects are discussed briefly following a review of the characteristics of water supply.

Although a number of the relationships noted in this chapter have been studied and developed in varying degree, only a limited discussion is presented. It is hoped that the following comments and suggestions will lead to further studies and to useful applications of the maps prepared for this report.*

2. Climatic Classification

Many climatic elements, singly and in combination, have been classified so that regional description and comparison may be facilitated. We might very usefully compare the potential evapotranspiration of different regions in order to locate areas with similar crop growth potential and products. This index is comparable to various degree-day indices, e.g. above 42°F, and is used in the same ways. Its advantage is that the values are expressed in terms of the amount of moisture needed, thus comparisons with water supply are facilitated. Thornthwaite has grouped the values for easier regional comparison into nine major divisions for the world. Five of these are present in the Prairie Provinces (Fig. 60).**

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* Space limitations preclude publication of more than a selected portion of the maps that have been prepared.

** "Frost" (below 5.61 inches potential evapotranspiration) in alpine ice fields and "Tundra" (5.61 to 11.22 inches PE) in alpine areas, generally above the tree line, are not differentiated on the map; "Cool Microthermal" (11.22 to 16.83 inches PE) in the lower mountain areas and near Hudson Bay; "Warm Microthermal" (16.83 and 22.44 inches PE) in most parts of the Prairie Provinces; and "Cool Mesothermal" (22.44 to 28.05 inches PE).

The warmer-than-average half of the Warm Microthermal (19.64 to 22.44 inches PE) and the Cool Mesothermal divisions contain almost all of the cultivated land of the prairies. Climatic analogues elsewhere, e.g. the cool margin of the Cool Mesothermal division in Eastern Canada runs from southern Georgian Bay to just northeast of Montreal (Thornthwaite, Mather & Carter, 1958, Chapman, 1965), may be identified and it is apparent that the warmest parts of the prairies, e.g. Medicine Hat, have shorter and cooler growing seasons than parts of Southern Ontario and British Columbia.

Various moisture indices have also been plotted (Figs. 61, 62 and 63). The relation between water surplus and water need constitutes an index of humidity (Ih) which is expressed $Ih = \frac{100S}{n}$, where S is water surplus and n is water need (potential evapotranspiration). It will be noted (Fig. 61) that the range is from almost zero in the drier plains to over 15 in the more humid plains, and over 50 in the wetter parts of the Rockies. Comparison with patterns elsewhere shows that the prairie has higher index values than many grassland areas of other parts of the mid-latitudes.

A similar index (Fig. 62) using deficits rather than surpluses shows the aridity patterns present. Larger aridity than humidity index values are common indicating that deficits exceed surpluses in most parts of the prairies.

Both surpluses and deficits occur at most places in the Prairie Provinces. A "Moisture Index" in which both are included (Fig. 63) is calculated $Im = \frac{100S - 60d}{n}$. Since surpluses may be carried over in subsoil-moisture storage into a dry season, the deficit value is not stressed as much.* By this classification there are no arid areas (below -40) in the Prairies and most agricultural areas are semi-arid or sub-humid. Humid areas are present only in the Rockies and near Hudson Bay.

Although general patterns of climate, using Thornthwaite classifications, had been established previously for the Prairies and for other regions,** they are outlined more precisely here than has previously been possible. The revisions overcome many of the criticisms of the Thornthwaite procedures that have been made on the basis of patterns previously mapped, e.g. in the excellent preliminary study of M. Sanderson in 1948. The differences are attributable in large part to our using averages based on calculations of all of the years of the period rather than upon mean temperature and precipitation data.*** Several other publications, e.g. "Water Balance in Eastern North America" might usefully be refined in the same way.

Thornthwaite procedures have not been used here in mapping seasonal variation of effective moisture or summer concentration of thermal efficiency. The summer concentrations of heat and moisture are generally high in most agricultural areas.

Climatic maps, in addition to facilitating comparison with other regions, provide a good comparative pattern within the Prairies. Many of their uses are discussed in later sections.

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* In some comparisons of more recent years involving the use of larger storage in calculation of averages of surplus and deficiency, equal stress has been given to surplus and deficiency. The values in the older index presented here show useful patterns in the prairies.

** Sanderson, van Hylckama, etc.

*** See Chapter III.

3. Surface Water Supply

The characteristics of surface water supply vary greatly from one part of the Prairie Provinces to another.

In the mountain and foothill regions,* the water yields are large (Figs. 38 and 47) because of the high precipitation (Fig. 1) and low evapotranspiration (Fig. 64).** The variation from one year to the next is large but there is a significant and dependable flow in every year. Streamflow is concentrated largely in the late spring and early summer months when winter snows melt and run off. Detention storage in colluvial, alluvial, and glacial deposits is significant, however, and flow in other seasons except for early spring is larger than that of the plains. Flooding is generally not a major problem because stream channels are naturally able to contain a large flow, and snow melting is not highly concentrated in time because of the wide ranges in elevation and temperature present. The streams are turbid much of the time but most of the material carried has been mechanically weathered. The erosion of weathered soil is limited where forest cover is present and organic materials are not abundant in streams. Lime contents are high.

Many local variations are present in the mountain and foothill region. Some of the lower eastern-mountain valleys, e.g. Jasper, Kootenay Plains, Yaha Tinda, Canmore, etc., have only small surpluses while the higher back-range areas, some with ice fields, have local yields of over 50 inches.

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* See PPWB Report No. 6 for a more detailed review.

** It is thus apparent why water yields are so much larger than those of plains origin, e.g. in the dry year 1948-49 the mountains and foothills with only 16% of the basin area contributed approximately 90% of the flow of the North and South Saskatchewan Rivers (Laycock 1954 and 1960).

The heavy back-range snowfall in winter is more dependable than the summer rainfall which is a greater part of the foothills precipitation. In addition, the carryover of ice from one year to the next in ice fields tends to result in higher flow than might otherwise be present in low-flow years which are usually warm, and a reduction of yield in the high-flow years which are usually cool. The snow and ice of the back ranges starts to melt later in spring and the melting period lasts longer in the summer than in lower areas to the east. Surface detention storage is low because of the widespread bare rock and stony-surface material, and the limited extent of lakes and marshes. Lakes in cirques and in valleys behind moraines are present but the high rate of in-filling and the heavy cutting at outlets makes most of them relatively short-term features. Flash flooding is a far greater problem in southern foothill areas than in mountains behind the front ranges because of the greater exposure to occasional rainstorms of long duration and great intensity in late spring or early summer. More organic soil is eroded and carried, particularly where man and/or fire has accelerated natural processes. Lime contents are lower in the foothills however, because limestone rock is less widespread than in the mountains.

The sub-humid plains (Fig. 63) have moderate to small but variable yields (Fig. 38). The largest and most dependable yields within the plains occur in the foothills margin in the west, outlying hill areas, e.g. Swan Hills, and the "mountains" along the Manitoba Escarpment, and on the Shield margins in the east. Precipitation (Fig. 1) is frequently less than potential evaporation (Fig. 2), and the surpluses of spring (Fig. 38) are followed by larger deficits in summer (Figs. 3, 4 and 6). The surpluses are normally small but above normal fall rains, heavy snowfall and cold temperature in winter, late cold springs with heavy snow or rainfall, and intense rains in the early summer before soil-moisture reserves are depleted may in combination contribute to heavy runoff. Most areas will contribute to streamflow in the wetter years (Figs. 39, 41 and 48). In the drier years the lesser runoff may not be sufficient to fill local basins and contribute to streamflow (Figs. 40, 42 and 49). In undulating to rolling-glaciated terrain these depressions are numerous and surface-detention storage in sloughs, lakes and marshes is large. Controlled drainage of some of these depressions might add to streamflow and to the improvement of land use (Laycock, 1959). Normally, the greatest and most dependable streamflow occurs during the snowmelt period (Figs. 51, 52, 56 and 57), but heavy rains in spring and early summer may produce large local runoff (Figs. 53, 54, 58 and 59). A significant part of the streamflow is derived from runoff before soil-moisture storage capacities have been filled, e.g. in lacustrine plains. This flashy flow creates local flood problems, particularly since "normal" flow is inadequate to develop large or well-defined channels. The streams are turbid with organic and finely-weathered topsoil, particularly where summerfallow has been eroded. Since the greatest urban and industrial use of water is on the plains, pollution may reduce the value of water for other uses here more than in Shield or mountain areas. In the more humid northern areas surpluses are larger, deficits are smaller and extensive marshes and lakes provide surface-detention storage which results in a less flashy flow. Flooding sometimes occurs when channels are blocked by ice and cannot carry the local runoff or streamflow from warmer upstream areas. Streamflow volumes are larger than these maps indicate, thus errors in snow measurement, etc. are probably involved.*

Local variations in the plains are again very great despite the much smaller topographic variety (Laycock 1959a). North-facing slopes have a delayed snowmelt runoff, lower potential evapotranspiration, and possibly slightly greater precipitation, and thus have larger water yields and better regimen than most south-facing slopes. Undulating to rolling terrain has greater local drainage into depressions than the flatter lacustrine plains. Some of this may move as groundwater to streams but a large part evaporates leaving brackish or alkaline water, or almost useless encrusted alkali flats.** Sand plains with their limited soil-moisture retention-storage capacities have larger surpluses (Figs. 47, 48, 49 and 50). These contribute to a more stable streamflow because of slow release from detention storage, but marshes in many of these plains have heavy evaporation and transpiration losses. Most forest areas, with greater use of soil moisture from storage, have smaller surpluses (Fig. 46), less surface runoff and smaller deficits (Fig. 6) than adjoining cultivated-crop areas. They also have better flow regimen, less flooding and better quality flow. Gully erosion has been accelerated where cultivation and overgrazing has occurred, particularly on the margins of deeply-incised streams and spillway channels.

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* Appendix C

** Some of these are mined for sodium sulphate

The semi-arid plains usually have lower precipitation (Fig. 1), higher potential evapotranspiration (Fig. 2), larger deficits (Fig. 3), and smaller surpluses (Fig. 38) than the more humid plains. Surpluses frequently do not occur (Fig. 40), and streamflow is small and dependent upon areas of limited storage capacity (Figs. 47, 48, 49 and 50) and intense storms. The melt-water runoff period is short and early (most often in March or early April), but surpluses are limited in many years to areas of collected snow, e.g. in shelterbelts. Surface runoff can be highly erosive in the wetter years (Fig. 48) because the natural vegetative cover is light and offers only partial protection. Flooding is brief and may be succeeded quite soon by dry, or almost dry, channels.

The acceleration of erosion by man is facilitated by the climatic and geomorphologic patterns of the last ten thousand years. The terrain, following glaciation, was very youthful in terms of the fluvial erosion cycle. Streams could incise quickly and deeply into the soft-glacial drift, and gully erosion was facilitated by the steep gradients provided. Most of the period since glaciation has been drier than at present thus local erosion was not great. The protection afforded by natural vegetation has only recently been disturbed by cultivation and intensive grazing although there were local exceptions where buffalo, etc. were numerous in the past. Natural and cultural factors thus combine to favour exceptional erosion damage in wet periods today.

The Shield has higher yields than might be indicated on a map based on average moisture storage. Large areas of bare rock and thin soil are present and runoff often takes place before there is significant evapotranspiration. Water surfaces are extensive but water and air temperatures are lower than to the south and west thus evaporation is low (Fig. 2).* Permafrost impedes subsurface drainage in many of the areas with some overburden and soil and the "live" storage capacity may not be fully used. The major surpluses occur late in spring during snow melting but flash flooding is rare on the larger streams because of the widespread detention storage in lakes and marshes. These natural reservoirs also act as settling basins and erosion is minor on the old crystalline rocks, thus streams are usually very clear. Rapids are numerous and artificial improvement of both head and storage on the hard-rock base is much less costly than in the soft-sedimentary rock and glacial-drift areas of the plains.

The major sources of large and dependable streamflow are the mountain and Shield regions and much can be done in each to improve their streamflow characteristics (i.e. in regime, quality, flood limitation, erosion limitation, but only marginally in yield) according to our growing needs for surface water. In most parts of the plains the streamflow per unit area is small yet it has a major use potential, partly because of its location. Management for streamflow improvement is possible and desirable yet in most areas it is more important to reduce runoff and erosion and promote better moisture storage where the precipitation occurs, so that the vegetative cover might develop at as close to optimum rates as possible.

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* This is particularly true for the larger and deeper lakes. Albedo patterns in summer are such that the greater part of the available solar insolation is converted to heat energy and the water temperatures of the shallower lakes and marshes rise to surprisingly high levels.

4. Groundwater Supply

In recent years many excellent studies have been conducted by provincial and federal research agencies concerning groundwater patterns. Relatively few of these have been in the field of groundwater recharge. It is apparent that sustained production cannot long exceed replacement, even when reserves appear to be quite large.*

Groundwater recharge in most areas of average to above average infiltration and soil moisture storage capacities is small in most years (Figs. 38 and 46). In some years it may be a significant part of the surplus although surface runoff is also large in many of the higher surplus years (Figs. 39, 41, 44, 56, 58 and 59). In the drier years the contribution of most areas to groundwater recharge is negligible (Figs. 40, 42 and 45). If these dry years occur consecutively, many wells and sloughs dependent largely upon groundwater discharge will dry up.

The most dependable groundwater supplies are those that are recharged from areas of coarse-textured soils, e.g. ½ inch storage capacity (Figs. 47, 48, 49 and 50), or from permanent streams. The indicated amounts of water available for groundwater recharge (based on Thornthwaite procedures) appear to be remarkably similar to those estimated and measured by other

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* Many of the volumes mentioned in groundwater studies are expressed in gallon units, e.g. the safe yield of the Regina aquifer is estimated to be a maximum of 5,500,000 Imperial gallons per day (Lissey, 1963). This is a relatively large aquifer yet this volume is only slightly over 10 cubic feet per second and is well under one-tenth of 1% of the mean flow of the South Saskatchewan River at Elbow. It is encouraging that safe yield rather than absolute volumes present is receiving increasing emphasis because the costs of pumping from greater depths are prohibitive, and much of the water present in many so-called "reserves" is excessively mineralized for most uses.

means. Meyboom (1963 and in personal discussion) suggests that groundwater discharge in evaporation basins (and by transpiration from phreatophytes on the margins of these basins) within the Arm River drainage basin and to Last Mountain Lake to the east is comparable to the annual discharge of the river. Each would thus represent an average of approximately one-third of an inch for the Arm River Basin and, with a similar or smaller allowance for surface runoff into local depressions, this amount would appear to be about the same as is indicated in our maps for the area (a total of almost one inch) if we allow for only slightly below average storage capacities (Figs. 38 and 47).

Groundwater supplies generally fluctuate less than surface water supplies and make the surpluses of brief periods (storms or snow-melt) available throughout the year. Local recharge predominates in the prairies and there are locational advantages in its use. Temperatures are not far from those of mean annual air temperatures and they do not fluctuate greatly; an advantage for certain use such as air conditioning. However, much of the groundwater present is highly mineralized and at such a depth that large-scale continued uses for irrigation or major industrial centres seems unlikely. However, some areas such as the extensive sand plains between Brandon and Portage la Prairie appear to have large potentials. This one in Manitoba has a relatively high surplus per unit area (Fig. 47), a large water movement for natural demineralization of subsurface layers, a favourable elevation relative to the plains to the southeast, and the latter plains in the Carman and Morden areas have water deficiencies large enough that supplementary water supplies might well be used (Figs. 3, 6, 10 and 15).

The structural patterns of bedrock, and the deep incision of streams within the plains, are unfavourable for significant groundwater movement from areas of high water yield, e.g. mountains and foothills. Most groundwater that might be used is relatively local in origin. Some of the most promising aquifers are buried in preglacial or interglacial stream channels, pro-glacial delta and kame deposits, spillway channels and some freshwater sandstones. To this we might add riparian groundwater near streams, but it should be recognized that withdrawal from this source is actually very largely from streamflow. Water which has moved at depth in bedrock for great distances is almost always brackish or worse, and movement within formation is sometimes very slow.*

The potential for domestic, smaller urban, industrial, local supplementary irrigation, and other uses is a very large one despite the limitations noted. The costs of pumping may be high, yet these may be minimized if users locate to take advantage of telluric water movements to or near the surface, and select aquifers that have adequate recharge potentials.

5. Natural Soil and Vegetation Patterns

The major differences in naturally developed soils can be attributed in large part to differences in eluviation and illuviation. These vary almost

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* In the Milk River sandstone it does not exceed 20 feet per year, thus the production capacity of this extensive aquifer is estimated at 700,000 gallons per day or 1.3 cubic feet per second (Meyboom 1960). This is less than two acre-feet per day; a very small amount compared to streamflow in the South Saskatchewan River.

directly with the amount of water available to leach and transfer soil materials and thus with surplus and deficiency patterns. Very humid regions with large surpluses (Figs. 38, 47 and 61) tend to have highly podzolized soils, and those with lesser surpluses or roughly a balance of surplus and deficit tend to have grey-wooded or transitional to chernozemic soils. In the drier regions where droughts are pronounced (Figs. 3, 4, 62), chernozemic soils (black, shallow black, dark brown, and brown) are found. The amount of organic matter in these soils is determined in part by the rate of plant growth and this varies largely with actual evapotranspiration (Fig. 64). The depth of rooting is limited in part by the depth of available moisture, but this may be relatively shallow in most of the drier parts of the prairies for the greater part of most years (Fig. 55) because complete recharge to capacity is unusual.

Solonetzic soils owe their development in large part to parent materials, but occasional water surpluses to provide groundwater and the presence of many depressions without normal surface drainage outlet contribute to their presence (Figs. 38, 44 and Meyboom 1963). Some of the local variations in soil patterns might also be explained. Differences in aspect, e.g. north and south slopes, result in differences in evapotranspiration and sometimes in precipitation which are in turn reflected in differences in water deficits and surpluses. Concentrations of blown snow, surface drainage and groundwater might also be considered. Man may be a more significant indirect agent than is sometimes recognized, e.g. fallow tends to have greater surpluses than land under vegetative cover. If fallowing is frequent in the wetter areas, or in the wetter years, extra leaching will occur. Surface runoff and erosion is greater (Figs. 39, 44, 56, 57 and 59) and losses of topsoil by wind action may also be critical (Fig. 10).

Natural vegetation patterns reflect most of the water surplus and deficit patterns discussed. The general patterns conform to those of Fig. 63; the semi-arid areas having predominantly grassland; the dry sub-humid areas having a mixed grass and woodland (largely deciduous broadleaf), or parkland and the more open-mixed forests; and the moist sub-humid and humid areas having the better forest development. Forest growth is affected by severe drought (Figs. 7, 9, 12 and 15), and the incidence of intense and widespread fires is also greatest in these years. Very large areas of the prairies having adequate moisture in average years, but inadequate moisture in some years, are covered by burned-over scrub and young growth forest that is of little commercial value.

The growth rate of plants (grasses, crops, trees, etc.) varies largely with actual evapotranspiration patterns (Fig. 64). In the colder north-eastern and higher mountain areas, the temperature limitations are dominant. In the drier plains, moisture limitations (Fig. 3) result in lesser growth than might be expected with the amount of heat available (Fig. 2). Other factors are significant e.g. soil fertility which varies in part with surplus patterns; available moisture varying with soil limitations; natural and introduced plant species; and the effects of drought. In many respects the deficit patterns reflect the possibilities for cover improvement with better use of moisture, i.e. with irrigation.

Similarly, the surpluses reflect the possibilities for deficit reduction using local water supplies. A major objective in land management is to reduce surface runoff, reduce the removal of snow by wind action, and reduce subsurface flow so that plants might use this water and grow at a rate as close to that indicated by potential evapotranspiration as possible.

Annual growth rates vary greatly from one year to the next, particularly with variations in drought intensity. These may be indicated in part by maps of individual years (Figs. 11, 12, 13 and 14), but care should be taken in determining the relevant soil-moisture use from storage. Drought intensities are not as high if 12 inches of moisture can be available from storage as if only 4 inches can be available (Figs. 6 and 3), although recharge to the higher capacities is rare in most parts of the Prairies.

The species composition of grassland, parkland and forest is affected by drought and other patterns mapped. In grassland areas drought will initially curtail height of growth. Cover density changes and the death of less resistant species follow. Range carrying capacities are reduced and if stock numbers are not reduced accordingly the more palatable and nutritious species suffer greatest depletion. The time of the drought (Figs. 27, 28 and 29) is significant because some species withstand early season drought better than others. Grasshoppers are most numerous in drought periods. In forest areas the effects of fire are particularly noticeable. Lodgepole pine or various poplar are most numerous in burned-over and young-growth forests and in time may give way to spruce.

Deciduous broadleaf trees withstand drought better than coniferous evergreens. Grasses recover from drought more quickly than trees and the drought-fire patterns of the past probably controlled the tree-line location; possibly with some help from browsing and grazing animals on the forest margins. It is probable that the drought factor has not been recognized sufficiently, e.g. by Moss 1932 & 1955, Sauer 1944, and Bird 1961, and that its effects here are similar to its effects in the "Prairie Peninsula" of the midwest of the United States (Borchert 1950). The limitation of fires and the clearing of large areas so that snow might drift more freely into remaining wooded areas, e.g. along road allowances, has resulted in apparently vigorous woodland well to the south of the former limits. Very dry years such as 1936 and 1937 in the south exacted a great toll in dead trees in these areas. Information on average moisture conditions alone is not enough if we are to account for vegetation distribution patterns.

Forest site classification must include some reference to drought patterns in the northern parts of the Prairie Provinces. It is not enough for us to know that particular soils have particular soil-moisture storage capacities if these are recharged dependably in one area and not in another. Water surplus patterns and their relationships to marshy or muskeg conditions should also be considered.

Many of the water surplus and deficit patterns illustrated * might be used in both forest and range management. The meteorological data upon

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* Other patterns have been mapped but space limitations preclude their publication here.

which they are based are more widely available and have been gathered for a longer period of time than data on plant species, densities, vigour, growth rates, etc. Interpolation and extension of observed patterns of forest and range to other parts of the prairies, and to periods preceding such observations can be more soundly based if correlations with water patterns can be established. Cutting rates for an allotment in forestry (for sustained yield production), and stocking rates in range management might be recommended for different areas in part on the basis of these correlations. If current drought intensities are known to be above or below normal, range management specialists might gauge the carrying capacity of the range, estimate how species composition might change, and suggest more or less intensive land use. Many associated patterns might also be developed. In range management the availability of water in streams for direct use, or for ponding in stockwatering reservoirs, and the use of groundwater (in springs and wells) can be very important. Knowledge of surface runoff and groundwater recharge patterns can be very helpful. In forest management, recognition of surface erosion, sedimentation, and streamflow patterns can be helpful, e.g. if it is known that erosion hazards are much greater in southern foothill areas than in northern foothills, clear cutting and wide-strip cutting may be limited in the former and not in the latter.

6. Agriculture with Natural Water Supplies

In agriculture, as in forest and range management, a major objective is to make the best use of available moisture so that plants may grow as closely as possible to the rate limits imposed by the heat and light supply, e.g. as indicated by potential evapotranspiration (Fig. 2). In most agricultural areas, under average moisture-storage conditions, average deficits of 4 to 10 inches are experienced annually (Fig. 3). Moisture surpluses are small (0 to 4 inches, Fig. 38) and they usually occur in early spring (Figs. 51, 52, 53 and 54).

Cultivation, and particularly the use of summerfallow, has usually resulted in greater surpluses than those indicated because transpiration withdrawal has been reduced for at least part of the summer. Because of this, less recharge is needed before surpluses occur. Additional moisture has been lost from the fields through the removal of snow by wind action, and by surface runoff during snowmelt and heavy-rain periods. Water that was formerly stored for plant use runs or blows into depressions or percolates to beyond root depth. Surface erosion by water has been accelerated and wind erosion has also been accelerated on the drier unprotected soil. Although erosion damage prevention is sufficient reason for runoff control measures, e.g. Toogood 1950, a strong case can also be made for the retention and use of the water that might otherwise be lost because moisture deficits are increased by the amount of surplus increase (a feature that is much less important in the more humid agricultural regions of the world). In some cases the runoff may be used to provide supplementary irrigation to crops but this is generally less efficient and much more costly than limiting runoff in the first place. Complete limitation is virtually impossible and the surplus remaining might be used. Field runoff is often unfavourable in amount, timing, and quality for supplementary irrigation, yet the ponding of surplus waters on lower-level fields behind low dykes can be very helpful in augmenting soil-moisture supplies in some fields in most agricultural areas. Similarly, the collecting of blown snow by windbreaks or snow fences in and near dugouts is an important use of this surplus water.

The need for retaining precipitation within the fields upon which it falls is indicated in part by size of the deficit (Figs. 3, 5, 9, 10, etc.). The means for retaining this moisture have been improved in the last several decades, particularly with the development of tillage and harvesting implements and machinery that leave high stubble, stubble-mulch or a trash cover, and that permit basin listing, contour and strip farming, terracing (rarely feasible), etc. Snow plowing in winter may be helpful in some situations. Snow fences and shelterbelts reduce losses by drifting and may hold snow from adjoining areas as well as that which has fallen on the field. The fences are moderately costly and their erection, removal and repair is time consuming. Shelterbelts are less costly and time consuming but the trees and shrubs present consume a significant part of the moisture saved.

The general patterns of agricultural land use in the prairies are strongly affected by moisture patterns (Fig. 63). The semi-arid regions have extensive grazing and extensive forms of dry farming, but local soil and terrain variations contribute to better and poorer-than-average conditions for crop and livestock production, and there are accordingly areas with different intensities of land use within these regions. The extremes partly reflect the drought conditions mapped for 12 inches and ½ inch storage capacities (Figs. 6 and 4). In addition, most areas can be highly productive in some years when deficits are small (Figs. 8, 9 and 11), and of very limited productivity in the drier years (Figs. 7, 9 and 12). The hope that the next year would be a moist one has kept many small-scale operators farming in this region when there seemed little other reason for them to continue. Large-scale operators, with capital to withstand losses in the driest years and low overhead per unit area, have done extremely well in some of the wetter years, particularly in the flatter better-soil areas where yields have been high and large-scale mechanization has been efficiently employed.

In the drier sub-humid areas (Fig. 63) cultivation has been more general and only in the rougher terrain and coarser-soil areas are there large tracts of limited development, e.g. extensive grazing. The better lands (e.g. Regina Plain, Drumheller Plain), are very largely cultivated. The still more humid areas (e.g. Edmonton, Red River Plain) have more intensive mixed farming practices and more diversified production. Mixed farming is present on a reduced scale on the forest fringes where the greater water surpluses contribute to soil leaching (Figs. 38, 48, etc.). Drainage problems are more widespread and muskeg and gleysolic soils limit productivity. Droughts occur in these areas but they are less intense and less frequent (Figs. 3 and 10) than in the drier parts of the sub-humid regions. In these areas the drier sites, e.g. where drainage is facilitated near major valleys, are better for cultivation and the wetter sites are in forest or bog. Frost is a problem, particularly when spring and fall operations are impeded by wet conditions (Figs. 51, 52, 53, 54, 56, 57, 58 and 59). The growing seasons are shorter and cooler, and crop production becomes sub-marginal in the northern and higher western areas (Figs. 2 and 31). Forests make better use of the available moisture, soil and growing season, than annual crops in these cool and moist regions.

The specific crops grown are in part a reflection of moisture patterns. Annual crops, that are in part drought evading because they do not require a full growing season in which to mature (Figs. 23, 24, 25, 26 and 35), predominate in the semi-arid and drier sub-humid areas. These crops, e.g. wheat and barley, have limited root development in spring and thus leave a part of the soil moisture in storage until later stages of growth. Droughts may occur during these early stages of growth (Figs. 27 and 28), but are most severe in July in most years (Fig. 29). The deficiency for the season (Fig. 30) is less than that for the full growing season or the longer season required for alfalfa (Figs. 19, 20, 21, 22 and 34).

Alfalfa may do better initially than it will after several years of growth. In the first year after a cereal grain (still better after fallow) it will employ moisture stored beyond wheat root depth in previous seasons and may also benefit from storage accumulated in the long fall period after the wheat harvest. In the following years the alfalfa will be dependent upon the precipitation of those years. The greater depth of rooting is little advantage because precipitation is normally inadequate to recharge storage to the 4 inch capacity in the semi-arid areas (Fig. 55 and compare Figs. 25 and 26). In the wetter years alfalfa makes better use of the moisture available than wheat and water surpluses are small (Figs. 38 and 46). It would appear that alfalfa has greater prospects for sustained success in the more humid agricultural areas. Similarly, most other plants that have a full season of growth and are able to withdraw moisture from deeper storage, e.g. trees and shrubs, do better in the more humid parts of the Prairie Provinces. If they do well in the drier areas it is because they have obtained supplementary water from drifting snow, surface runoff, and from telluric or riparian sources.

The moisture and potential evapotranspiration patterns discussed might be related to the ecological range and optimum conditions for many plants. Phenology, agrometeorology, agro-climatology, zoo-climatology, and related fields of study might usefully employ these derived data.* The correspondence of drought-intensity patterns and wheat-protein-content patterns** is striking and understandable (Figs. 13, 14 and other annual maps not published). Other factors such as soil fertility, the use of fertilizers, cultural practices, the time of rain occurrence within the dry period, etc. are significant, yet the areas with over 8 inches deficit correspond generally with those with over 14.9% wheat-protein content. Closer examination indicates other relationships within this pattern. It would appear that if areas with the better soils (only moderate deficiency and little surplus normally) have relatively severe drought, protein contents are likely to be higher than in those areas that usually have severe drought. Grasshopper and rust patterns also appear to be closely related to the drought patterns mapped.

Many of the relationships discussed, and others, have been established using other criteria for drought measurement. The patterns established here appear to be more definitive than some of those previously employed

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* Numerous uses have already been made, see Holmes and Robertson 1959, and Robertson & Holmes 1959 and other references.

** Canada Department of Trade and Commerce, Grain Research Laboratory, 1950.

and their use should be helpful in crop insurance studies, crop and fallow planning, community pasture location, land use studies, and many associated fields.

One of the most widely employed means of moisture conservation is that of summerfallowing. It has probably been overrated in this role in the past because full appreciation of how little additional moisture can be stored for crop use in most areas by this means and of how much moisture might be stored has not been present.* As shown by Staple and Lehane (1952) in the Swift Current area, most of the soil-moisture recharge occurs in the fall, winter and spring, between crop seasons, and only one inch of the four inches available for use at the start of the crop season after a fallow year was added during the summerfallow season.** This inch (plus the 0.7 inches stored in the second winter) is significant, for it is present at depth within the soil and is usually available for use during the July head-filling stage of growth (Fig. 29). This extra moisture may mean the difference between a fair and a poor crop, but it does not make any inflexible rotation with fallow every second or third year desirable because other factors must be considered. It is assumed in the illustration that efficient weed control is possible in the fallow year, particularly early in the spring of that year. This may not be feasible because of weather conditions and competitive labour demands.

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* Laycock, 1961

** Appendix B

The addition of 1.7 inches of moisture in a fallow year is not enough to explain the significantly larger yields of crops following fallow. A part of it might be attributed to the smaller loss of moisture to weed growth and this means of weed control is still very important, although chemical means make better use of the land and moisture available. In recent years studies such as those of Michalyna and Hedlin in Manitoba (1961) have shown that the higher yields on fallowed plots were, in large part, related to the accumulation of available nitrates during the fallow year. This yield differential can be greatly reduced by mineral fertilizer and manure treatments. In the study area in the Red River Valley (a more humid area than Swift Current, see Fig. 3), during the years 1956, 1957 and 1958, there was an average of only 0.7 inches more available moisture to a 4-foot depth on fallow plots at seeding time than on plots which had been cropped in the previous year.

The negative features of summerfallowing are receiving increased recognition. The exposure of soil to wind and water erosion is not as great if strip-farming and stubble-mulch tillage are undertaken, but there is still greater exposure than in grassland or annually cropped areas. The organic and nitrogen contents of the soil decline in time and the soil becomes less productive, less receptive to precipitation infiltration, and less able to store moisture for later use. The non-use of most of a growing season's moisture and of the land results in much smaller productivity for most parts of the prairies than is possible with annual cropping, chemical weed control, and suitable fertilizer application. Part of this advantage is lost in the greater costs of producing a crop each year.

The prairie climate is significantly different from one year to the next (Figs. 11, 12, 13 and 14). If this is recognized and fallow operations become more flexible in timing, some advantage might be gained. The moisture in storage in spring is a significant part of that used by the crop in the growing season. It can be measured or calculated and if it is high in spring after stubble, and weed growth is not excessive, there is little reason to fallow. If fallowing is decided upon, weed control will be difficult because there is a good reserve of moisture available. If a crop is planted the application of fertilizer and spraying of weeds will probably be warranted by the larger returns. If, on the other hand, moisture reserves in spring are very low (and this is possible even after fallow) then fallow might be preferred. The chances that a good crop will be produced from current precipitation alone are poor. The dry spring is likely to be a good one for fallow because weeds will probably have less than average moisture supplies for growth. There are objections to basing planting decisions upon moisture-storage observations (Laycock 1961), but from the standpoint of most efficient moisture use the advantages appear to be great.*

In the last few decades there has been a greatly increased use of stubble and stubble mulch for moisture conservation. Shallow disking and subtillage leave a trash cover upon the surface that reduces snow blow-off and

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* Preliminary calculations indicate that if crops are sown in years with 4 inches in storage at the start of the growing season (fallow in other years), they would be sown 23 out of 30 years in Edmonton, 22 out of 30 in Lacombe, 19 out of 29 in Olds, 22 out of 30 in Calgary, 19 out of 30 in Gleichen, 21 out of 29 in Lethbridge, 19 out of 26 in Midale, 16 out of 30 in Moose Jaw, 17 out of 30 in Swift Current, 18 out of 30 in Saskatoon, 21 out of 30 in Scott, and 25 out of 30 in Brandon. In almost all cases, the calculated average deficiency in the crop season was smaller than in the alternate crop years of an arbitrary two-year rotation.

runoff, thus larger storage of moisture can take place between crop seasons. In the more humid regions particularly, this storage may be equal or almost equal to the capacity of the soil to store moisture for cereal crop use, and the use of fallow for additional moisture conservation may not be justified.

7. Agriculture with Supplemented Water Supplies

Supplementary water supplies may be used in crop production if the increased productivity warrants the development of the necessary facilities. It is apparent that increases in productivity are possible wherever and whenever deficits occur (Figs. 1 to 37), and that these greatly exceed the local surpluses available in most agricultural areas (Figs. 38 to 59). Projects dependent upon local surface runoff and groundwater supplies are generally small (Fig. 38) and are subject to the seasonal and quality limitations previously noted. Despite these limitations, it is probable that the long-run potential for increasing agricultural production in the Prairie Provinces is significantly greater in these projects than in larger projects employing water from rivers that rise in the more humid regions.

The "small water" or individual farm and community storage and irrigation projects focus upon the use of local runoff. The federal government pays about 50 percent of the cost of construction and provides all agricultural and engineering services through PFRA. In the period 1935-1964, 76,732 dugouts, 9,416 stockwatering dams and 4,732 individual irrigation projects had been constructed under the programme (PFRA Annual Report 1963-64). A large proportion of these are in the semi-arid and drier sub-humid areas (Fig. 63) where deficits are large (Fig. 3, etc.) and surpluses are small (Fig. 38, etc.). Most take advantage of surplus concentrations (natural and artificial) where infiltration of snowmelt water and heavy spring rain is slow because of fine-textured soils (e.g. in lacustrine plains), or snow drifting (e.g. in shelterbelts, along gullies, and within or on the lee side of other topographic and cover obstructions) has taken place, sometimes at the expense of moisture supplies in adjoining open fields. The supplies are small, highly variable from one year to the next and are concentrated usually in short periods of early spring. In irrigation these are usually used to supplement soil-moisture reserves and are applied by temporarily ponding water on relatively flat fields. Stockwatering dams and dugouts provide domestic water supplies for stock and farmstead use, and some are used for supplementary irrigation of gardens and small fields.

In the more humid agricultural areas, there has been a lesser development of small water projects except for dugouts in some lacustrine plains, e.g. in Southern Manitoba, where groundwater supplies for domestic use are not readily obtained.* In addition, federal assistance has been available for only a few years in many of these areas. It is likely that supplementary irrigation and storage will be of increasing importance in these regions in the future because large deficits do occur (Figs. 3, 7, 10, 12, 13, 14, 15 and 30), larger surpluses are available for use (Figs. 38, 44, etc.), and groundwater supplies are better than in the drier regions.**

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* In these clay plains groundwater recharge is small because the soils can retain most of the surplus remaining after runoff for use in the summer season. Subsurface movement to wells is slow in the fine material in some areas, the water is too far below the surface because of deep incision of major valleys nearby, e.g. Peace River, or the clay overlies saline formations.

** The lack of federal assistance in the use of groundwater for supplementary irrigation has resulted in much lesser development of this resource than in the development of surface supplies.

Some of the best prospects appear to be in Southern Manitoba below the Escarpment where the heat supply is large (Figs. 2 and 60), and the position is downslope from extensive sand plains which have abundant surpluses in groundwater storage (Fig. 47). Some intriguing possibilities in the use of natural groundwater seepage around sloughs might be developed, e.g. substitute alfalfa for the phreatophyte tree and shrub rings now drawing upon telluric water supplies.

Large community projects for irrigation, stockwatering, village and town use and industrial purposes are also present in the prairies. Many of these have employed federal or provincial aid in planning and development. A part of the irrigation involved is upon low terraces and is supplementary in spring or early summer when water is most readily available. Winter feed is the major product. Although the effects of drought have been lessened in these areas, the very limited water supplies of some of the drier years make an import of feed necessary (Figs. 9, 40 and 45).

The major irrigation projects draw, and will draw, water from streams that rise in the mountains and foothills (Fig. 38, etc.). These have a more dependable flow than those of plains origin but artificial storage is necessary if summer demands are to be met. Although streamflow is moderately large in the South Saskatchewan River and its tributaries, and some diversion from the north may be feasible, there is far less water available than might be used in areas with severe droughts (Figs. 3, 10, 38, 45, etc.).*

Past experience indicates that if average deficits are not very large (Fig. 3) and may be quite small in some years, e.g. in the Western Irrigation District (Fig. 9), many farmers prefer large-scale dry-farming to the relatively small-scale irrigation farming, or will defer irrigation too long in anticipation that rain will meet their needs. In these marginal areas heavy rains after irrigation have contributed to water-logging, drainage and alkalinity problems in some of the wetter years (Figs. 8, 11, 39 and 44). The projects with the greatest chance of success because of farmer co-operation in all years are those in the driest regions. On the other hand, the low cost of supplying water and the growing demands for supplementary feed supplies in some of these marginal areas in Alberta contribute to an increasing dependence upon irrigation.

The amount of crop growth and production is proportional to the potential evapotranspiration of the area (Fig. 2). In the agricultural areas of the prairies this ranges from just below 20 to just over 24 inches, and

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* The water supply is approximately 5,000,000 to 8,000,000 acre-feet per year or enough for 3,000,000 to 5,000,000 irrigated acres if no allowance is made for hydro-electric power, urban, industrial and other demands. In contrast, the demand at optimum level of use in areas with average deficits of over 8 inches (Fig. 3) could exceed this by ten times. Large parts of the drier regions could not be irrigated economically because of excessive pumping costs, unfavourable soil and terrain and other limitations, but the area that might be served at moderate cost still greatly exceeds that for which water supplies might be available. In years of low flow and high demand, the irrigable acreage would be still smaller. With storage carryover and less than optimum use in some areas in some years, larger areas might be assigned for at least some irrigation. In some areas of the United States, even flood flow is allocated, e.g. the South Platte to over 300% of average flow.

varying proportions of from half to almost all of this amount are supplied by precipitation, e.g. approximately half in the Medicine Hat area to almost all in average years in the more humid areas. In some years the deficits at Medicine Hat exceed 16 inches (Fig. 7). In subtropical and tropical dry regions the potential evapotranspiration is from 65 to 80 inches per year and proportions of up to 100% must be supplied by irrigation. Irrigation projects in the lower latitudes must supply much more water per unit area than is needed in the Prairies, but crop production is correspondingly large. The production per unit area and per unit investment is quite low per year in the Prairies because of our low temperatures and short growing seasons. The range of crops that might be grown is also limited. Only the low-cost operations have been feasible and then only if high value crops that cannot be produced dependably without irrigation, e.g. sugar beets, canning crops and some forage, were produced. This pattern appears to be changing with increasing local and world demands for produce, and the "insurance" role of irrigation in supplementing forage and other supplies in the drier years is becoming more important.

The variation in heat supply in the prairies is critical in the choice of crops to be irrigated. (Appendix C, Laycock 1959b, Figs. 2 and 60). It is likely that commercial production of those crops that are marginal in the prairies such as sugar beets, corn, tomatoes, other canning and frozen-food crops, etc. will be concentrated in the most favourable areas. The advantages of such locations as Medicine Hat and Morden are apparent, and it is likely that irrigation areas with these crops will continue to be the most successful, e.g. Taber rather than Strathmore or Hanna.

Irrigation and crop scheduling are possible in a very general way if monthly data on potential evapotranspiration and precipitation are available. Both procedures can be refined greatly if daily data are used, e.g. Thornthwaite and Mather 1955. Further refinements might be made if allowances are made for different soil-moisture storage use rates and different crops in different stages of growth (Thornthwaite and Mather 1955 & 1957, Blaney and Criddle 1952, and others). Procedures appropriate to careful water management in the prairies are described by Holmes and Robertson (1959). It would appear that at least some of these refinements are desirable, particularly for the irrigation and growth of specialty crops.* The major purpose of this report is to show regional variations in patterns. If allowances are made for the various refinements in procedure, it will be noted that the regional patterns discussed are not significantly affected. Most of the refinements in procedure concern the time of application; the seasonal totals are much the same as those indicated in the basic calculations.

The proper amounts of water for field application tend to be smaller than is very often applied to the land, and the excess frequently contributes to problems of drainage, alkalinity, ditch erosion, ponding in waste-water reservoirs etc. Irrigation in the Prairies is supplementary to precipitation and the total amounts needed by the plants from irrigation are indicated in Figs. 3 to 33. To this must be added sufficient water to balance field, ditch and canal losses by seepage and evaporation.

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* Whether they are used in their most complex forms or not, these procedures have added much to our understanding of the variables involved.

The maximum efficiency of irrigation is obtained by refilling only the root-zone-retention storage reservoir except when the presence of salinity requires some leaching. Overfilling will result in a leaching of soil nutrients and other problems previously noted. Underfilling will result in less than optimum growth rates. If fertilization is combined with irrigation, e.g. through use of sprinklers, a waste will occur with over-filling and the amounts used will not be employed most efficiently with underfilling.

Drainage problems in the prairies are greater than in many other irrigated areas of the world, at least partly because heavy rains may occur after soil-moisture recharge has been supplied by irrigation. The surpluses from this, and sometimes from excessive irrigation and seepage from canals, may result in water-logging, alkali problems, slumping, etc. These problems are accentuated in the prairies by the diversity of glacial-drift soil parent materials with large amounts of clay. Very few other glacial drift plains of the world are irrigated. In addition, there is a relative lack of naturally developed drainage channels due to the short period and generally dry conditions since glaciation. Perched water tables and telluric groundwater movements to local evaporation basins are common. In some areas the bedrock of marine origin causes groundwater to be saline or alkaline. Alkali concentrations upon the surface are common, particularly in irrigated lands which do not have adequate drainage provision. This problem can be limited in part by the careful application of only the required amounts of water (Figs. 3 to 33). Some drainage will still be needed and forecasts of requirements might be based in part upon patterns of water surplus and deficiency with due allowance for the amounts of irrigation water employed.

Soil flushing is needed in areas with natural alkalinity problems and in the rehabilitation of irrigated areas not provided with adequate drainage facilities. It tends to be most effective in the wetter years and seasons when surplus waters are most likely to be available, and when return flow is well diluted in streams which will not then have major withdrawals for irrigation downstream. It is assumed here that leaching is downward toward ditches. If it is not, the wetter years may present the greatest problems because of increased groundwater discharge and evaporation from the surface. In either case knowledge of surplus frequency and intensity patterns (Figs. 38 to 59) is necessary for planning.

The prediction of return-flow volumes can be based upon water demand, water surplus and irrigation application patterns. Return flow is large in prairie irrigation because water is still very inexpensive and is often delivered at rates well in excess of the actual field or district requirements. Diversion is based upon maximum potential demand, but demands, i.e. daily potential evapotranspiration values, vary greatly and may be supplied in large part and sometimes to excess by precipitation. A part of the surplus runs into local evaporation basins and does not return to streams. Local water balance patterns reflect the frequency and intensity patterns of water surplus and deficiency mapped in this report. Further detail is available for specific locations in the data tabulations upon which the maps are based. Calculations on a daily basis provide further refinement.

Most aspects of water supply relating to irrigation can be based upon direct long-term observations of streamflow. However, this map series may usefully supplement streamflow information in various ways. The seasonal and annual demand patterns indicated in Figs. 3 to 37 might be related to known supply patterns (streamflow data and Figs. 38 to 59), and the potential needs for storage reservoirs, diversion channels, canals, siphons, etc. of different capacities may be estimated. Streamflow data are not available for many local streams and estimates of flow and flow variations can be made using the surplus maps. The necessary allowances for this flow in irrigation water supply, drainage, culvert and drop-structure construction, etc. may be estimated. The degree to which erosion, flooding and sedimentation problems may be present may also be estimated. Much of this may be a cross-check on estimates based upon streamflow data which, if available for long-time periods, are usually better bases for estimation.

8. Other Water Uses

Most of the major uses of fresh water not previously discussed, i.e. urban, industrial, hydro-electric power, navigation, mining, commercial fishing, recreation in its many aspects, and wildlife, are well represented in the Prairies. There is a need for additional information on water balance patterns for all of these. For some the direct supply and demand patterns are indicated in this map series. For others the indirect competitive or complementary position in the allocation of limited supplies may be suggested. Only some of these supply and demand patterns can be discussed in the space available.

The major surface and groundwater supply patterns and their variations have been discussed in Sections 3 and 4 of this chapter and are indicated in Figs. 38 to 59. It is quite apparent why supplies of local origin are relatively small and undependable in the southern plains (Fig. 38). In Shield and mountain areas the soil-moisture storage for plant use is very small in the bare rock and stony areas, thus Fig. 47 should be used with Fig. 38. This imbalance in the regional distribution of water supplies is accentuated by the greater demands for water in the plains areas, thus water shortages and competitive use problems are most apparent in this region.

Urban and industrial use is largely non-consumptive and thus return flow is almost equal to withdrawal. The change of major portions of city areas, from high soil-moisture storage for plant use to very low storage on rooftops, streets and compacted surfaces, has resulted in much greater local runoff. This is only partly balanced by withdrawal for the irrigation of lawns and gardens. Most cities in even the drier portions of the prairies have a greater contribution to streamflow than withdrawal from it. The total volumes of water used are still small but industrial needs particularly are growing rapidly. The needs for dependable supplies of pure water make storage and some diversion from major streams necessary to supplement local supplies or serve as better alternatives to them. The change of quality that results from urban and industrial use is such that much larger volumes of water are needed to dilute pollutants and hasten their decomposition. The major problem areas are in the southern plains. Fortunately, rivers that rise in the relatively large and dependable surplus areas of the mountains and foothills flow through these plains and supply most of the present industrial needs, although some storage for increased winter flow is required. In the future, there may be a need for diversion from larger streams in the north, and for movement or placement of some industries that seriously pollute streams to and in northern areas. The water is available, but costs and competition for use will grow.

Hydro-electric power plants may be located on relatively poor sites if these are much closer to markets than much better sites. Accordingly, many excellent sites in the more northerly areas have not yet been developed, e.g. on the Slave and Fond du Lac Rivers, and only some of the sites on the more accessible margins of the Shield and mountain areas have been, e.g. on the Bow, Brazeau, Winnipeg, Nelson, and middle Churchill Rivers. Relatively few of the rivers in these regions have more than a short-term record of flow. Longer precipitation and temperature records are available for many more stations. These records may be processed in water balance calculations to extend the streamflow record in time and areal coverage. Some of these relationships have been developed in this report. Several sites in the plains on rivers of mountain origin, e.g. on the South Saskatchewan and Saskatchewan Rivers have been developed but local surpluses contribute little to the basic flow (Figs. 38, 40, etc.). Natural storage in lakes and marshes partly overcomes problems of seasonal variation in flow in Shield areas, but much more artificial storage is needed on mountain and plains streams. Since this storage is needed for urban and industrial purposes also, these uses are complementary. However, such storage is or may be competitive with that for irrigation (Figs. 3 to 37) because the demands in the latter are seasonal and the head needed for power may also be needed for irrigation diversion. In some projects, although there is some degree of competition, neither might be present if it were not for the other meeting some of the costs of development.

Thermal-electric power plants in the plains are sufficiently low cost in operation that major additional hydro-site development may be limited there. These plants are also major water users but frequent reuse for cooling is involved, thus lakes and reservoirs with relatively small streamflow may meet most needs.

Navigation for commercial transport has almost disappeared except on the Lower Athabasca and Slave Rivers and a few of the major lakes. Competitive means of transport, low and variable streamflow, ice and flood conditions, and the presence of numerous rapids, make it less than feasible in most parts of the prairies. Diversion of water from northwestern areas toward the south and east through the more populated areas and toward markets may make navigation more important in the future. Winter transport on snow, ice and frozen ground is very important in the north.

Commercial fishing is focused upon the lakes on and near the Shield, e.g. Lake Winnipeg, Reindeer Lake and Lake Athabasca. These are in areas of relatively large water surplus (Figs. 38 and 47) where the water is fresh, cool and widespread. Some lakes in the northwestern plains, e.g. Lac la Biche and Lesser Slave Lake, are of moderate importance but most of those farther south are too variable in level, quality and temperature for significant fish production. Some fishing is possible in irrigation reservoirs in these areas because of the better water supply.

Recreation and habitation are related to an increasingly important degree to water supply patterns. The use of lakes and rivers and their shorelines and banks for swimming, boating, recreational fishing, picnicking, hiking, viewing of scenery, cottaging, and the locating of homes is rapidly growing and the more accessible areas are becoming crowded. Different stresses are placed upon sites in urban and rural areas, and in plains and Shield or mountain areas. Some sites have been reserved for recreational and residential use by governments, e.g. in federal, provincial and municipal parks and by zoning. Other areas in and near settlements are rapidly being reserved privately.

Lake and shoreline qualities vary greatly with water balance patterns. For any lake, precipitation upon the lake surface plus surface and groundwater inflow will equal evaporation from the lake plus surface and groundwater outflow.* In the more humid areas (Figs. 61 and 63) precipitation exceeds or is very close to being equal to evaporation, thus relatively little if any inflow is needed for outflow to take place. Most lakes in humid areas remain fresh, have little fluctuation in level, and shorelines are well developed at outlet levels. In the more arid areas (Figs. 62 and 63), many of the lakes have relatively small basins and outflow is unusual.

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* In central Alberta, for example, the average values for Beaverhill Lake would be approximately as follows: average precipitation $16\frac{1}{2}$" for 60 square miles of lake area plus a surplus of 1" from 330 square miles (surface and groundwater flow) almost equal evaporation of 25" from 60 square miles plus 0 surface and groundwater outflow (70,400 acre feet is less than 80,000 acre feet thus the lake level would drop approximately 3 inches, see Figs. 1 and 38 and PPWB Report No. 5). In a slightly wetter than average year there might be 18" precipitation plus $1\frac{1}{2}$" surplus to produce a small outflow. The appreciable variation from one year to the next is indicated in the fluctuating lake levels and variable streamflow. These are suggested by Figs. 1 to 64 in this report.

These lakes stagnate, drop seasonally in level, have many different shorelines and in many cases become alkaline. Some dry up completely in the drier years (Figs. 40, 42, 45, 49, etc.). Some of the lakes, e.g. those in spillway channels such as the Qu'Appelle Valley and Chin Coulee, Tramping Lake, Manitou Lake, Coal Lake, Saunders Lake, etc., in the drier regions have larger basins. These have outflow in the wetter years (Fig. 39, 41, 44, 48, etc.) but may drop to very low levels in the drier years when the unit area flow is negligible and basin areas shrink.

In most parts of the prairies the recreational and habitation qualities of lakes and streams can be improved by physical improvement of the water supply and/or by zoning shoreline and bank areas to higher order uses. Storage of seasonal surpluses for later flow into lakes and streams, the controlled drainage of some depressions to concentrate local surpluses in potentially favourable sites, and the development of reservoirs based upon streams that rise in high surplus areas can result in major improvements in most water bodies for recreational purposes. Many problems of flooding might also be reduced by such action. The habitability of some environments is closely related to the degree that recreational development may be undertaken. Most environments might be more or less attractive according to how we use our water resources.

Many other patterns such as the location of sodium sulphate deposits, the tractionability of soils, the availability of water for oil-well drilling and the habitat of game and fur-bearing animals, and of shore and other birds might be related to the patterns mapped and discussed.

9. Watershed Management

Watershed management objectives include the improvement of streamflow yield, regime and quality, the reduction of erosion and flood damage, and the direct economic use of the region (Laycock 1960). Some of these are directly competitive but others are complementary. Not all can be achieved at once and decisions must be made as to which are needed most urgently and in the long run. It is apparent that, since it is the major source of the North and South Saskatchewan River flow, the mountain and foothill portion of these basins must receive major consideration in planning for watershed management (Section 3 of this chapter and Figs. 38 and 47). The forest reserve portion of this region has watershed protection as its major management function.*

The physical potentials for obtaining management objectives vary greatly from one part of the reserve to another, largely because of differences in water balance equation patterns (Laycock 1957 & 1960). Bare rock, coarse colluvial deposits, and very shallow stony soils have little potential for management change anywhere in the mountain and foothill region. In contrast the widespread drift, glaciofluvial, alluvial and palustrine materials may have major water yield, regime and quality changes with changes in vegetative cover and use, but the potential for these changes may be very limited if the climatic conditions are unfavourable. In the back-range areas, precipitation is large every year and water yields may be increased by cover removal because there will then be

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* Eastern Rockies Forest Conservation Board Acts of 1947.

some reduction in evapotranspiration withdrawal of water from the deeper soil horizons. Such a cover removal need not result in serious erosion or flow regime change because most of the precipitation falls as snow, melting occurs over a long period because of the cool temperatures at these elevations, summer rainfall is rarely intense and the natural ground cover recovers quickly in this humid environment.

In the front-range and foothill areas, particularly in the south, precipitation varies greatly from year to year and in the drier years when streamflow is most needed, moisture is not sufficient to penetrate to the deeper soil horizons. Cover removal would not result in significant yield increases because there is little moisture at depth to be saved from evapotranspiration loss. Clearing here might result in serious erosion and flooding because the dry periods might be followed by intense rains from tropical marine (Gulf) air masses which rarely and only locally penetrate beyond the front range. The natural cover is not as dense or vigorous as that of back areas because of the frequent drought, and its capacity to protect surfaces from erosion has been further reduced by more intensive use, particularly in grazing. In these areas, watershed management objectives should be oriented toward regime and quality improvement, and to erosion and flood limitation, not yield increase. Although the map scales used in this report are too small for direct management application, some of the general contrasts between back and front range areas are shown in Figs. 1, 3, 8, 38, 40, 46, 47, etc. and are discussed separately (Laycock 1957a and b, 1958 and 1965).

Watershed management cannot be limited to only the Forest Reserves in the mountain and foothill region, or to the mountain and foothill region of these basins. In the National Parks there is little conflict between watershed and recreation objectives, except for provision for artificial storage of water. Additional dams and some management for yield increase (in conjunction with the removal of aged, diseased trees) may be needed in the future. Limitations upon the intensive use of privately owned and leased land in the foothills would help greatly in reducing erosion, flood and sedimentation damage. Lease restrictions and subsidy payments for shorter term grazing, etc. might be helpful. In the plains there is almost no potential for yield increase (except possibly by slough drainage), but much might be done about erosion and flooding limitation, regime and quality improvement, and development of local supplies for local use. Both land management and engineering works are needed, not just one or the other in haphazard developments.

IX. SUMMARY, CONCLUSION AND RECOMMENDATION

The objective of this study was to employ recently developed procedures in defining and mapping the major patterns of water deficit and water surplus in the Prairie Provinces more closely than had previously been possible. The water balance approach, employing particularly the procedures outlined by C. W. Thornthwaite in 1948, was used and the major frequency and intensity patterns of drought and surplus have been mapped. The 64 maps selected for inclusion in these reports depict the major patterns defined in the study. Many additional maps have been drawn to show variations of frequency and intensity, additional annual and seasonal patterns, etc. The calculations for many stations have been processed in other ways and have been related to observed patterns of deficit and surplus, and to many patterns of land and water use, e.g. see Chapter VIII. For reasons discussed in Appendix C, some of the generalizations and assumptions made may result in significant errors in the values mapped for specific areas, yet the major mapping gradients have been confirmed in corroborative studies using other techniques (Figs. 31 to 37) by the streamflow data available and in local detailed studies.

It would appear that improved measurements of the local water balance patterns will now be more useful than additional attempts to develop or apply empirical procedures. Some of these measurements will be made in studies associated with the International Hydrologic Decade programme. It is hoped that the new data can be related closely to those available from existing and continuing records and that all may be related to the patterns established for the period 1921-1950. Some of the precipitation and temperatures data of the period since 1950 have been processed so that some of the relationships discussed could be established or confirmed. The remaining derived data should now be obtained and processing on a continuing basis is recommended. The forecasting value of these data has been suggested in Chapter VIII, e.g. in range management, estimation of spring-moisture supplies for summerfallow and crop planning, explaining current patterns in lake and well level fluctuation, and in estimating irrigation requirements, forest increment, etc. Additional forecasting may be done, but perhaps the greatest value of the present report and continuing calculations could come from the improved understanding and regional and time perspective we might obtain concerning our water resources.

APPENDIX A

DATA SUPPLIES

The quality and range of available data have greatly affected the selection of procedures and the accuracy of maps in this study. Many qualifications and limitations are recognized yet it would appear that most of the errors are sufficiently minor, compensating or relatively uniform in their distribution that the major gradation patterns of water surplus and deficiency are as indicated. Recognition of data deficiencies can add to our understanding of the local variations within the generalized patterns and may contribute to improvements which will enable us to define patterns more correctly in the future.

Procedures

The possibilities for errors in mapping arising from limitations in the procedures used have been discussed by various authorities (e.g. Mather 1954, Penman 1963, N.R.C. Symposium on Evaporation 1961, I.A.S.H. Assembly Proceedings of 1957, 1960 and 1963 etc.) and several aspects are noted in Chapter III. The Thornthwaite procedures of 1948 have been used more than any othersbecause: (1) they can be employed for all stations having monthly temperature and precipitation data; (2) a complete water balance for each year can be calculated; (3) they are easily used at relatively low cost; and (4) the patterns developed appear to correspond closely to those of vegetative cover, irrigation demand, measured streamflow, etc., without significant procedural modification. The more complex Thornthwaite procedures of 1955 and 1957 add to our understanding of some relationships but the results are not very different in regional pattern and do not appear to be any more correct when checked against streamflow and other patterns in this region.

Mr. George Robertson, meteorologist with the Canada Department of Agriculture, has provided us with daily data for eight stations based upon Thornthwaite procedures for the period 1921-1956. Both surpluses and deficiencies were larger for the lower storage values than those based upon monthly data but the differences were relatively minor for storage of over two inches. Some regional differences are indicated, e.g. winter evapotranspiration is greater in the southwestern plains "chinook belt" than in areas further north and east, but they are less striking and regular in gradation pattern then we had expected and we have not corrected our final maps accordingly. These data can be very useful in more detailed local studies and particularly in crop scheduling and forecasting.

The 1948 Thornthwaite procedures do not include direct allowance for regional differences in wind, humidity and solar radiation. Each should result in greater deficiencies and smaller surpluses in the southwestern plains then in the calmer, more humid and cloudier areas to the north and east but, since these differences are partly reflected in temperature patterns, the errors do not appear to be large. The longer days in summer in the northern areas undoubtedly affect potential evapotranspiration and thus plant growth etc., but the Thornthwaite procedures do not allow for extra day-length north of 50° N. latitude. It is possible that the greater frost hazards within the growing season in these northern areas at least partly compensate for this apparent error but further research is needed before corrections can be applied.

Many other procedures have been tested for at least some stations and two, Blaney-Criddle and Lowry-Johnson, have been applied for 89 and 43 stations respectively. Neither provides a water balance for the year and if Thornthwaite moisture storage allowances for spring are employed, both show patterns very similar to those based on Thornthwaite procedures. The allowances for greater day-length at higher latitudes in the Blaney-Criddle procedure appear to be excessive but we cannot suggest modifications that would make the procedure more useful in this region. Allowances for sun height above the horizon might help.

Comparative studies employing methods outlined by Penman, Ture and others have been less complete, largely because data on variables such as sunshine duration, mean humidity, wind movement, etc., are not widely available or easily estimated. In addition, the procedures are sufficiently complex and time consuming that major use would be costly. In general, the values obtained do not indicate that major regional corrections should be made.

The greatest need in procedure evaluation and refinement would appear to be for detailed water balance studies to be carried out within different parts of the region. Fortunately, a number of such studies are being initiated within the International Hydrologic Decade programme. The most advanced at present is in the Marmot Creek Basin (southeast of Banff) and the author is engaged in two, in the White~~wood~~mud Creek Basin near Edmonton and the Baker Creek Basin near Yellowknife.

Basic Data

The basic data on precipitation in the Prairie Provinces and most of the maps based upon them are much less reliable in showing regional patterns then is commonly believed. The errors present are probably greater than those due to basing potential evapotranspiration upon the procedure used. Some of the greatest improvements in mapping regional patterns of surplus and deficiency can result from improvements in precipitation data collection and in mapping with adjustments for the effects of topographic and other variables.

The most striking errors in mapping relate to unrepresentative location of precipitation gauges. In mountain and foothill areas, most of these instruments are located in the relatively dry valleys (e.g. Jasper, Banff, Lake Louise and Coleman) and most maps (e.g. Atlas of Canada, plates 25, 27 and 28) based upon the data obtained show far below average precipitation for these regions. Precipitation storage gauge, snow course and streamflow data indicate much higher values and allowances for topography (elevation, aspect, slope, position relative to other ranges and moisture bearing winds, etc.) have been made in some studies (e.g. Laycock, 1957).

In the foothills and plains areas, many stations in the deeper valleys (e.g. Nordegg, Entrance, Sunnegan, Peace River, Drumheller and Fort Qu'Appelle) receive less precipitation then is received on the neighbouring plains and much less than is received in hill areas nearby. There are few stations in the hill areas particularly, but recent past year records, the different vegetative cover, the greater streamflow and presence of lakes and other evidence indicate that the "mountains" on the Manitoba Escarpment, Turtle Mountains, Moose Mountain, the Missouri Coteau, Cypress Hills, Hand Hills

Wintering Hills, Swan Hills, Clear Hills, Brick Mountains, Caribou Mountains and many other hills have significantly more precipitation than the adjoining plains and valleys.

Many stations with anomalous values may have particular micro-relief or exposure relationships. Reading or recording errors may be present for others. Some anomalies cannot be explained. Red Deer has significantly higher readings then Penhold and Hillsdown nearby, but both of the latter have low values for the region. Muenster has high values and Humboldt nearby is low. Pinawa, Outlook, Fort Chipewyan and others are low while High River and Swift Current are high for their respective areas.

Snowfall is particularly hard to measure and snow gauges in exposed sites do well if they catch over 60% of the total fall. The conversion ratio of 10 inches of snow to one inch of water is not correct for all regions and storms. It has been asserted that 80% of our streamflow is derived from snowmelt (Durrant, p. 20 Water Studies Institute Symposium, 1964). This seems reasonable as a generalization for the plains, and data based on the Thornthwaite procedures support the assertion. Improvements in data supply for snowfall, particularly in the hill and mountain areas would help us to improve the record.

Figure I of this study was drawn in 1957 because base maps showing precipitation distribution, including a very conservative allowance for topographic effects, were not otherwise available. Other attempts to show regional variations have been published in the last decade (e.g. Fryers 1956, Muttit 1962, McKay 1961 and 1965, Chapman 1965, etc.). Most of the other maps in this study are based in part upon Figure I. If these were to be redone at this time, greater allowance for topography would be given and local variations would be more pronounced. Improved data for the next few decades will add greatly to mapping accuracy.

Temperature maps do not indicate the local variations due to elevation, aspect, slope, exposure, etc., but interpolation is easier than for precipitation. The smaller potential evapotranspiration of the more elevated areas and particularly the north in contrast to the south slopes is very conservatively shown in the generalized maps. The combination of higher precipitation and lower potential evapotranspiration in hill areas results in much larger surpluses and much smaller deficits then occur in the lower plains but again the contrasts are shown in a very conservative manner for only some of the major hills. No allowances for potential evapotranspiration variations relating to lengths of frost free and growing seasons or for cool season temperatures over 32°F. have been made. These refinements must await more detailed mapping at a later date. The temperature data available are generally good but improvements in site location and inspection are recommended, e.g. the instrument shelter at Exshaw is still green to match the building trim rather than the standard white.

If allowances for factors other than precipitation and temperature are to be made, there must be improvements in the data supplies available. Wind speeds at different levels, radiation, albedo in different seasons, and other variables must be measured more closely. Little is known about how much moisture is obtained from fog, mist, dew and the direct condensation of moisture upon cool surfaces (e.g. snow) and allowances for evaporation from snow and ice are still largely guesswork. These variables may compensate for each other in some areas but imbalances in most areas are likely. Intensive local studies will help us to improve upon the maps we have drawn. Meanwhile, we might assume that the major patterns have been established.

APPENDIX B

SOIL-MOISTURE STORAGE

The moisture supply available to plants from soil-moisture storage varies with the soil, the plant and the time and amount of recharge. If we assume that recharge does take place, the most important variables are soil texture and depth of root development.

In the following table by Colman (1948) the moisture-storage capacities of soils of different textures are indicated.

MOISTURE CONTENT OF SOILS
(inches of water per foot of soil depth)

Soil Texture Class.	Pore Saturation	Detention Storage	Field Capacity	Retention Storage	Wilting Point
Sand	5.0	4.1	0.9	0.5	0.4
Sandy Loam	5.0	3.2	1.8	1.1	0.7
Loam	5.0	2.3	2.7	1.6	1.1
Clay Loam	5.4	2.0	3.4	1.7	1.7
Clay	5.4	0.4	5.0	2.5	2.5

Most of the water available to plants is that held in retention storage. It is the amount of water held after most of the gravity flow has taken place less that which is unavailable at sufficient rates of use to maintain turgor. In practice a small part of the water held in detention storage upon and within, particularly the finer, soils is also available. This amount is significant in the Prairies because our frequent showers provide at least partial recharge a number of times.

A table provided by the Soils Research Laboratory at Swift Current in 1949 shows similar values to those indicated by Colman except for a less abrupt change in capacity for clays.

INCHES OF WATER AVAILABLE FOR THE CROP
FOR DIFFERENT DEPTHS OF MOIST SOIL

Depth of Moist Soil	Sandy Loam	Loam and Silty Loams	Clay Loams and Silty Loams	Clays and Heavy Clays
1	.10	.13	.15	.17
6	.60	.78	.90	1.02
12	1.20	1.56	1.80	2.04
24	2.40	3.12	3.60	4.08
36	3.60	4.68	5.40	6.12
48	4.80	6.24	7.20	8.16

W. E. Bowser* has suggested that a rough guide might be that water-holding capacities increase by 1% for each 1% increase in clay content in the finer soils. Robertson and Holmes (1956), Duffy 1964, and others in various soil-survey reports, etc. report similar moisture storage, soil texture relationships.

Soil textures are rarely uniform with depth and variation in organic matter content, structure, salinity, use, etc. may greatly affect available moisture supply. Bowser* has suggested that water-holding capacities increase approximately 2 to 3% with each 1% increase in naturally-integrating organic matter content. Surface organic matter has a large detention-

* Personal communication in 1963.

storage capacity but retention-storage capacities are very low. These materials contribute to improved infiltration of water into the soil. If soil structure is favourable, e.g. in clay soils, roots will penetrate more readily and employ soil-moisture storage capacities to greater depths. "Hardpan" layers may greatly limit root penetration but they may also limit movement of water in detention storage to greater depths. "Alkali" or saline soils have limited useful storage because wilting points are high. Soil fertility contributes to the development of root systems and the better utilization of storage capacities. Tillage, grazing practices, forest fires and cutting greatly affect storage by changing the vegetative cover, organic material content, structure, fertility, runoff-infiltration ratios, etc. Local surface runoff and groundwater movements have subtracted from available moisture supplies in some areas and added to them in others.

Plant demand patterns are not uniform. Root penetration varies with plant species, age and vigor as well as soil characteristics. Root occupance tends to be more complete in surface soils than at depth, and actual withdrawal by roots that penetrate to four-foot depths may range from 60% to 0% at 1 to 4 feet (G. W. Robertson 1964*). Seasonal variations are important because seedlings may wilt during early season droughts even though moisture may be present at slightly greater depth. The time and amount of recharge is included in the calculations based upon Thornthwaite procedures.

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* In a seminar in the Soil Science Department, University of Alberta, Edmonton.

If we recognize that many local and regional exceptions are present because of variations in soil, plant cover and recharge patterns, we might suggest that water storage available to plants in the prairies might vary approximately as follows:

WATER STORAGE CAPACITIES
(in inches)

	Cereals (annual)	Forage Crops (perennial)	Forest Trees (early maturity)
Sand	1	2	6
Sandy Loam	2	4	8
Loam and Silt Loam	3	7	11
Clay Loam	4	8	12
Clay	5	8	11

In general, the greater depth of rooting in the course and medium-textured soils only partly compensates for the greater retention-storage capacity of the clay.

Regional patterns are very complex and only some of the more general pattern variations need be noted. The drier parts of the Prairies tend to have relatively low soil-moisture storage because of the limited recharge, the low organic matter and sometimes high salt contents of the soil and also because the sparse cover has an incomplete and shallow root occupance of the soil. The black soils have better recharge, humus content, fertility, plant cover and root occupance, and are less likely to be solonetzic. The grey-wooded and podsol soils tend to have still better recharge, less humus and clay in surface horizons, and a more complete root occupance to greater depths, although widespread fires in the recent past have resulted in much of the cover being relatively young with variable rooting patterns. Widespread muskeg areas with impeded drainage have large use of surface-detention storage and groundwater, and rock areas have very limited storage. Clay plains are more widespread in the eastern and northwestern plains than in the southwest. Sand plains are less extensive but they tend to be more widespread in the east and northwest. The till plains are widespread but many of the tills, except for those near the Shield, in the Rocky Mountains and Foothills are high in clay content.

The complexity of soil moisture storage patterns is such that general maps for a wide range of storage values, e.g. $\frac{1}{2}$, 1, 2, 4, 6, 8 and 12 inches might be most useful. The appropriate map for a particular soil and plant-cover combination might then be selected. In the future, more detailed maps showing local patterns of moisture storage capacity for specific soil depths and crops may be available.

APPENDIX C

A COMPARISON OF CLIMATIC PATTERNS AT SELECTED LOCATIONS WITH PRESENT AND PROJECTED IRRIGATION PROJECTS*

	VAUXHALL	LETHBRIDGE	MEDICINE HAT	STRATHMORE	HANNA	BROOKS	OUTLOOK	SASKATOON
	21 years	29 years	30 years	15 years	21 years	26 years	28 years	30 years
Growing Season	151.8	167.8	173.6	152.6	150.4	156.0	153.9	146.7
Degree Days	6286	6584	7303	5947	5637	6532	6401	5908
Consumptive Use	21.7	22.5	23.8	21.3	20.7	22.3	22.1	21.1
Deficiency (Lowry-Johnson)	13.9	12.7	16.1	11.0	12.0	14.5	14.4	12.4
Deficiency (" " - Thornthwaite)	11.7	9.5	14.1	8.1	9.1	12.1	12.3	9.3
Potential Evapotranspiration	22.6	22.7	24.3	22.1	21.4	22.4	22.6	21.6
Average Deficiency	10.7	7.9	11.5	7.6	8.1	10.7	11.3	8.0
Maximum Deficiency	15.6	13.0	16.4	12.3	15.1	15.5	15.0	13.5
Minimum Deficiency	0.9	2.7	0.4	2.4	2.3	3.1	5.7	2.0
Lower Quartile	9.3	5.7	9.3	5.5	5.9	7.7	10.0	6.3
Upper Quartile	12.5	10.8	13.9	9.7	9.5	12.8	13.2	10.8

* Based on Laycock 1959b.

** 1. Growing Season - calculated using Lowry-Johnson procedure (1941)
2. Degree Days - " " " " " (using maximum temperatures)
3. Consumptive Use- " " " " " (see Fig. 31)
4. Deficiency - " " " " " (see Fig. 32)
5. Deficiency - " " " " " plus Thornthwaite procedures in determining soil-moisture storage in spring (see Fig. 33)
6. Potential Evapotranspiration - calculated using Thornthwaite procedure (1948) (see Fig. 2)
7. Average Deficiency - " " " " (see Fig. 3)
8. Maximum Deficiency - " " " " (see Fig. 7)
9. Minimum Deficiency - " " " " (see Fig. 8)
10. Lower Quartile Deficiency - " " " " (see Fig. 9)
11. Upper Quartile Deficiency - " " " " (see Fig. 10)

SELECTED BIBLIOGRAPHY

1. Ackerman, E. A., "Technology in American Water Development," John Hopkins Press, 1959, 710 pp.

2. Alberta Department of Agriculture, Colonization Branch, "Farm Irrigation Brochure", prepared for District Agriculturists Tour, July, 1962, Lethbridge, 96 pp.

3. Atlas of Alberta Committee, "Atlas of Alberta." Preliminary maps and graphs to be included in the Atlas which is to be published in 1967 by the University of Alberta and the Alberta Department of Lands and Forests.

4. Baier, W., "The Interrelationship of Meteorological Factors, Soil Moisture and Plant Growth," (a Review), Symposium on Water and Climate, Saskatoon, November, 1964, Ag. Met. Tech. Bull. 5, Ottawa, 39 pp.

5. Berry, W. M. and W. Stichling, "Evaporation from Lakes and Reservoirs in the Northern Plains Region of North America, "International Union of Geodesy and Geophysics, General Assembly at Rome, 1954, Tome III, pp. 121-134.

6. Bird, Ralph D., "Ecology of the Aspen Parkland of Western Canada in Relation to Land Use", Canada Department of Agriculture Publication 1066, Ottawa, 1961, 155 pp.

7. Blaney, H. F. and W. D. Criddle, "Determining Water Requirements in Irrigated Areas from Climatological and Irrigation Data," (Revision), 1952, United States Department of Agriculture SCS-TP96, Washington, D. C., 48 pp.

8. Borchert, J. R., "The Climate of the Central North American Grassland", Annals of the Assn. of American Geographers Vol. XL, March 1950, pp. 1-39.

9. Bracken, John, "Dry Farming in Western Canada", The Grain Growers Guide, Winnipeg, 1921, 386 pp.

10. Canada Department of Agriculture, Prairie Farm Rehabilitation Administration, "Handbook for the Classification of Irrigated Land in the Prairie Provinces," Regina, Saskatchewan, 1964, 92 pp.

11. Canada Department of Agriculture, Prairie Farm Rehabilitation Administration, Engineering Service, Hydrology Division, "Full Development Possibilities in the Saskatchewan River Basin", Regina, 1952, 44 pp. Report No. 1.

12. Canada Department of Agriculture, Prairie Farm Rehabilitation Administration, Engineering Service, Hydrology Division, "Water Supply and Utilization in the Bow River Watershed", Regina, 1955, 50 pp. Report No. 9.

13. Canada Department of Agriculture, Soil Research Laboratory, Swift Current, "Soil Moisture, Wind Erosion and Fertility of Some Canadian Prairie Soils", Publication 819 Technical Bulletin 71. Ottawa, June, 1949. 78 pp.

14. Canada Department of Agriculture Committee, "Handbook for the Classification of Irrigated Land in the Prairie Provinces", PFRA, Regina, June, 1964. 92 pp.

15. Canada Department of Mines and Technical Surveys, Geographical Branch, "Atlas of Canada", Ottawa, 1957, 110 plates.

16. Canada Department of Northern Affairs and National Resources, Water Resources Branch, "Water Resources Papers, Arctic and Western Hudson Bay Drainage", 1920-1963. (Note: These have been supplemented by station summaries and more recent data from the Calgary Office.)

17. Canada Department of Transport, Meteorological Branch, "Monthly Record", Monthly for the Period 1920-1965, Toronto.

18. Chapman, L., "Agro-Climatological Maps for Canada", Preliminary maps prepared for ARDA by the Ontario Research Foundation, Toronto, 1965, Ozalid 15 pp.

19. Colman, E. A., "Soil Surveying on Wildlands: The Problem and One Solution," Journal of Forestry, Vol. 46, No. 10, October, 1948, pp. 755-762.

20. Colman, E. A., "Vegetation and Watershed Management", Ronald Press, N. Y., 1953, 412 pp.

21. Connor, A. J., "The Temperature and Precipitation of Alberta, Saskatchewan and Manitoba", Meteorological Service, Ottawa, 1933, 170 pp.

22. Connor, A. J., "Droughts in Western Canada", The Canada Yearbook, Dominion Bureau of Statistics, 1933 pp. 47-59.

23. Currie, B. W., 1953, "Precipitation, Prairie Provinces and Northwest Territories", Saskatchewan Research Council, Saskatoon, Saskatchewan, 63 pp. (Note: Others in the series - "Temperature", "Snowfall", "Vegetative and Frost-Free Seasons", "Wind and Storms", "Ice and Soil Temperatures" are still useful.)

24. Dionne, J. L., Robertson, G. W. and R. M. Holmes, "Agricultural Meteorology, A Brief Literature Review and Bibliography", Canada Department of Agriculture, Experimental Farms Service, Ottawa, 1956, 59 pp.

25. Duffy, P. J. B., "Relationships between Site Factors and Growth of Lodgepole Pine in the Foothills Section of Alberta", Canada Department of Forestry Publication No. 1065, Ottawa, 1964, 60 pp.

26. Foster, J. W. and R. N. Farbolden, "A General Outline of Groundwater Conditions in the Alberta Plains Region," Alberta Research Council, Government of Alberta, Edmonton, 1958, 35 pp.

27. Fryers, W., "A Map of Prairie Precipitation Patterns", prepared for Canada Department of Agriculture, Prairie Farm Rehabilitation Administration, Regina, 1956, Unpublished.

28. Held, Clawson, Marion and Burnell, "The Federal Lands: Their Use and Management", Resources for the Future, Johns Hopkins Press 1957, 501 pp.

29. Hind, Henry Y., "British North America" Eyre and Spottiswoode, London, England, 1860, 219 pp.

30. Holmes, R. M. & G. W. Robertson, "Heat Units and Crop Growth", Canada Department of Agriculture, Experimental Farms Service Publication 1042, Ottawa, 1959, 31 pp.

31. Holmes, R. M. & G. W. Robertson, "A Modulated Soil Moisture Budget," Reprint from the Monthly Weather Review Vol. 87, No. 3, March, 1959, 7 pp.

32. Hope, E. C., "Weather and Crop History in Western Canada," C.S.T.A., March, 1938. pp. 347-58.

33. International Association of Scientific Hydrology, "Proceedings, General Assembly of Toronto", September 3-14, 1957. Publication No. 45 Gentbrugge, Belgium, 1958. 596 pp.

34. International Association of Scientific Hydrology, "Proceedings, General Assembly of Helsinki", July 25 - August 6, 1960. Publication No. 51 Gentbrugge, Belgium, 1960. 628 pp.

35. International Association of Scientific Hydrology, "Proceedings, General Assembly of Berkeley," August 19-31, 1963. Publication No. 62 and No. 63, Gentbrugge, Belgium, 1963. 304 and 615 pp.

36. Jacobson, W. L., "Irrigation on the Canadian Prairies," Appendix, Report of the Royal Commission on the South Sask. River Project, Ottawa, 1952. pp. 278-285.

37. Kendrew, W. G. and B. W. Currie, "The Climate of Central Canada," Queen's Printer, Ottawa, 1955, 194 pp.

38. Koeppe, Clarence E., "The Canadian Climate," McKnight and McKnight, Bloomington, Ill., 1931, 280 pp.

39. Laycock, A. H., "Soil and Watershed Survey Reports 1952, 1953, and 1954," Eastern Rockies Forest Conservation Board, Calgary, (Typewritten), pp. 73, 80 and 41.

40. Laycock, A. H., "A Physiographic Classification of Soils for Land Use Planning on the Eastern Slopes of the Canadian Rockies," Ph. D. Thesis, University of Minnesota, 1957. Typewritten and microfilm, 453 pp.

41. Laycock, A. H., "Precipitation and Streamflow in the Mountain and Foothill Regions of the Saskatchewan River Basin, "Prairie Provinces Water Board Report No. 6, Regina, January, 1957, 47 pp.

42. Laycock, A. H. "Water", Proceedings, First Alberta Resources Conference, January, 1959, Department of Lands and Forests, Edmonton, 12 pp.

43. Laycock, A. H. "Drought Patterns in the Canadian Prairies," Proceedings Helsinki Congress, August, 1960, Publication No. 51, International Association of Scientific Hydrology, Lanvain, pp. 34-47.

44. Laycock, A. H. "Local Water Supplies in the Prairies," address to the Canadian Association of Geographers, Saskatoon, Saskatchewan, May 27, 1959. Multilith, 15 pp.

45. Laycock, A. H. "Geographic Aspects of Water and Climate," Proceedings Symposium on Water and Climate, Saskatoon, November, 1964. Saskatchewan Water Studies Institute, Saskatoon, 1965, pp. 1-20.

46. Laycock, A. H. "The Need for a Regional Approach in Watershed Management Planning," Proceedings First Annual Meeting, American Water Resources Association, Chicago, December 1965, A.W.R.A., Urbana, Ill. 1965, pp. 146-154.

47. Laycock, A. H., "Summerfallowing as a means of Moisture Conservation in the Prairie Provinces", paper at the Annual Meeting, Canadian Association of Geographers, Montreal, June, 1961. Mimeo. 10 pp.

48. Laycock, A. H., "Soil Surveying in Mountain Watersheds: The Problem and One Solution," paper at the Annual Meeting, Association of American Geographers, Santa Monica, August, 1958. Mimeo. 8 pp.

49. Laycock, A. H., "The Climate of the Bow River Project Area: Regional Comparisons and Local Variations," Report for Dr. C. C. Spence, 1959 (b) Mimeo. 5 pp.

50. Lissey, A., "Hydrogeology of the Regina Aquifer, Saskatchewan," N.R.C. Symposium on Groundwater, Calgary, 1962. Ottawa, 1963. pp. 303-333.

51. Longley, R. W., "Variability of Annual Precipitation in Canada," Monthly Weather Review, Vol. 81, 1953. pp. 131-134.

52. Lowry, R. L. and A. F. Johnson, "Consumptive Use of Water for Agriculture", Proceedings American Society of Civil Engineers, Vol. 67, 1941, pp. 595-616.

53. McKay, G. A., "A Detailed Map of Prairie Average Annual Precipitation", Canada Department of Transport, Meteorological Branch, CIR-3519, TEC-365, 1961.

54. McKay, G. A., "Climatic Maps of the Prairie Provinces for Agriculture", Climatological Studies No. 1, Meteorological Branch, Toronto, 1965, 20 pp.

55. McKay, G. A., G. E. Curry and A. S. Mann, "Climatic Records for the Saskatchewan River Headwaters," East Slopes Watershed Research Program, Calgary, 1963, 82 pp.

56. Macoun, John, "Manitoba and the Great North-West," World Publishing Co., Guelph, Ontario, 1882, 687 pp.

57. Manning, Travis W. (ed.), "Proceedings, Irrigation Economics Conference," University of Alberta, Edmonton, June, 1964; Canada Department of Agriculture; Alberta Department of Agriculture; Canada Department of Forestry; and the University of Alberta; 72 pp.

58. Mather, John R. (ed.), "The Measurement of Potential Evapotranspiration," The John Hopkins University Laboratory of Climatology, Publications in Climatology, Vol. VII, No. 1, Seabrook, N. J., 1954, 225 pp.

59. Mather, John R. (ed.), "The Moisture Balance in Grassland Climatology in Grasslands," American Assoc. for the Advancement of Science, 1959 pp. 251-61.

60. Mathews, O. R., "Place of Summer Fallow in the Agriculture of the Western States," United States Department of Agriculture Circular No. 886, Nov. 1951, 17 pp.

61. Meyboom, P., "Patterns of Groundwater Flow in the Prairie Profile," N.R.C. Symposium on Groundwater, Calgary, 1962. Ottawa, 1963. pp. 5-33

62. Michalyna, W. and R. A. Hedlin, "A Study of Moisture Storage and Nitrate Accumulation in Soil, as related to Wheat Yields on Four Cropping Sequences". Can. Journal of Soil Science, Vol. 45, 1961. pp. 5-15.

63. Mohrmann, J. C. J. and J. Kessler, "Water Deficiencies in European Agriculture - A Climatological Survey," International Institute for Land Reclamation and Improvement Publication No. 5, Wageningen, Netherlands, 1959, 60 pp.

64. Moss, E. H., "The Vegetation of Alberta," The Botanical Review Vol. 21, No. 9, November, 1955, pp. 493-567.

65. Moss, E. H., "The Vegetation of Alberta, Part IV," Journal of Ecology, Vol. 20, 1932, pp. 380-415.

66. Moss, E. H., "The Vegetation of Alberta," The Botanical Review, Vol. 21, No. 9, Nov. 1955. pp. 493-567.

67. Muttit, G., "Spring and Summer Rainfall Patterns in Alberta," Meteorological Branch Circular 3589, 1962, 22 pp.

68. National Research Council, Subcommittee on Hydrology, "Proceedings of Hydrology Symposium No. 2 - Evaporation," held in Toronto, March, 1961, Water Resources Branch, Ottawa, 1962, 263 pp.

69. National Research Council, Subcommittee on Hydrology, "Proceedings of Hydrology Symposium No. 3 - Groundwater," held in Calgary, November, 1962, published by Water Resources Branch and Geological Survey of Canada, Ottawa, 1963, 394 pp.

70. National Research Council, Subcommittee on Hydrology, "Proceedings of Hydrology Symposium No. 4 - Research Watersheds," "Proceedings held in Guelph, May, 1964, Water Resources Branch, Ottawa, 1965, 321 pp.

71. Palliser, John, "Exploration, British North America," Eyre & Spottiswoode, London, England, 1863, 325 pp.

72. Penman, H. L., "Natural Evaporation from Open Water, Bare Soil and Grass," Proceedings Royal Society of London, Series 193A, 1948, pp. 120-145.

73. Penman, H. L. "Vegetation and Hydrology," Technical Communication No. 53, Commonwealth Bureau of Soils, Commonwealth Agricultural Bureau, 1961, Farnham Royal, Bucks, England, 124 pp.

74. Prairie Provinces Water Board, "Preliminary Report on an Integrated Basin Plan for the Saskatchewan River Basin and the Nelson River," "Appendix XIII annotated Bibliography," Regina, 1960. pp. 48-83.

75. Robertson, G. W. and R. M. Holmes, "Estimating Irrigation Water Requirements from Meteorological Data," Research Branch, Canada Department of Agriculture, Publication 1054, Ottawa, 1959, 11 pp.

76. Robertson, G. W., "A Summary of Literature Pertaining to Latent Evaporation and its Application to Soil Moisture Estimation and Irrigation Scheduling," Canada Department of Agriculture, AG. Meteor. Technical Bulletin No. 3, 1964.

77. Roe, H. G., "Moisture Requirements in Agriculture," McGraw-Hill, 1950, 413 pp.

78. Russel, B., "Report on Surface Water Supplies and Water Power of Alberta, Their Present and Ultimate Uses," Alberta Department of Agriculture, Water Resources Division, Edmonton, 1948, 95 pp.

65. Moss, E. H., "The Vegetation of Alberta, Part IV," Journal of Ecology, Vol. 20, 1932, pp. 380-415.

66. Moss, E. H., "The Vegetation of Alberta," The Botanical Review, Vol. 21, No. 9, Nov. 1955, pp. 493-567.

67. Mattit, G., "Spring and Summer Rainfall Patterns in Alberta," Meteorological Branch Circular 3585, 1962, 22 pp.

68. National Research Council, Subcommittee on Hydrology, "Proceedings of Hydrology Symposium No. 2 - Evaporation," Held in Toronto, March, 1961, Water Resources Branch, Ottawa, 1962, 26 pp.

69. National Research Council, Subcommittee on Hydrology, "Proceedings of Hydrology Symposium No. 3 - Groundwater," Held in Calgary, November, 1962, published by Water Resources Branch and Geological Survey of Canada, Ottawa, 1963, 394 pp.

70. National Research Council, Subcommittee on Hydrology, "Proceedings of Hydrology Symposium No. 4 - Research Watersheds," Proceedings held in Guelph, May, 1964, Water Resources Branch, Ottawa, 1965, 321 pp.

71. Palliser, John, "Exploration, British North America," Eyre & Spottiswoode, London, England, 1859, 325 pp.

72. Penman, H. L., "Natural Evaporation from Open Water, Bare Soil and Grass," Proceedings Royal Society of London, Series 193A, 1948, pp. 120-145.

73. Penman, H. L., "Vegetation and Hydrology," Technical Communication No. 53, Commonwealth Bureau of Soils, Commonwealth Agricultural Bureau, 1961, Farnham Royal, Bucks, England, 124 pp.

74. Prairie Provinces Water Board, "Preliminary Report on an Integrated Basin Plan for the Saskatchewan River Basin and the Nelson River," "Appendix XIII Annotated Bibliography," Regina, 1960, pp. 88-89.

75. Robertson, G. W. and R. M. Holmes, "Estimating Irrigation Water Requirements from Meteorological Data," Research Branch, Canada Department of Agriculture, Publication 1054, Ottawa, 1959, 11 pp.

76. Robertson, G. W., "A Summary of Literature Pertaining to Latent Evaporation and its Application to Soil Moisture Estimation and Irrigation Scheduling," Canada Department of Agriculture, Ag. Meteor. Technical Bulletin No. 7, 1964.

77. Roe, H. G., "Moisture Requirements in Agriculture," McGraw-Hill, 1950, 413 pp.

78. Russel, G., "Report on Surface Water Supplies and Water Power of Alberta, Their Present and Ultimate Uses," Alberta Department of Agriculture, Water Resources Division, Edmonton, 1948, 95 pp.

79. Sanderson, M., "The Climates of Canada According to the New Thornthwaite Classification," Scientific Agriculture Vol. 28, No. 11, 1948, pp. 601-517.

80. Sanderson, M., "Drought in the Canadian Northwest," Geographical Review Vol. XXXVIII No. , 1948, pp. 288-299.

81. Sauer, C. O., "A Geographic Sketch of Early Man in America," Geographical Review, Vol. 34 No. 4, October, 1944, pp. 529-573.

82. Sonmor, L. G., "Seasonal Consumptive Use of Water by Crops Grown in Southern Alberta and its Relationship to Evaporation," Canadian Journal of Soil Service Vol. 43, pp. 287-297.

83. Staple, W. J. and J. J. Lehane, "The Conservation of Soil Moisture in Southern Saskatchewan", Scientific Agriculture, Vol. 32, 1952. pp. 36-47.

84. Stichling, W. and S. R. Blackwell, "Drainage Area as a Hydrologic Factor in the Glaciated Canadian Prairies," I.A.S.H. Assembly, Toronto, 1957, Publ. 45, Gentbrugge, 1958. pp. 365-376.

85. Stupart, R. F., "The Canadian Climate", Report of the 8th International Geographic Congress, 1904. U.S. Government Printing Office, Washington, 1905, pp. 296-300.

86. Thomas, M. K., "Climatological Atlas of Canada", Meteorological Division, Department of Transport and Division of Building Research, National Research Council, Ottawa, 1953. 255 pp.

87. Thomson, A. and A. J. Connor, "The Climate of Canada,"Meteorological Division, Department of Transport, Toronto, 1949.

88. Thornthwaite, C. W., "An Approach Toward a Rational Classification of Climate," Geographical Review Vol. XXXVIII, No. 1, 1948, pp. 55-94.

89. Thornthwaite, C. W. and J. R. Mather, "The Water Balance," Drexel Institute of Technology, Laboratory of Climatology, Publications in Climatology, Vol. VIII, No. 1, Centerton, N. J., 1955, 104 pp.

90. Thornthwaite, C. W. and J. R. Mather, "Instructions and Tables for Computing Potential Evapotranspiration and the Water Balance," Drexel Institute of Technology, Laboratory of Climatology, Vol. X, No. 3, Centerton, N. J., 1957, pp. 185-311.

91. Toogood, J. A. and J. D. Newton, "Water Erosion in Alberta", Department of Extension, University of Alberta Bulletin No. 56, December, 1950, 39 pp.

92. U.S. Department of Agriculture, "Water," Yearbook of Agriculture, 1955, Washington, D. C., 751 pp.

93. van Hylckama, T., "The Water Balance of the Earth", Drexel Institute of Technology, Laboratory of Climatology, Publ. in Climatology Vol. 9, No. 2, Centerton, N. J., 1956, 117 pp.

94. Villmow, J. R., "The Nature and Origin of the Canadian Dry Belt," Annals of the Association of American Geographers, Vol. 46, No. 2, June, 1956 pp. 211-232.

95. Water Studies Institute, "Water and Climate," Proceedings of a Symposium held November 12 and 13, 1964, in Saskatoon, Saskatchewan. Saskatoon, 1965. 150 pp.

96. Watts, F. B., "The Natural Vegetation of the Southern Great Plains of Canada," Geographical Bulletin No. 14, 1960, pp. 25-43.

FIG -- I

HYD-A-1030

FIG — 2

HYD-A-1031

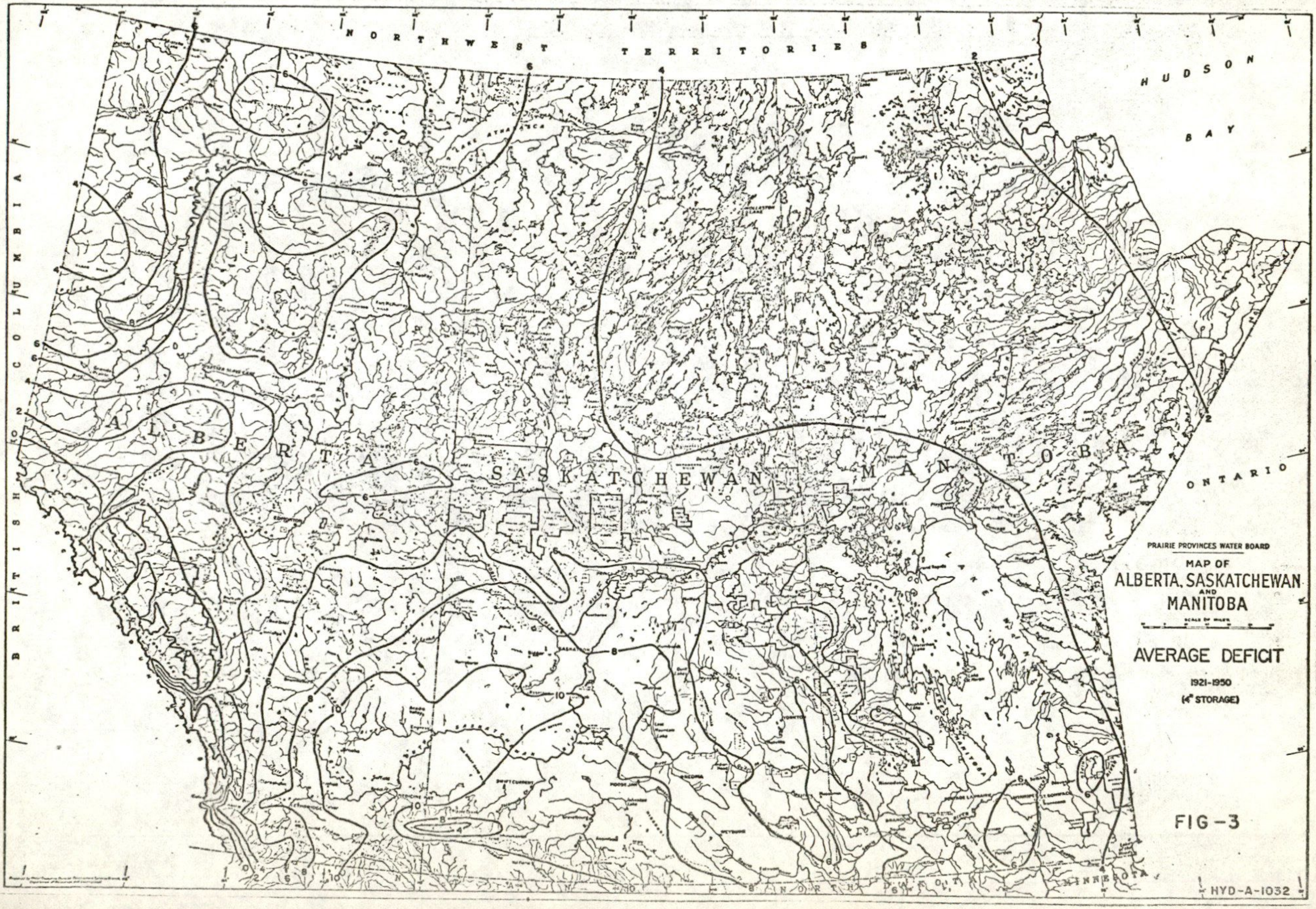
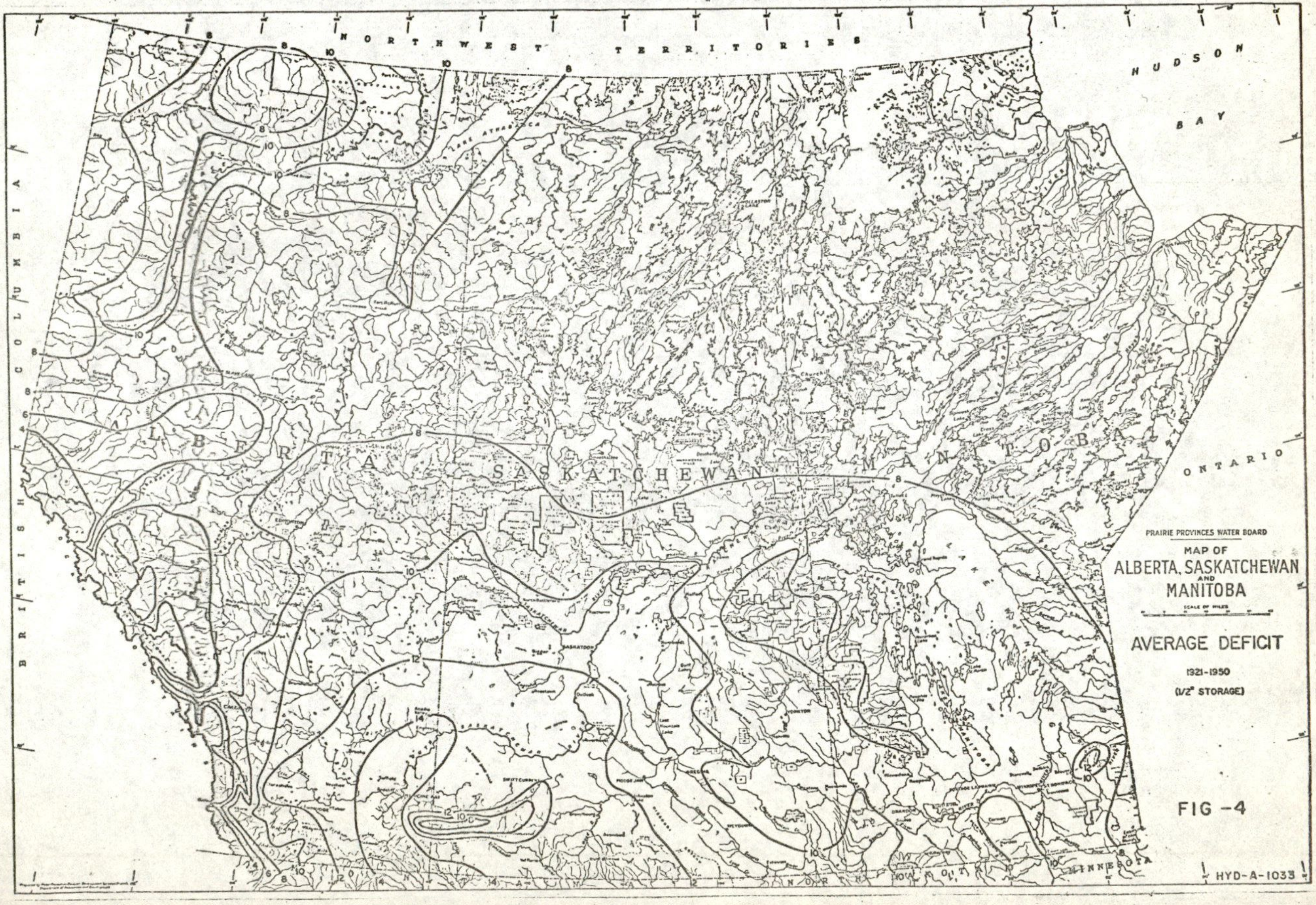

NORTHWEST TERRITORIES
HUDSON BAY
ONTARIO
BRITISH COLUMBIA
ALBERTA
SASKATCHEWAN
MANITOBA
NORTH
MINNESOTA
PRAIRIE PROVINCES WATER BOARD
MAP OF
ALBERTA, SASKATCHEWAN AND
MANITOBA
AVERAGE DEFICIT
1921-1950
(4" STORAGE)
HYD-A-1032

FIG-3



NORTHWEST TERRITORIES
HUDSON BAY
BRITISH COLUMBIA
ALBERTA
SASKATCHEWAN
MANITOBA
ONTARIO
MINNESOTA
NORTH DAKOTA
SASKATOON
SWIFT CURRENT
MOOSE JAW
YORKTON
EDMONTON
PRAIRIE PROVINCES WATER BOARD
MAP OF
ALBERTA, SASKATCHEWAN
AND
MANITOBA
SCALE OF MILES
AVERAGE DEFICIT
1921-1950
(1/2" STORAGE)
HYD-A-1033

FIG -4

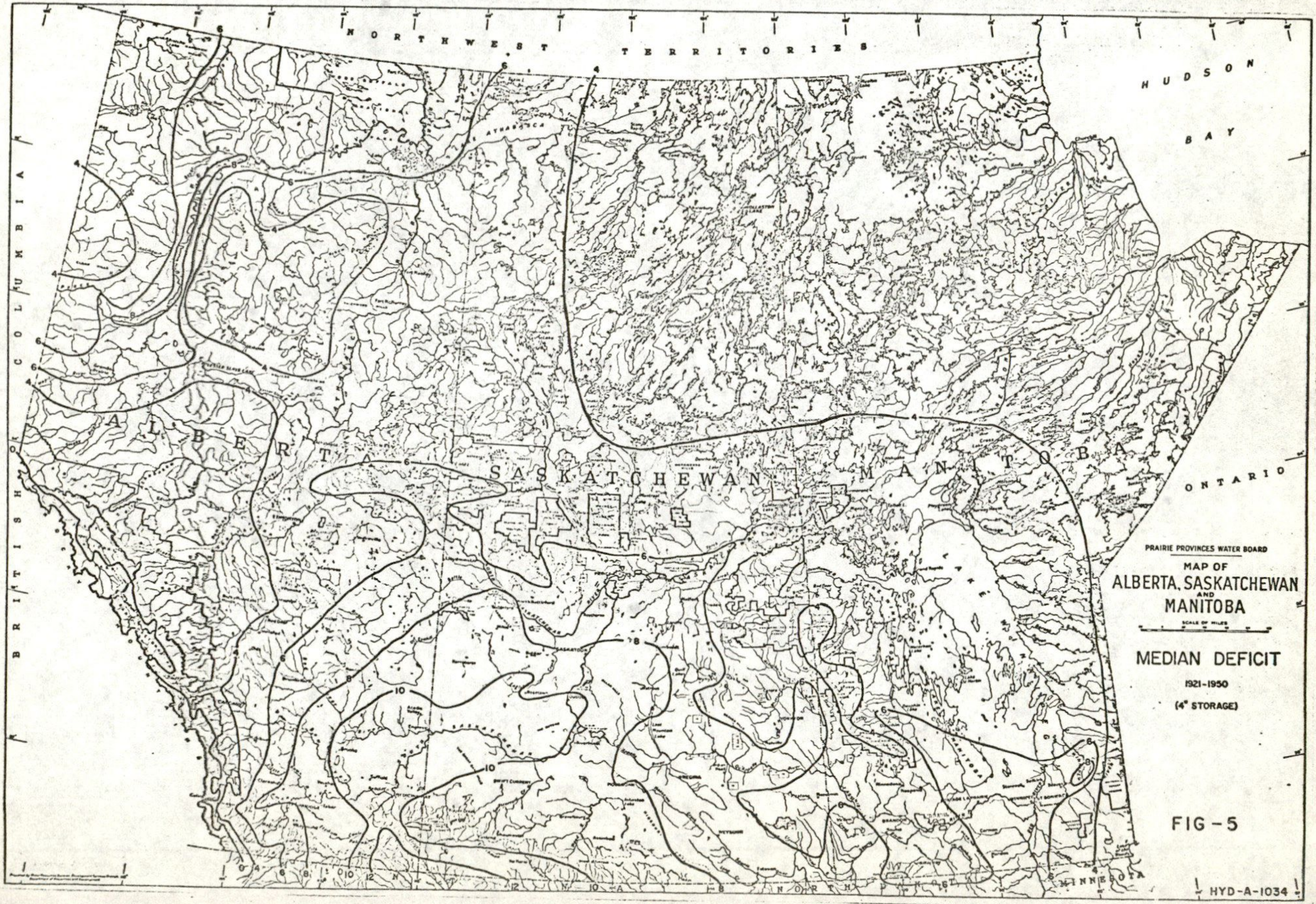


FIG - 5

HYD-A-1034

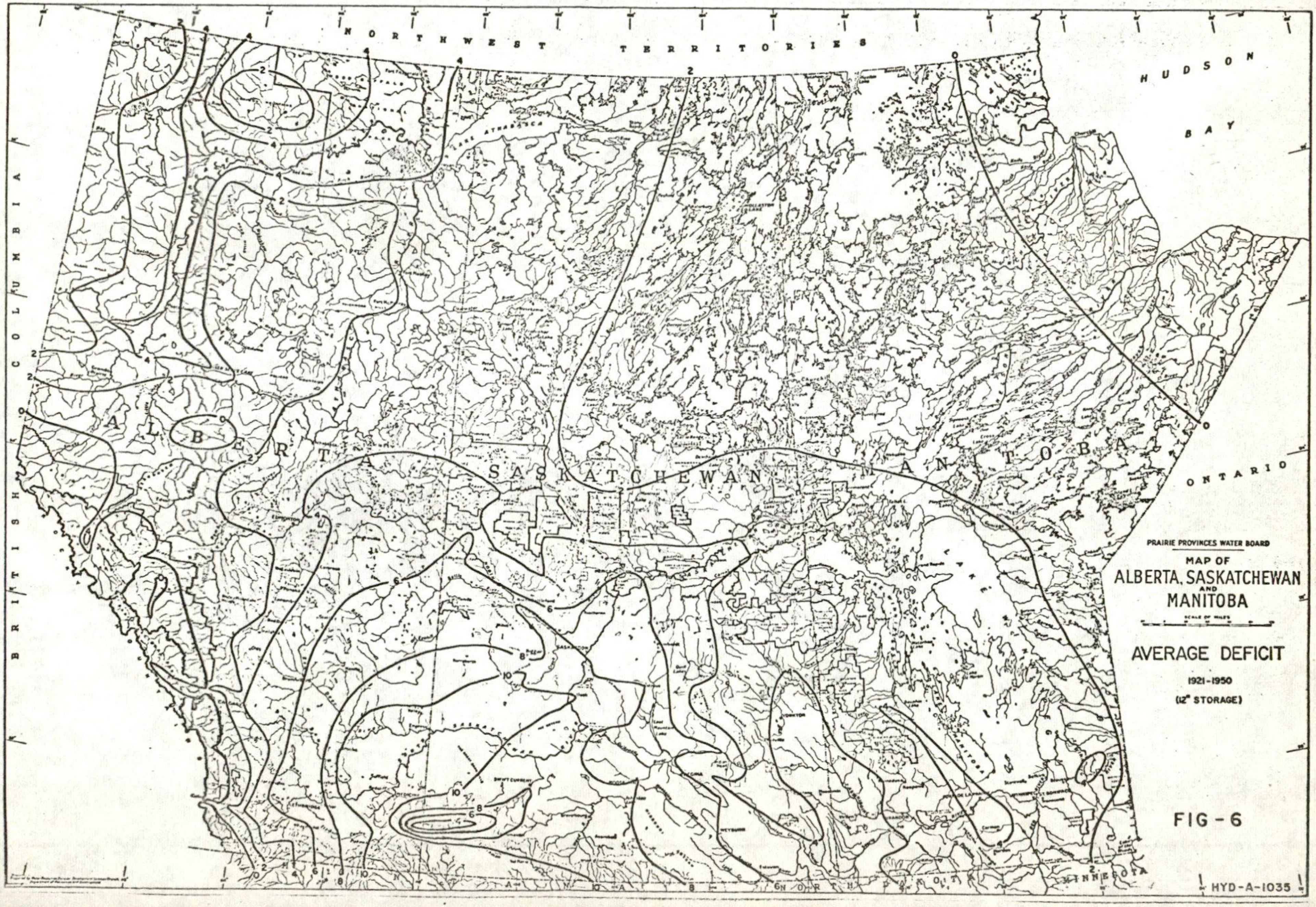
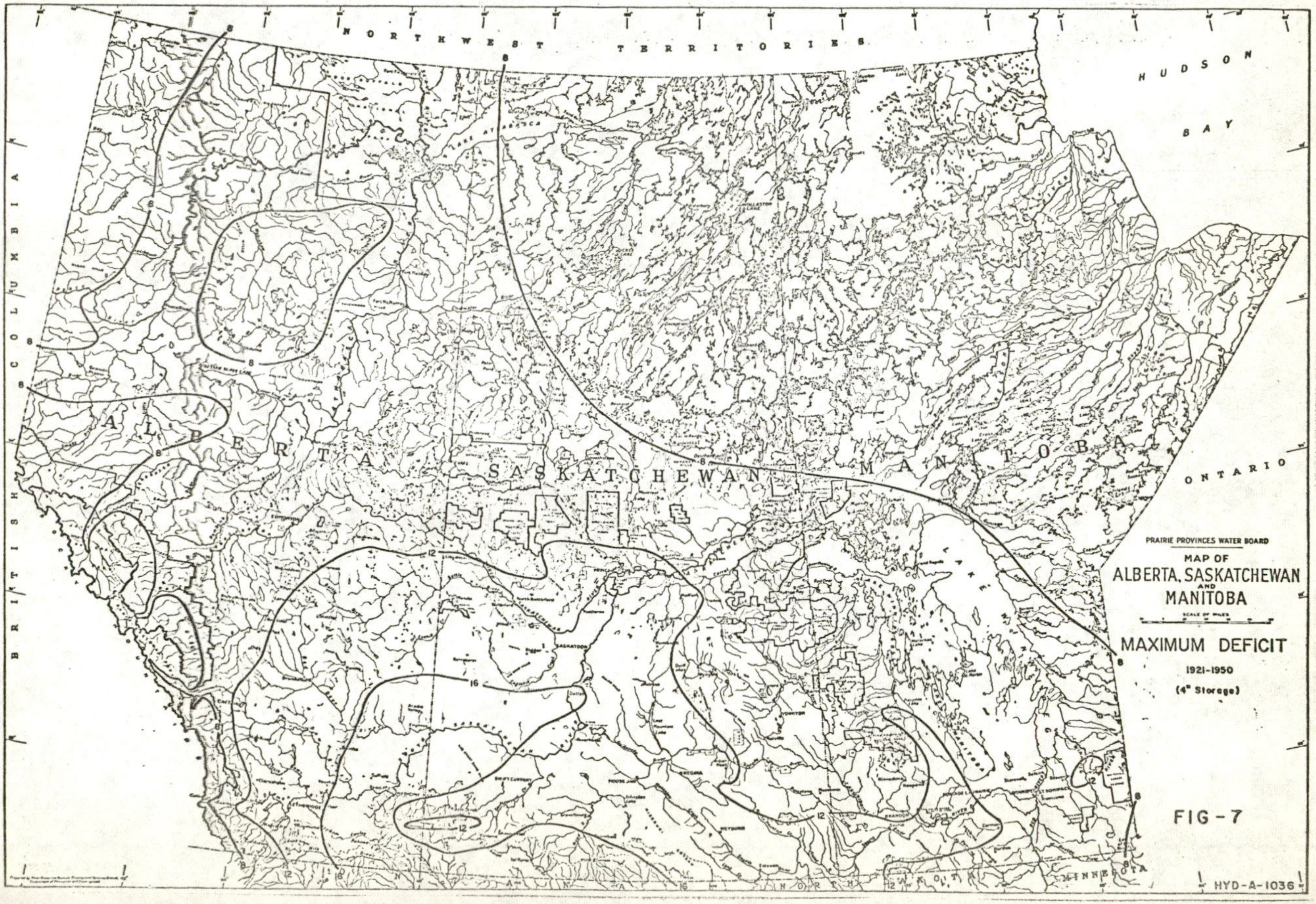


FIG - 6

HYD-A-1035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HUDSON BAY
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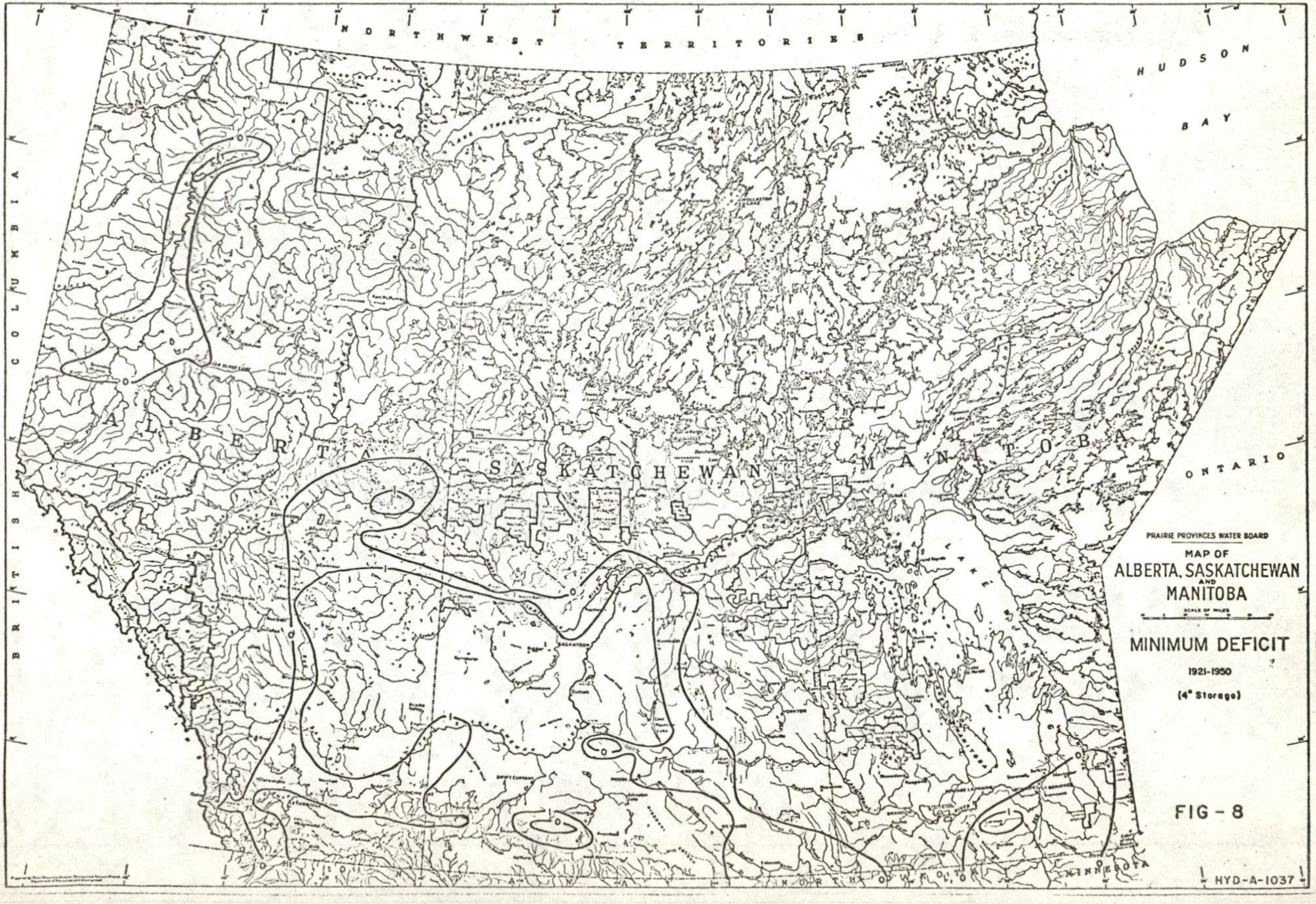
ALBERTA
SASKATCHEWAN
MANITOBA
ONTARIO
NORTH DAKOTA
MINNESOTA
PRAIRIE PROVINCES WATER BOARD
MAP OF
ALBERTA, SASKATCHEWAN AND MANITOBA
SCALE OF MILES
MAXIMUM DEFICIT
1921-1950
(4" Storage)
FIG - 7
HYD-A-1036



PRAIRIE PROVINCES WATER BOARD

MAP OF
ALBERTA, SASKATCHEWAN AND MANITOBA

SCALE OF MILES

MINIMUM DEFICIT
1921-1950
(4" Storage)

FIG - 8

HYD-A-1037


NORTHWEST TERRITORIES
HUDSON BAY
BRITISH COLUMBIA
ALBERTA
SASKATCHEWAN
MANITOBA
ONTARIO
LAKE WINNIPEG
MINNESOTA
PRAIRIE PROVINCES WATER BOARD
MAP OF
ALBERTA, SASKATCHEWAN
AND
MANITOBA
SCALE OF MILES
MOISTURE DEFICIT
LOWER QUARTILE
(1/4 OF THE YEARS HAVE
THIS DEFICIENCY OR LESS)
1921-1950
(4" Storage)
FIG-9
HYD-A-1038

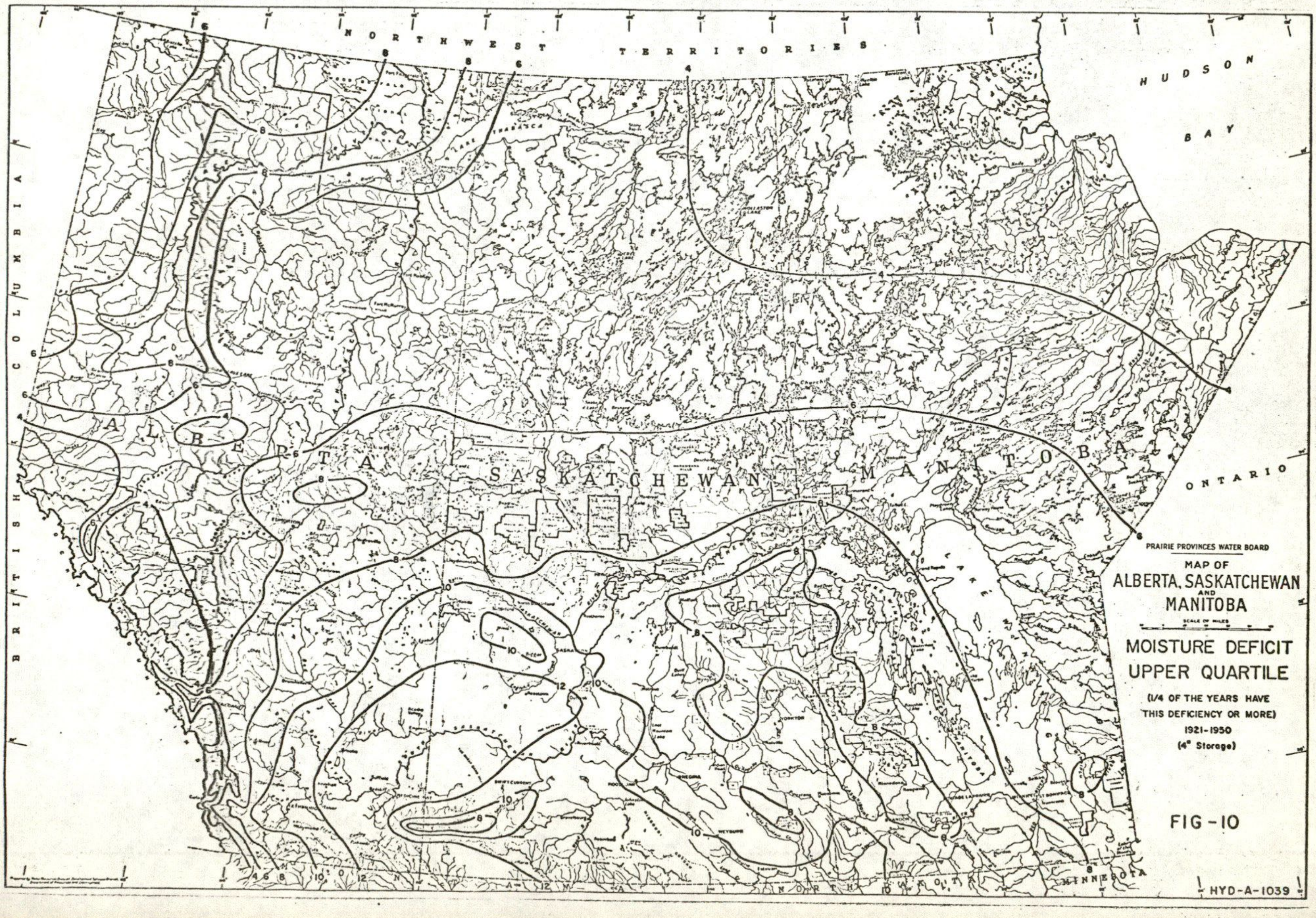


FIG - 10

HYD-A-1039

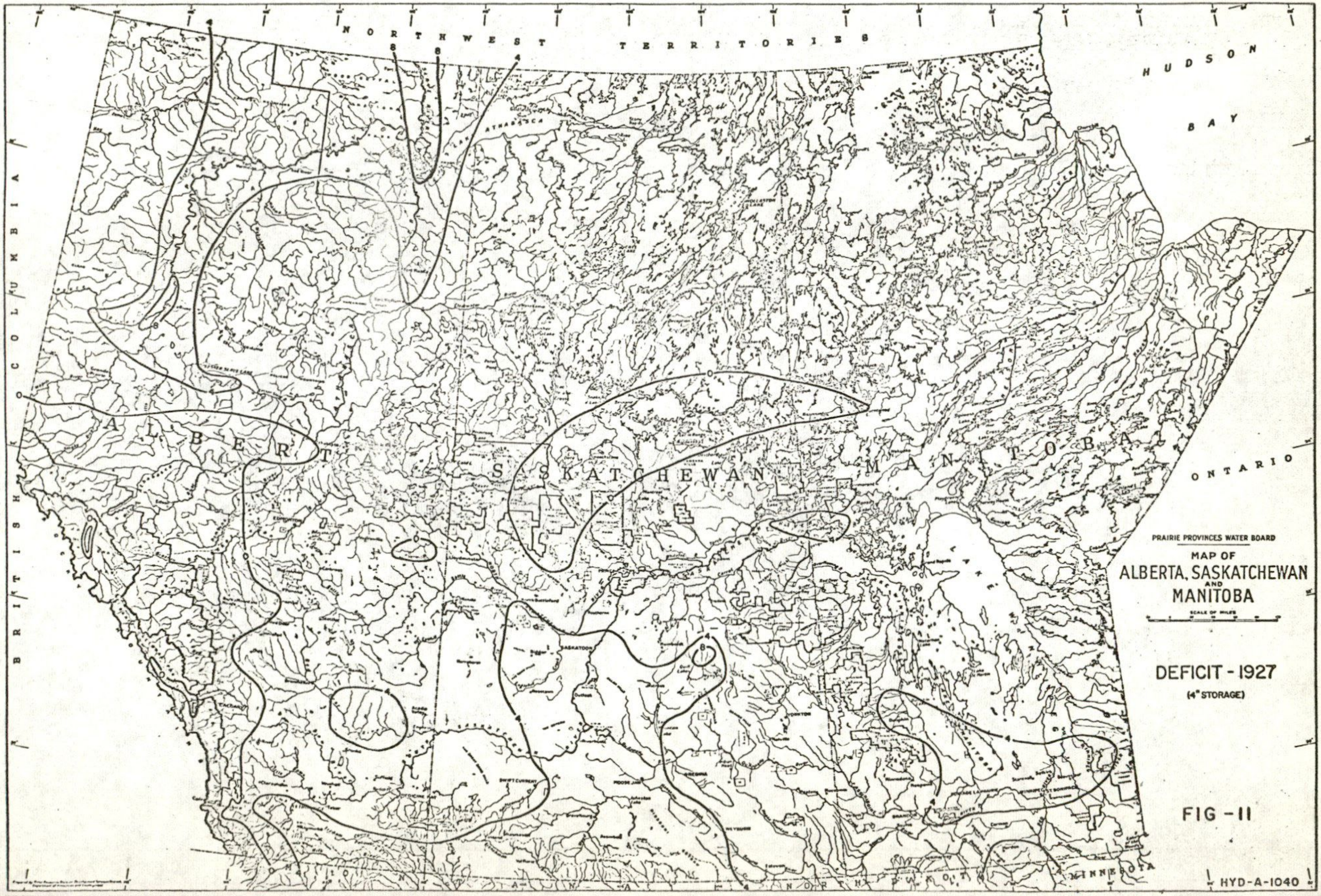
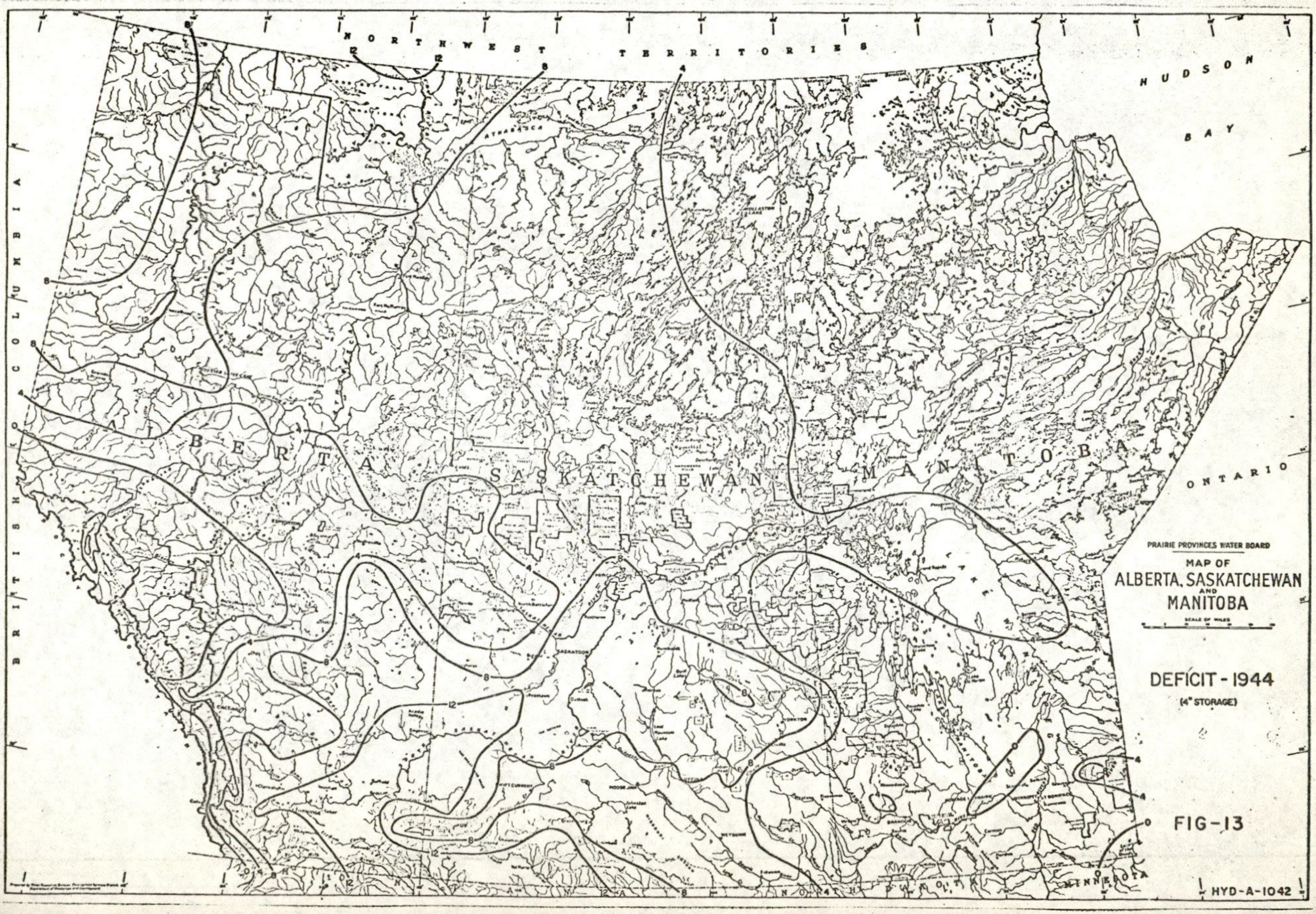


FIG - II

HYD-A-1040

FIG-12

HYD-A-1041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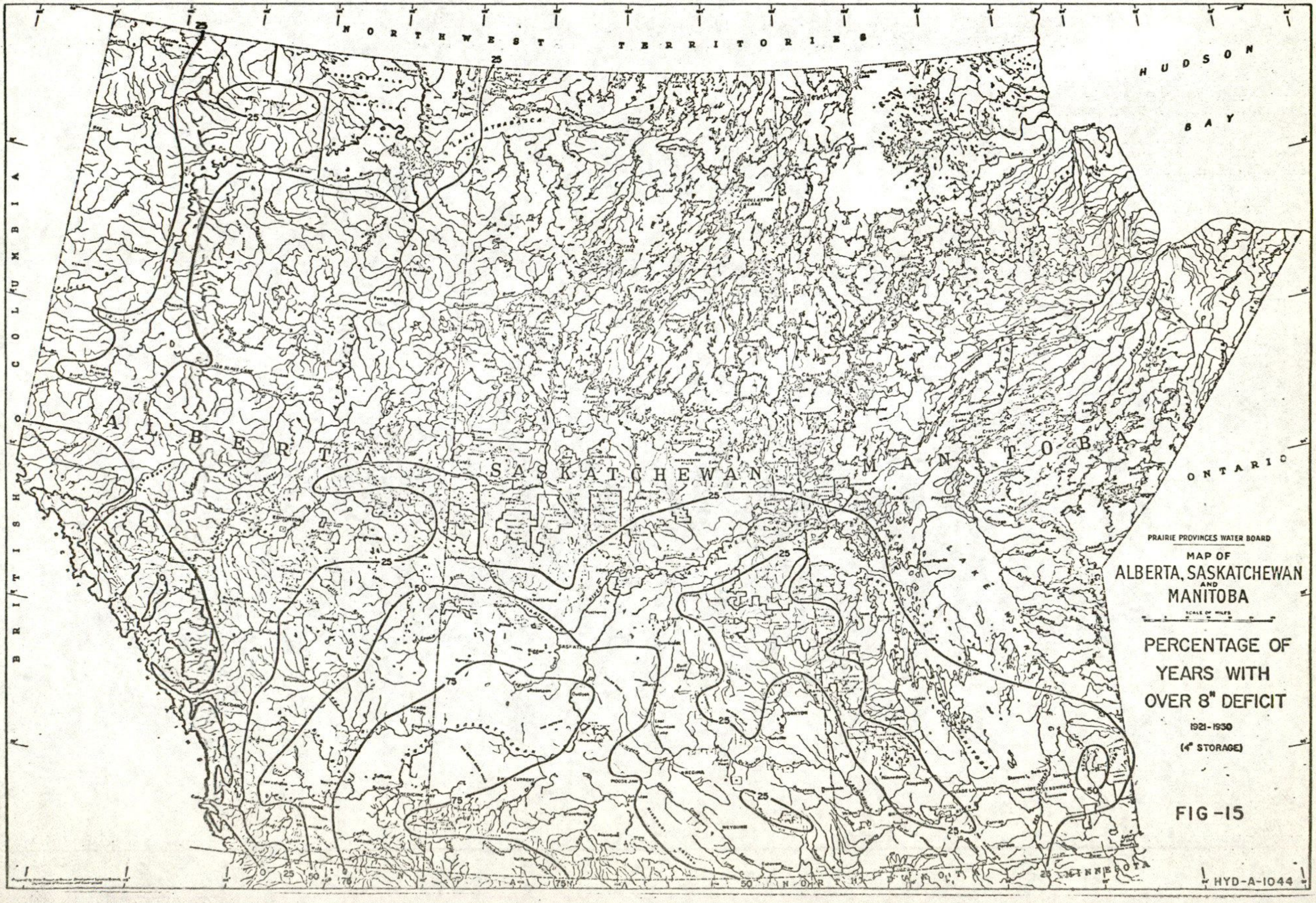
HUDSON BAY
BRITISH COLUMBIA
ALBERTA
SASKATCHEWAN
MANITOBA
ONTARIO
NORTH DAKOTA
MINNESOTA
SASKATOON
SWIFT CURRENT
MOOSE JAW
PRAIRIE PROVINCES WATER BOARD
MAP OF
ALBERTA, SASKATCHEWAN
AND
MANITOBA
SCALE OF MILES
DEFICIT - 1944
(4" STORAGE)
FIG-13
HYD-A-1042


NORTHWEST TERRITORIES
HUDSON BAY
BRITISH COLUMBIA
ALBERTA
SASKATCHEWAN
MANITOBA
ONTARIO
EDMONTON
SASKATOON
REGINA
CALGARY
MINNESOTA
PRAIRIE PROVINCES WATER BOARD
MAP OF
ALBERTA, SASKATCHEWAN
AND
MANITOBA
SCALE OF MILES
DEFICIT - 1950
(4" STORAGE)
FIG - 14
HYD-A-1043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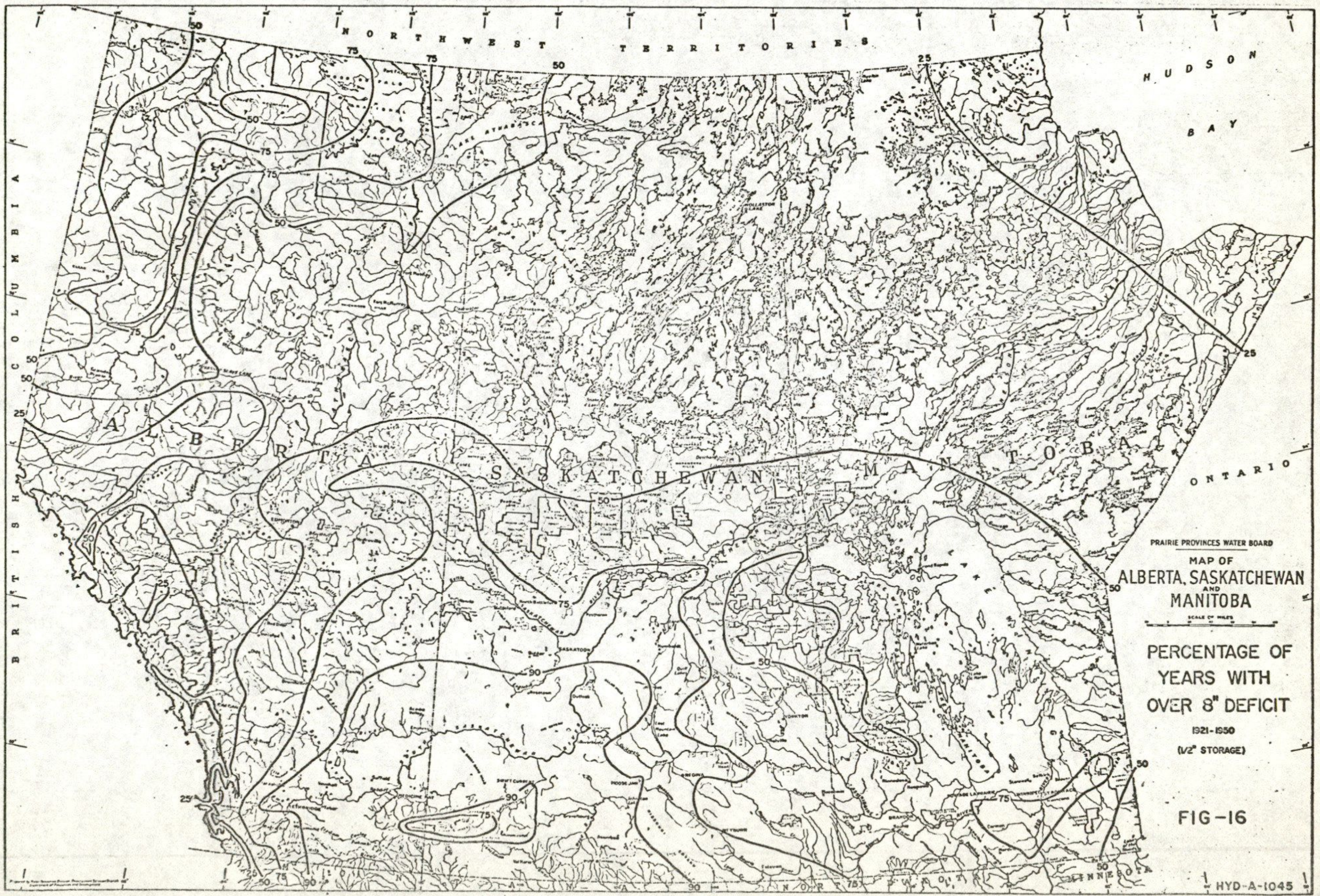
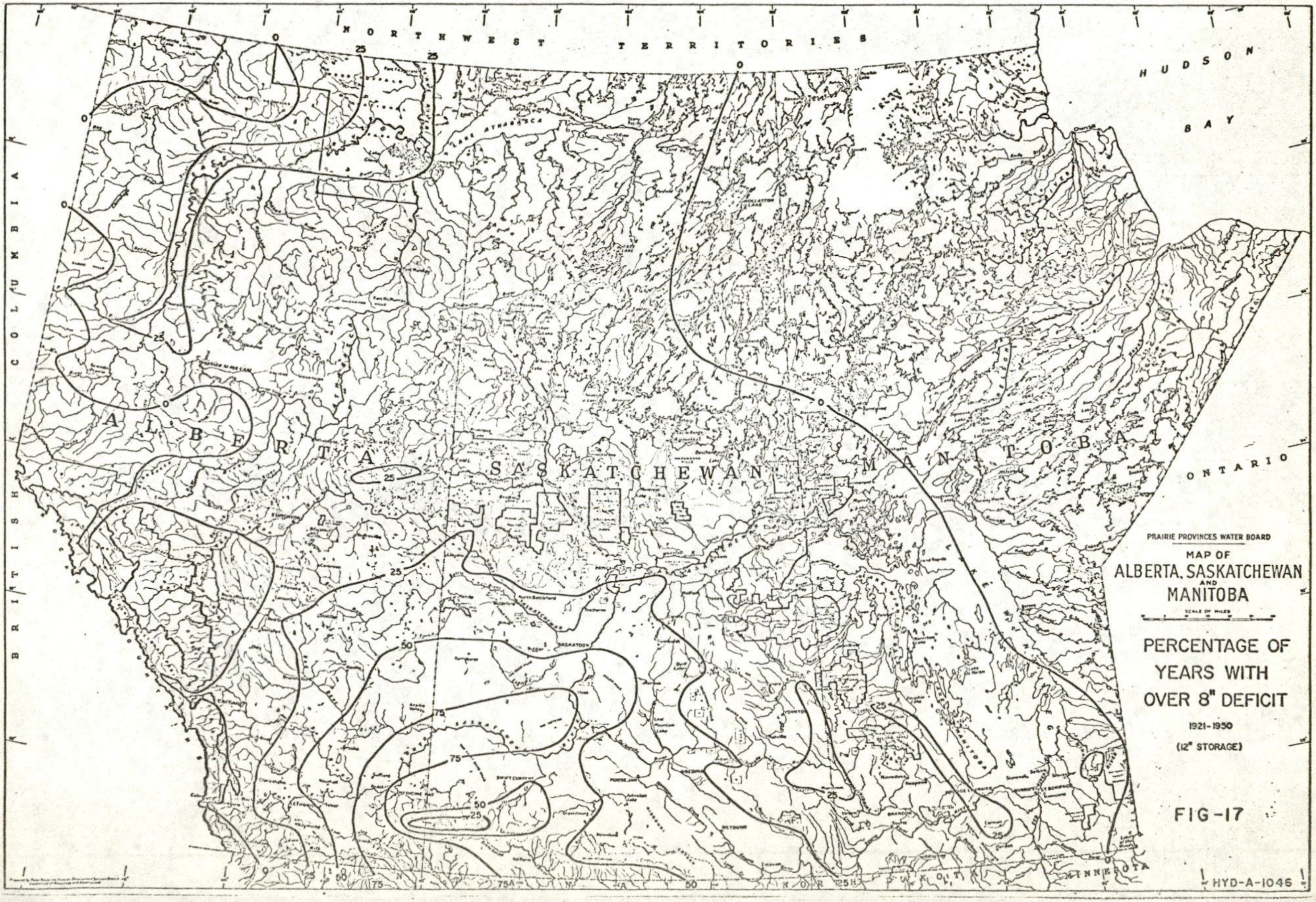
HUDSON BAY
BRITISH COLUMBIA
ALBERTA
SASKATCHEWAN
MANITOBA
ONTARIO
NORTH DAKOTA
MINNESOTA
25
50
75
PRAIRIE PROVINCES WATER BOARD
MAP OF
ALBERTA, SASKATCHEWAN
AND
MANITOBA
PERCENTAGE OF
YEARS WITH
OVER 8" DEFICIT
1921-1930
(4" STORAGE)
HYD-A-1044
FIG -15



NORTHWEST TERRITORIES
HUDSON BAY
ONTARIO
BRITISH COLUMBIA
ALBERTA
SASKATCHEWAN
MANITOBA
SASKATOON
PRAIRIE PROVINCES WATER BOARD
MAP OF
ALBERTA, SASKATCHEWAN AND MANITOBA
PERCENTAGE OF YEARS WITH OVER 8" DEFICIT
1921-1950
(1/2" STORAGE)
HYD-A-1045

FIG-16



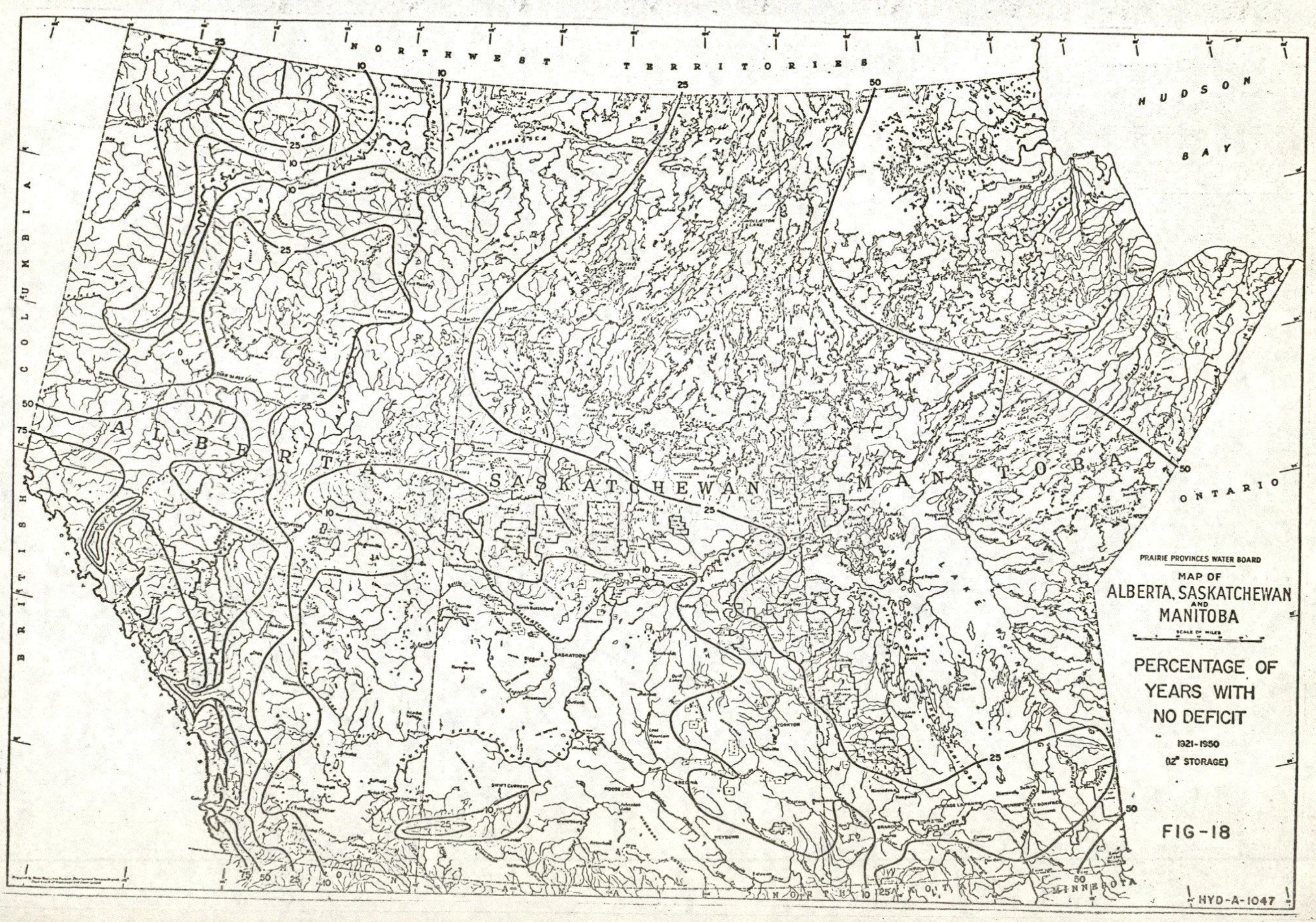
PERCENTAGE OF YEARS WITH OVER 8" DEFICIT

1921-1950

(12" STORAGE)

FIG-17

HYD-A-1046


NORTHWEST TERRITORIES
HUDSON BAY
BRITISH COLUMBIA
ALBERTA
SASKATCHEWAN
MANITOBA
ONTARIO
LAKE ATHABASCA
SASKATOON
SWIFT CURRENT
MOOSE JAW
BRANDON
YORKTON
WEYBURN
MINNESOTA
NORTH
PRAIRIE PROVINCES WATER BOARD
MAP OF
ALBERTA, SASKATCHEWAN
AND
MANITOBA
SCALE OF MILES
PERCENTAGE OF
YEARS WITH
NO DEFICIT
1921-1950
(12" STORAGE)
FIG-18
HYD-A-1047

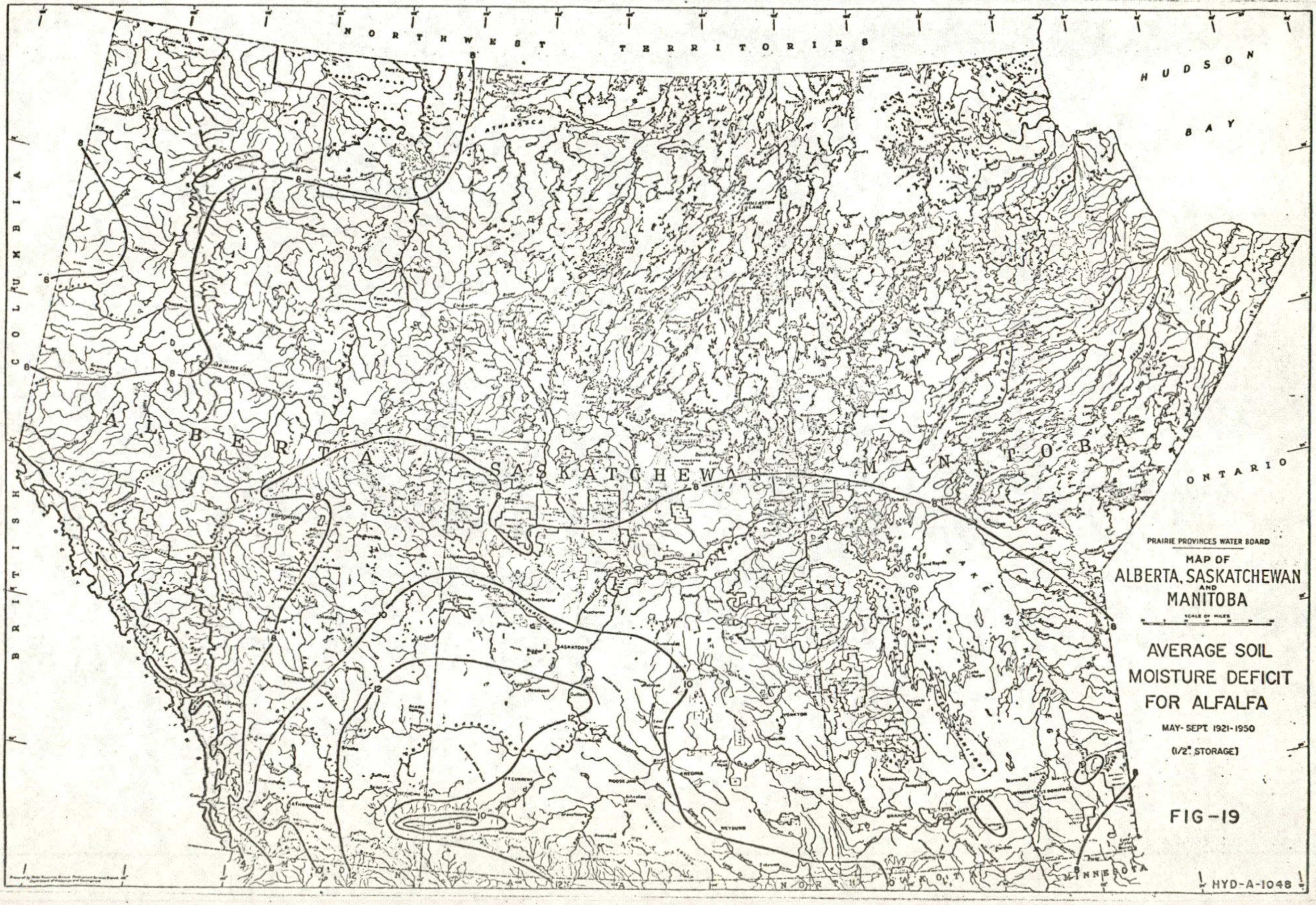
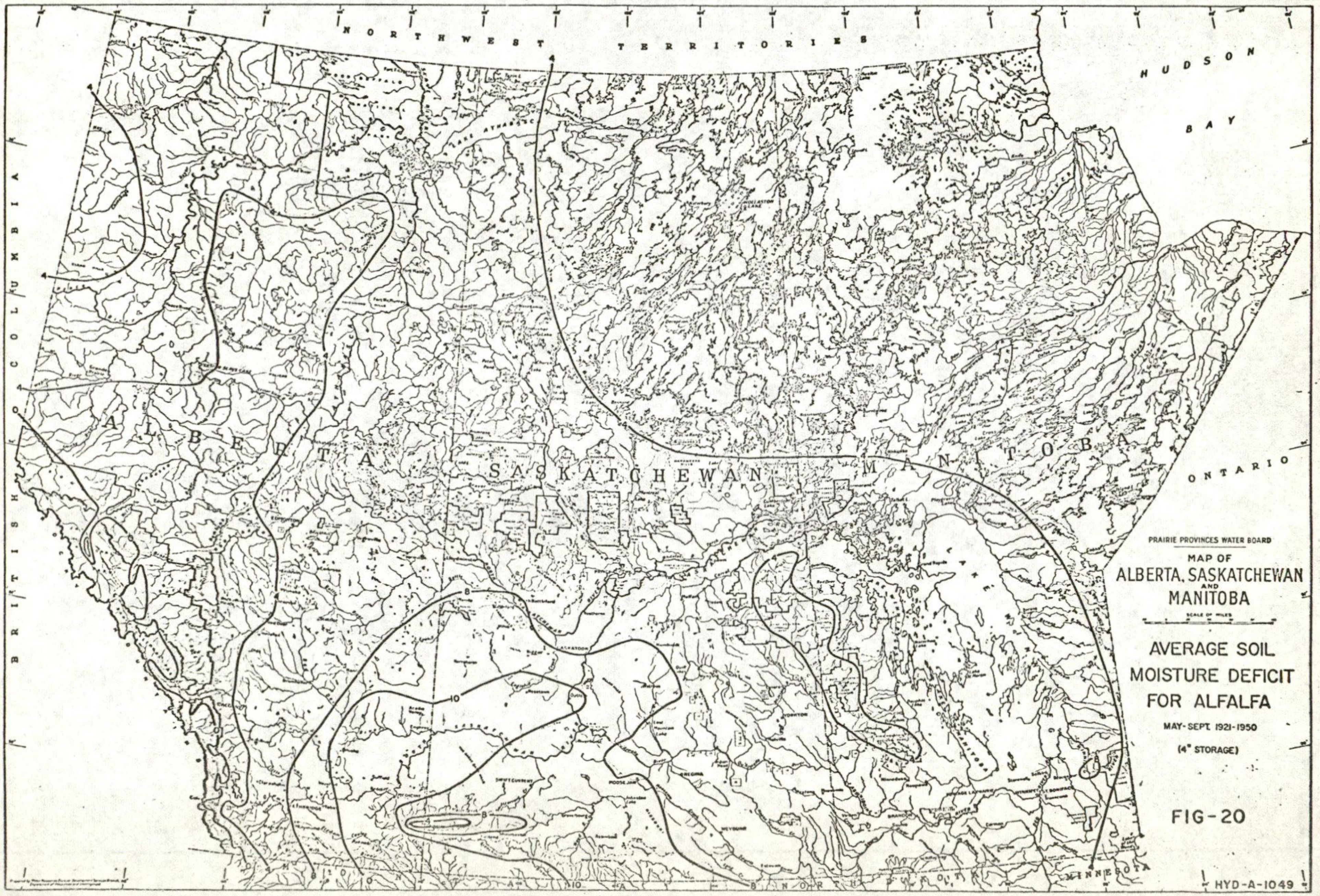
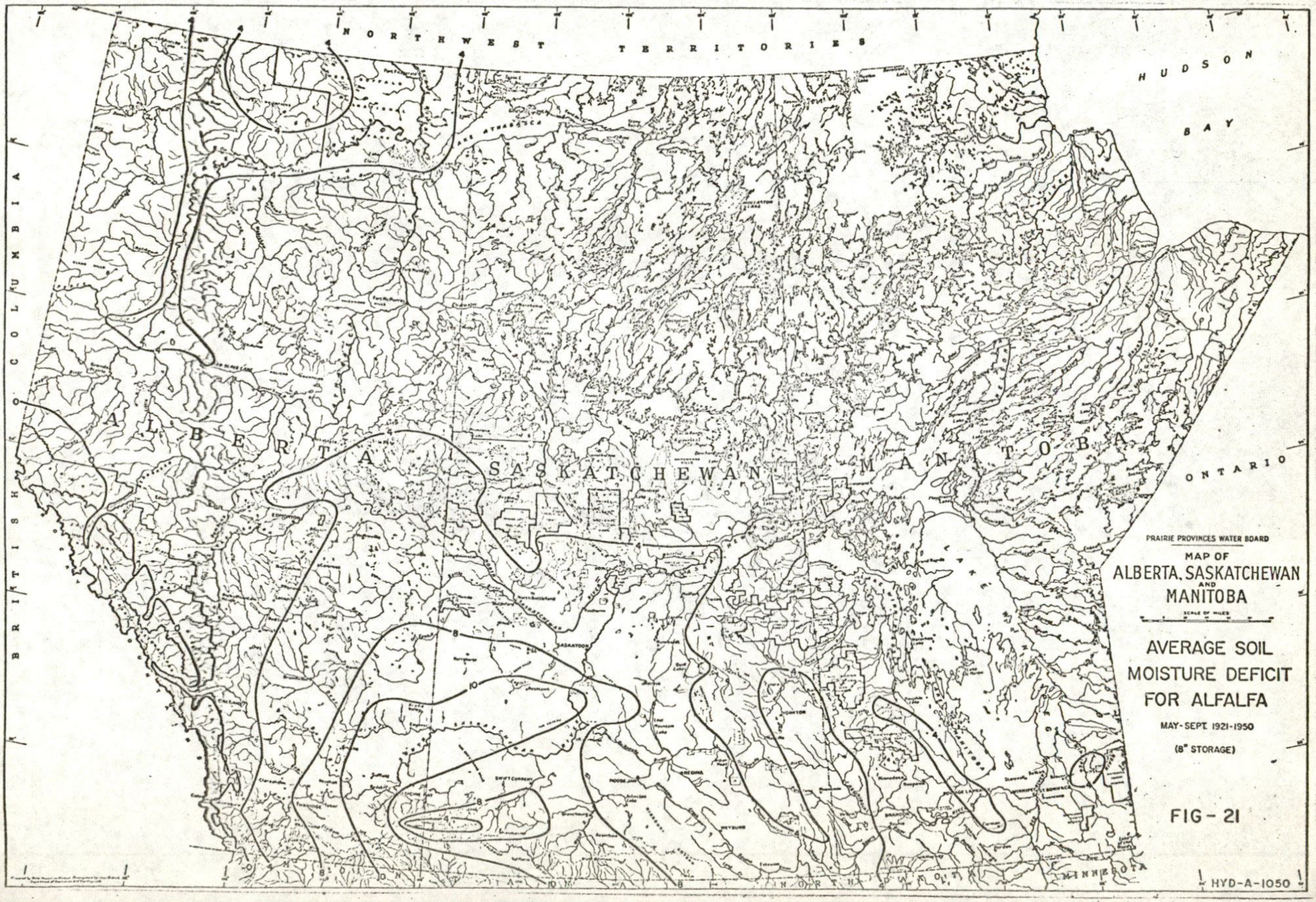


FIG-19

HYD-A-1048



NORTHWEST TERRITORIES
HUDSON BAY
BRITISH COLUMBIA
ALBERTA
SASKATCHEWAN
MANITOBA
ONTARIO
MINNESOTA
PRAIRIE PROVINCES WATER BOARD
MAP OF
ALBERTA, SASKATCHEWAN AND MANITOBA
SCALE OF MILES
AVERAGE SOIL MOISTURE DEFICIT FOR ALFALFA
MAY-SEPT. 1921-1950
(4" STORAGE)
FIG-20
HYD-A-1049



PRAIRIE PROVINCES WATER BOARD

MAP OF ALBERTA, SASKATCHEWAN AND MANITOBA

AVERAGE SOIL MOISTURE DEFICIT FOR ALFALFA

MAY-SEPT. 1921-1950

(8" STORAGE)

FIG - 21

HYD-A-1050

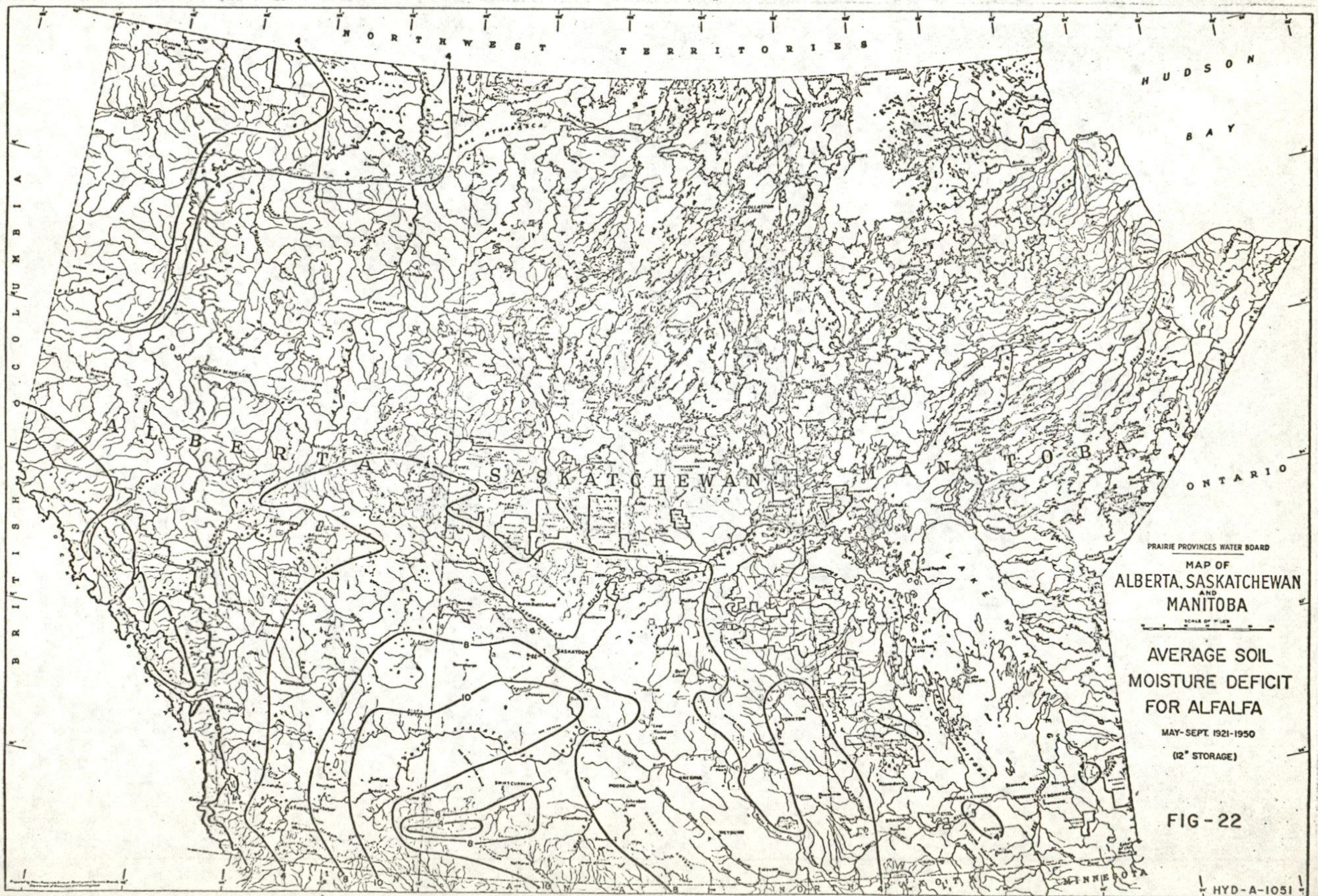
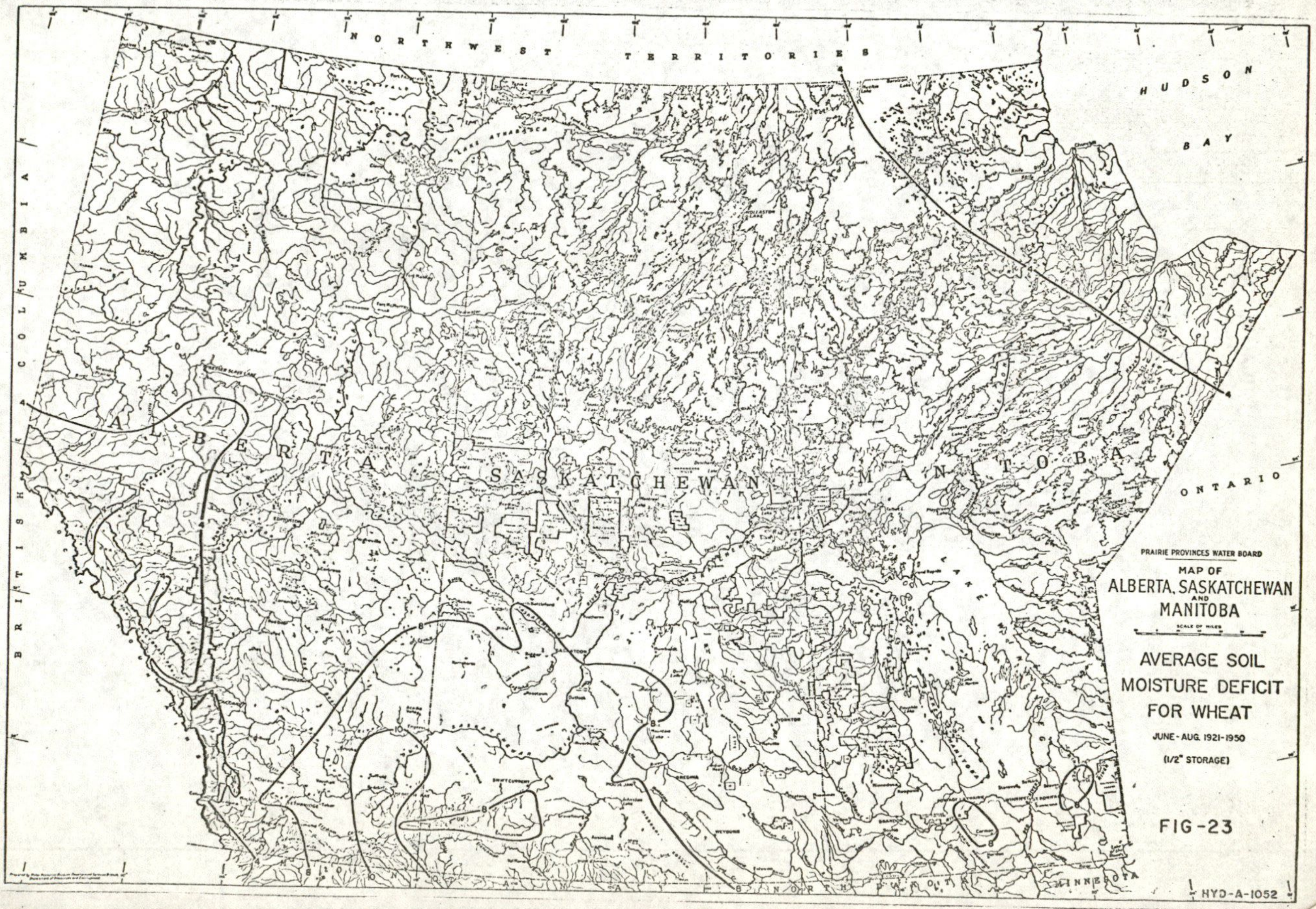


FIG - 22

HYD-A-1051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HUDSON BAY
BRITISH COLUMBIA
ALBERTA
SASKATCHEWAN
MANITOBA
ONTARIO
MINNESOTA
NORTH DAKOTA
PRAIRIE PROVINCES WATER BOARD
MAP OF
ALBERTA, SASKATCHEWAN AND MANITOBA
AVERAGE SOIL MOISTURE DEFICIT FOR WHEAT
JUNE - AUG. 1921-1950
(1/2" STORAGE)
HYD-A-1052

FIG-23

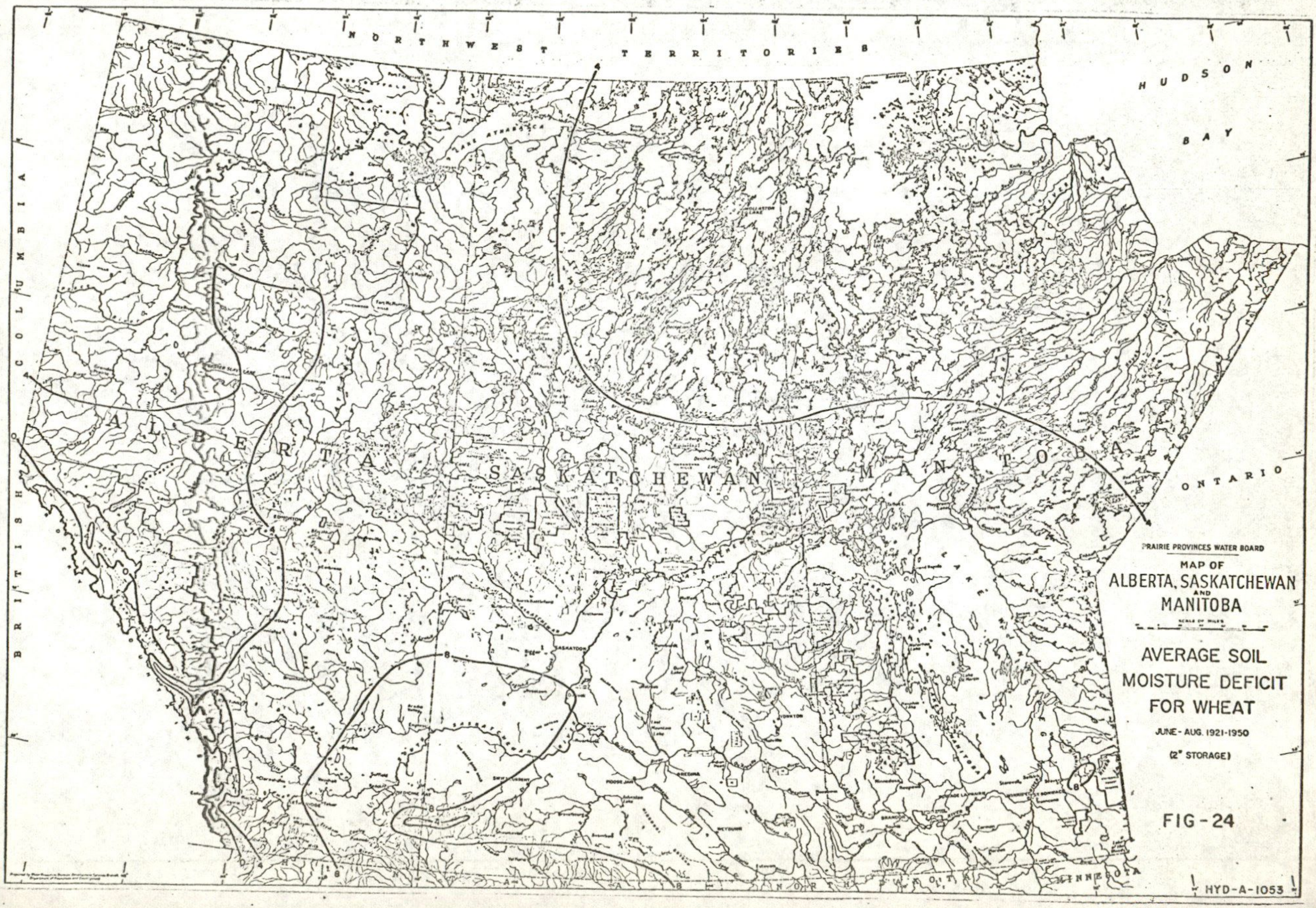
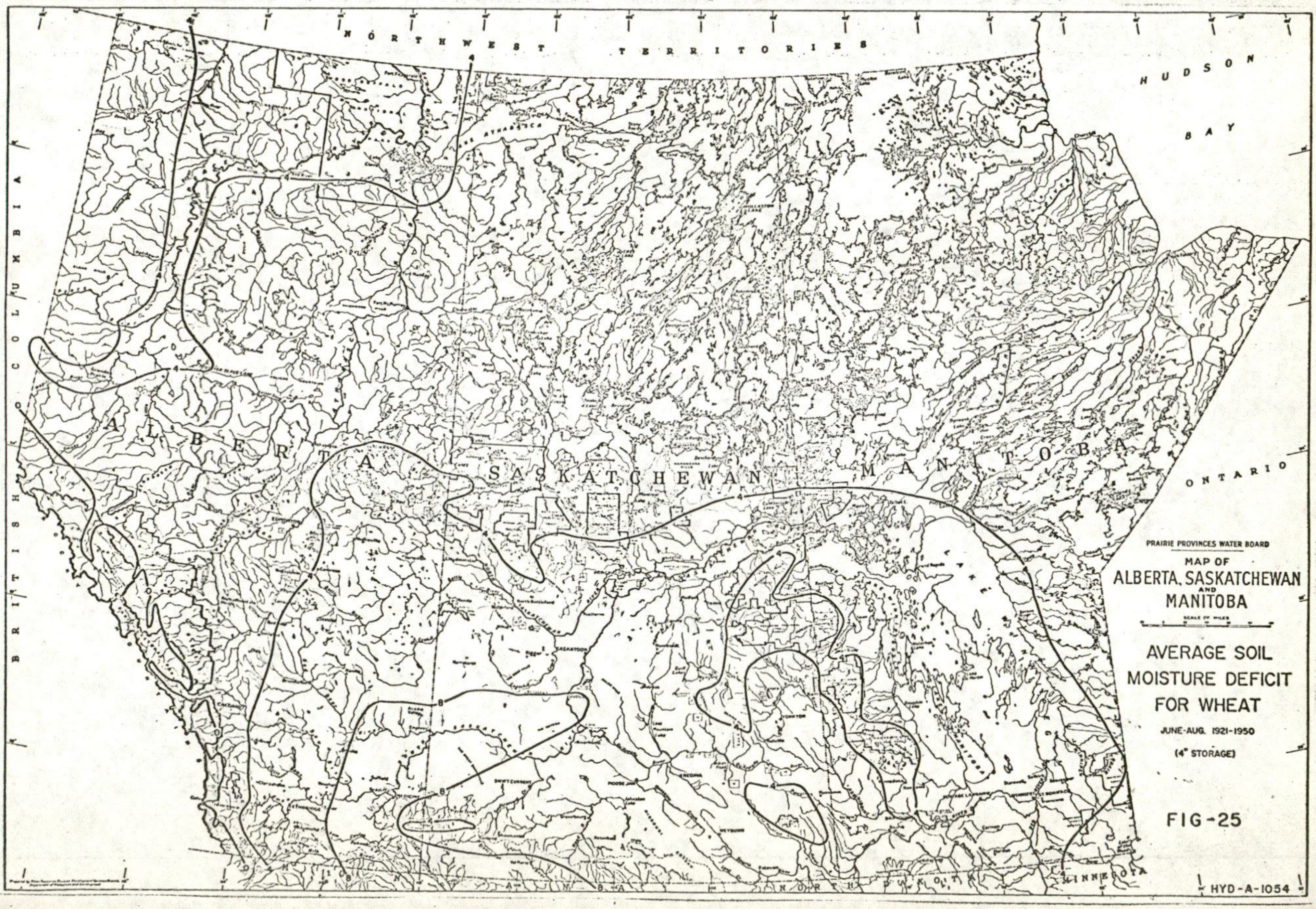


FIG - 24

HYD-A-1053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HUDSON BAY
BRITISH COLUMBIA
ALBERTA
SASKATCHEWAN
MANITOBA
ONTARIO
NORTH DAKOTA
MINNESOTA
SASKATOON
PRAIRIE PROVINCES WATER BOARD
MAP OF
ALBERTA, SASKATCHEWAN
AND
MANITOBA
AVERAGE SOIL MOISTURE DEFICIT FOR WHEAT
JUNE-AUG. 1921-1950
(4" STORAGE)
FIG-25
HYD-A-1054

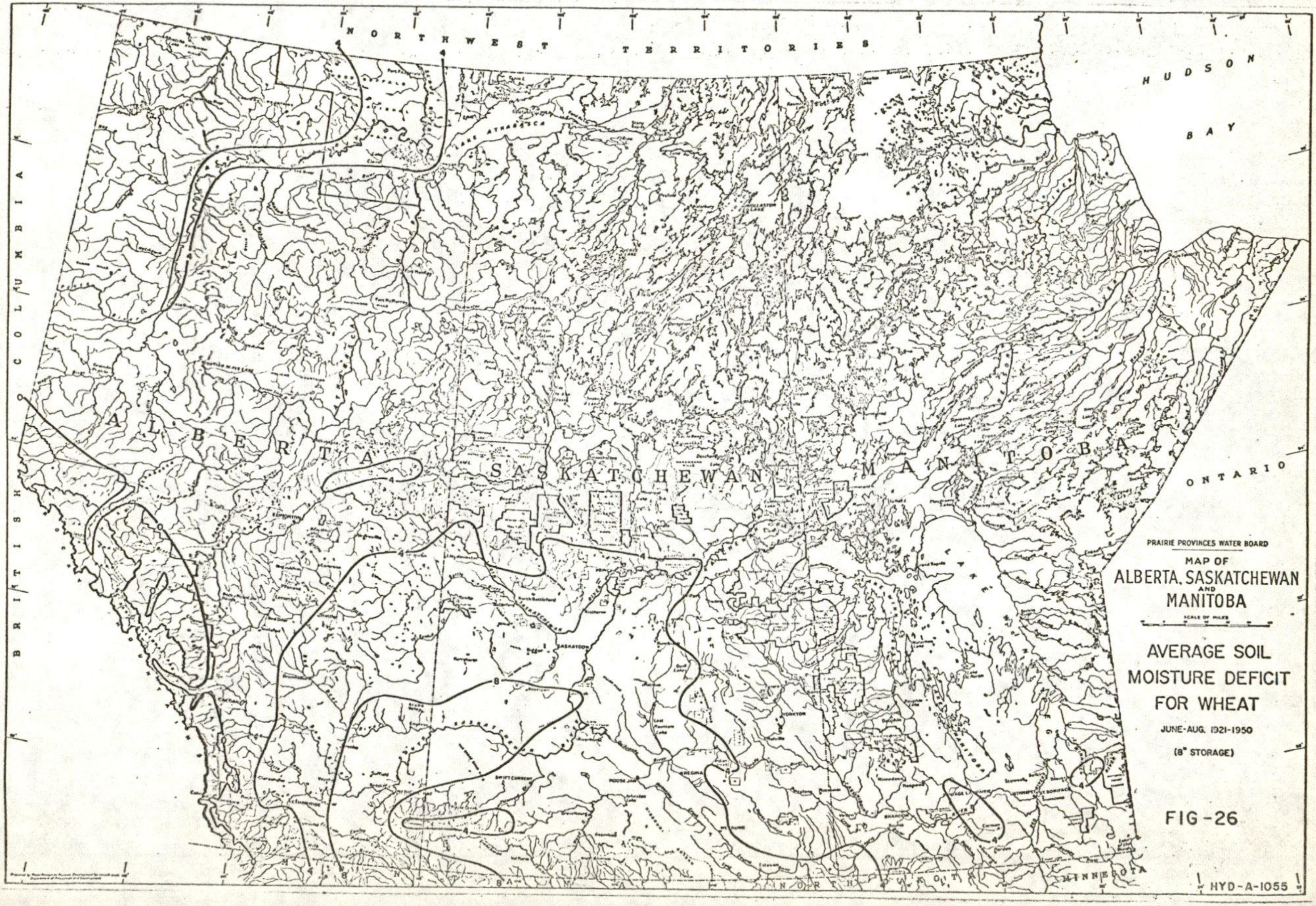
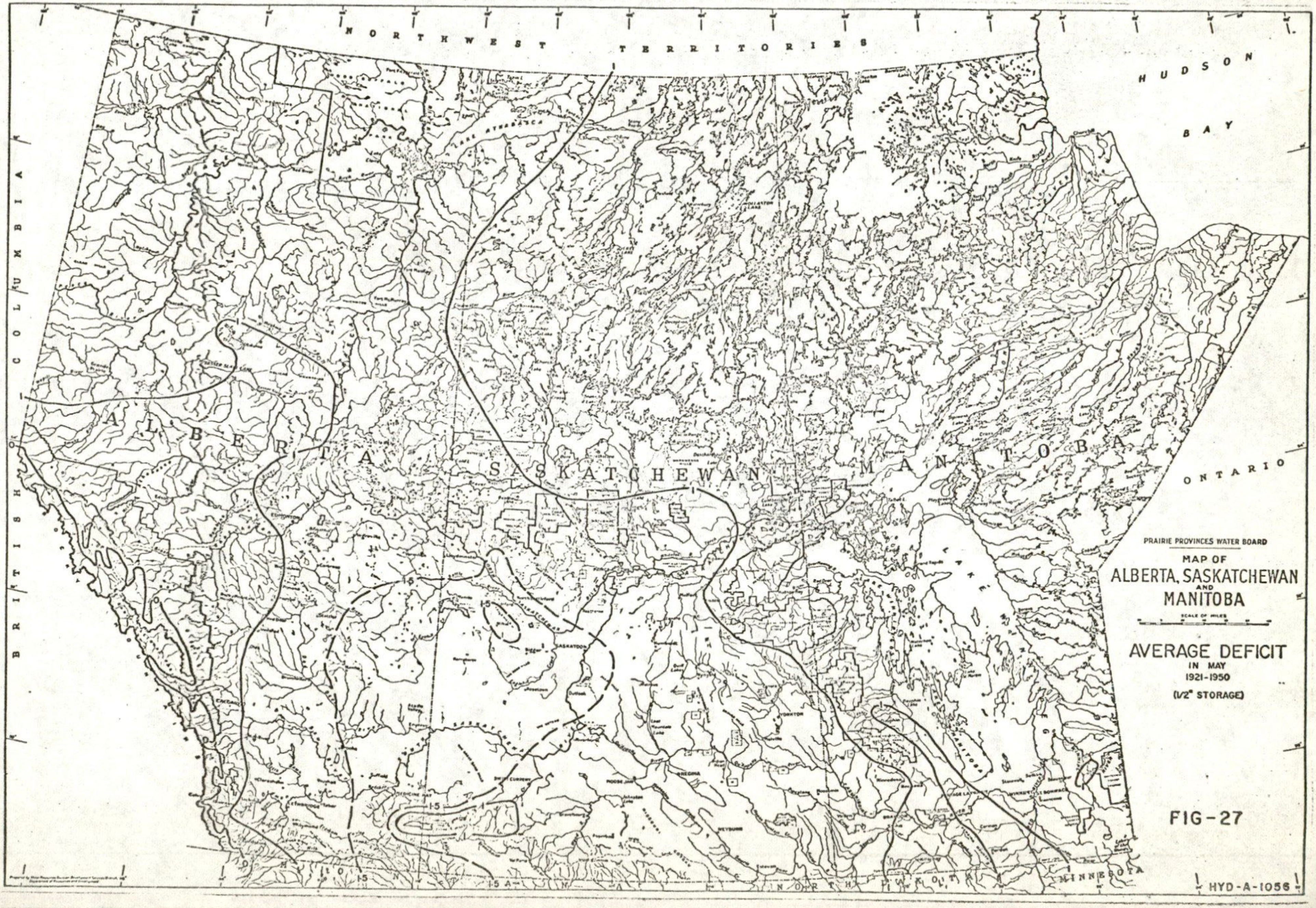


FIG-26

HYD-A-1055


NORTHWEST TERRITORIES
HUDSON BAY
BRITISH COLUMBIA
ALBERTA
SASKATCHEWAN
MANITOBA
ONTARIO
NORTH DAKOTA
MINNESOTA
LAKE ATHABASCA
EDMONTON
SASKATOON
REGINA
CALGARY
MEDICINE HAT
SWIFT CURRENT
MOOSE JAW
YORKTON
WEYBURN
LETHBRIDGE
LAKE WINNIPEG
LAKE MANITOBA
1.5
PRAIRIE PROVINCES WATER BOARD
MAP OF
ALBERTA, SASKATCHEWAN
AND
MANITOBA
SCALE OF MILES
AVERAGE DEFICIT
IN MAY
1921-1950
(1/2" STORAGE)
HYD-A-1056
FIG-27

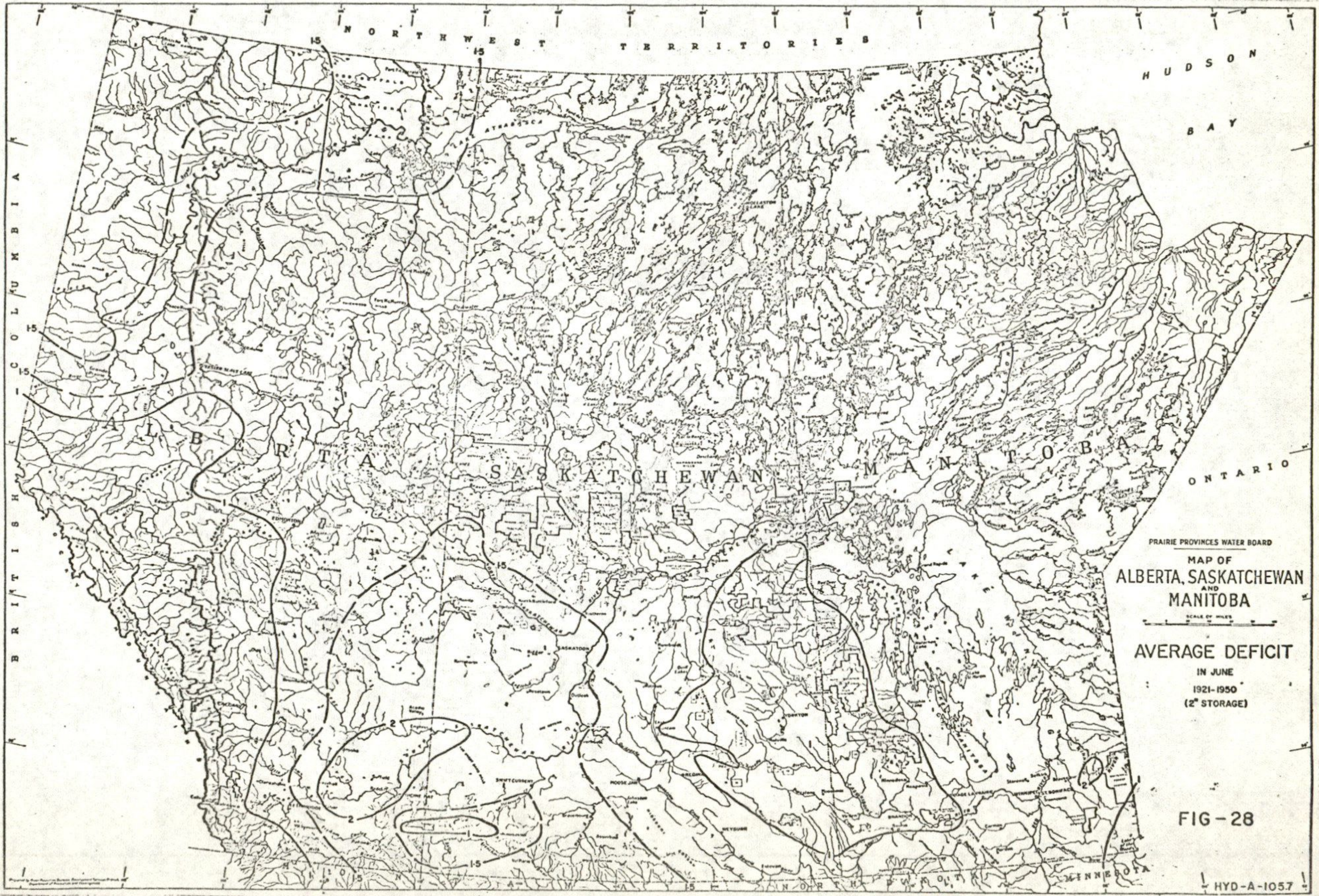


FIG - 28

HYD-A-1057

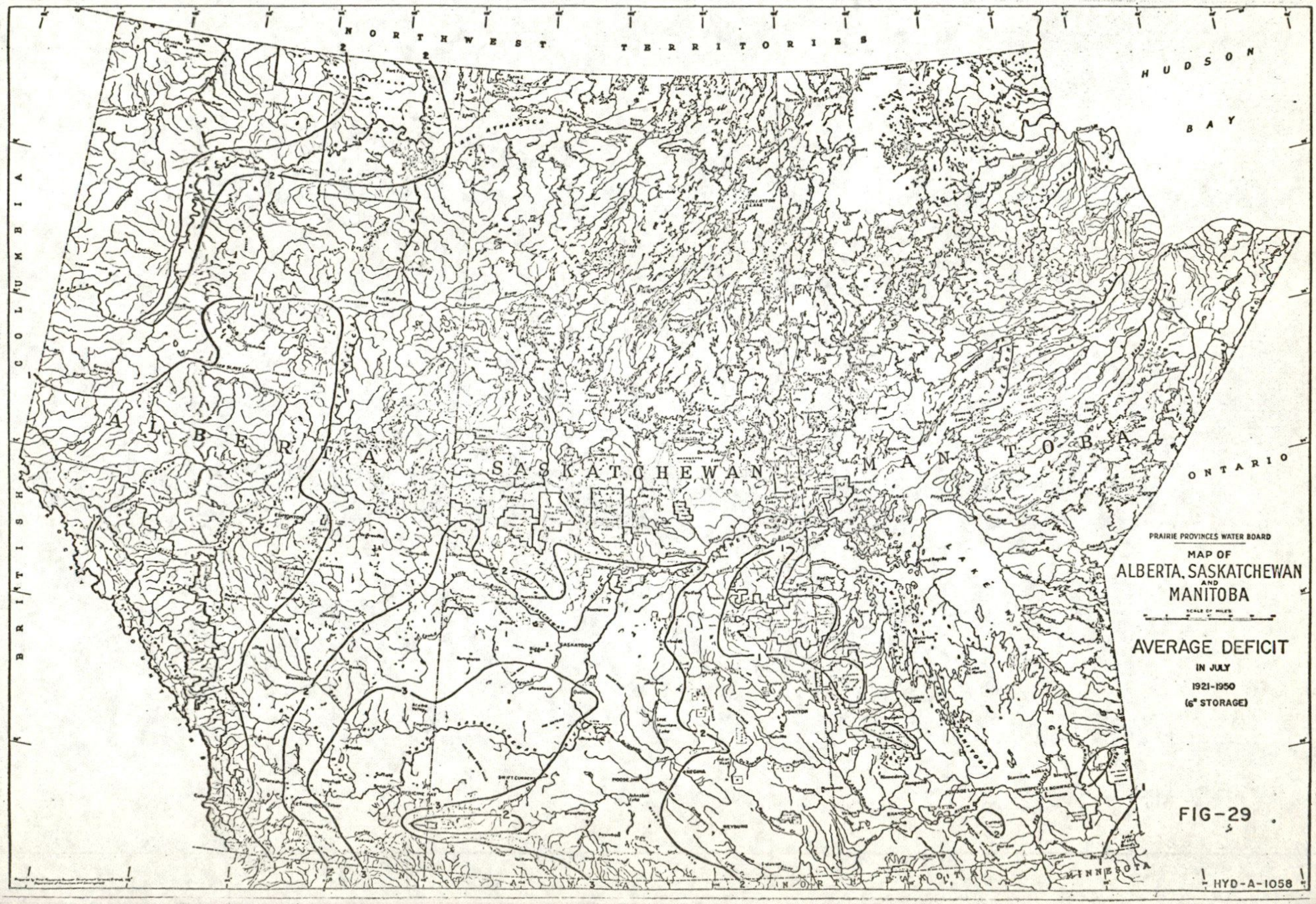


FIG-29

HYD-A-1058

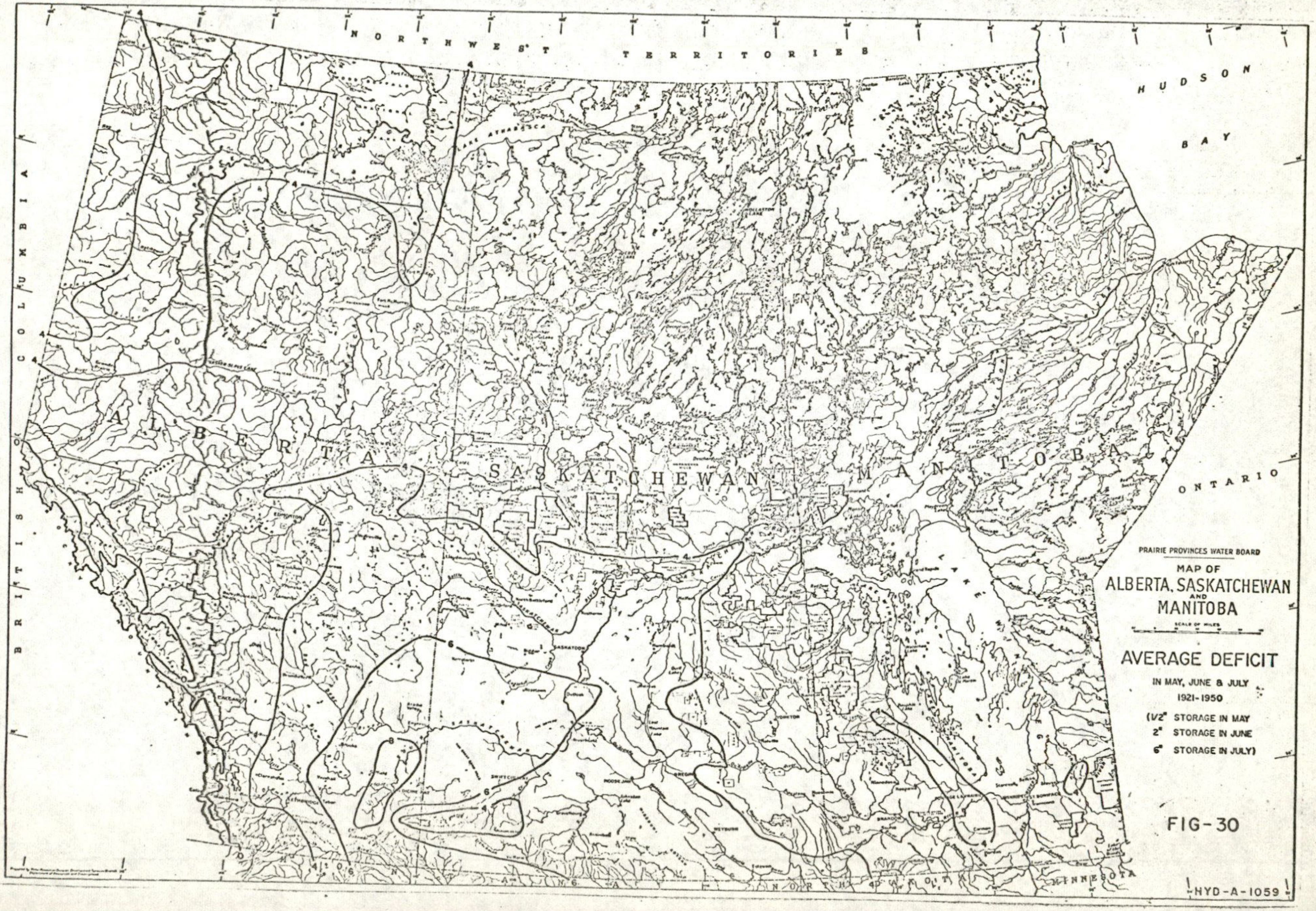
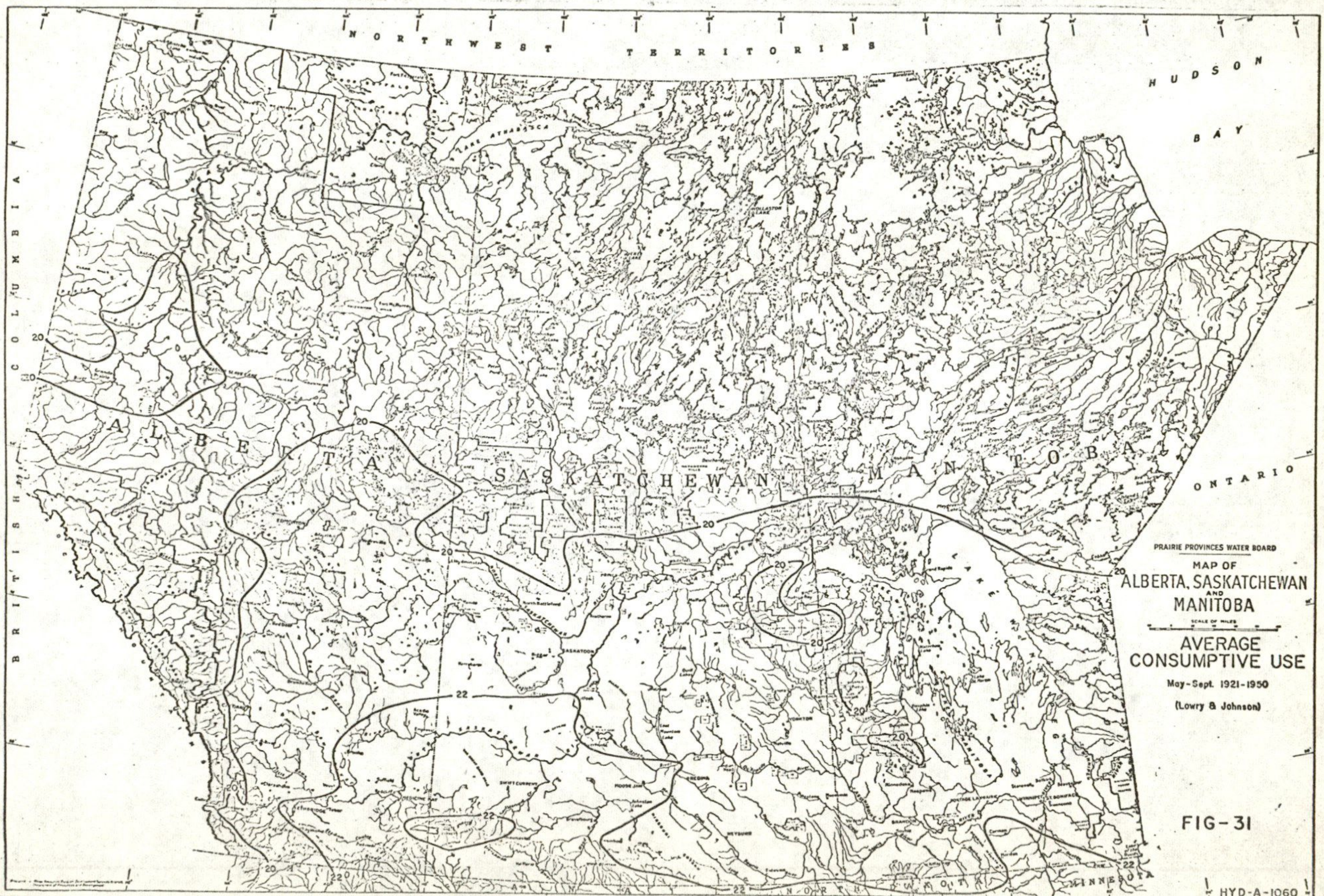


FIG-30

HYD-A-1059



PRAIRIE PROVINCES WATER BOARD

MAP OF
ALBERTA, SASKATCHEWAN
AND
MANITOBA

SCALE OF MILES

AVERAGE
CONSUMPTIVE USE

May-Sept. 1921-1950

(Lowry & Johnson)

FIG-31

HYD-A-1060

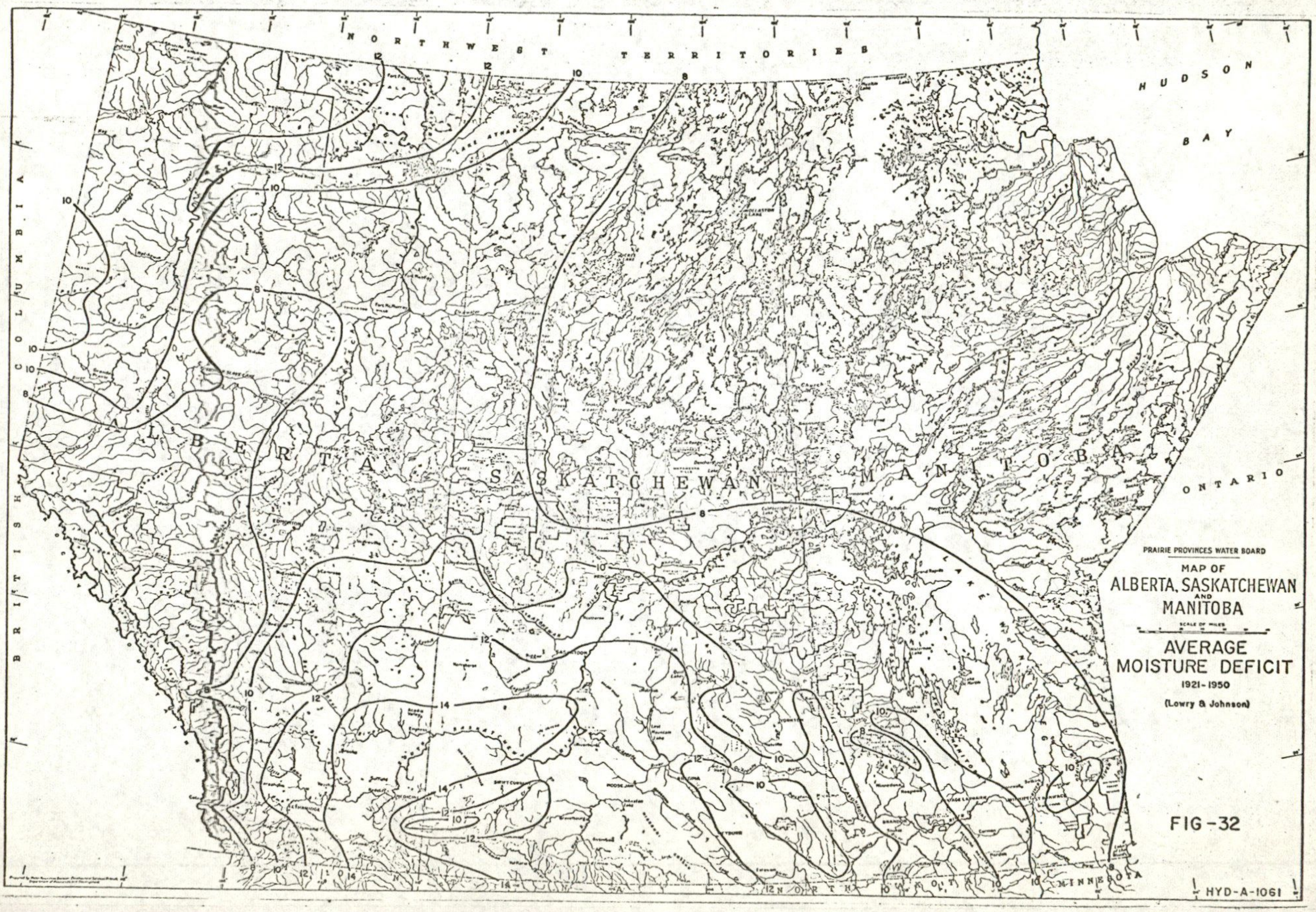

NORTHWEST TERRITORIES
HUDSON BAY
BRITISH COLUMBIA
ALBERTA
SASKATCHEWAN
MANITOBA
ONTARIO
LAKE WINNIPEG
NORTH DAKOTA
MINNESOTA
SASKATOON
MOOSE JAW
PRAIRIE PROVINCES WATER BOARD
MAP OF
ALBERTA, SASKATCHEWAN
AND
MANITOBA
SCALE OF MILES
AVERAGE
MOISTURE DEFICIT
1921-1950
(Lowry & Johnson)
HYD-A-1061

FIG-32

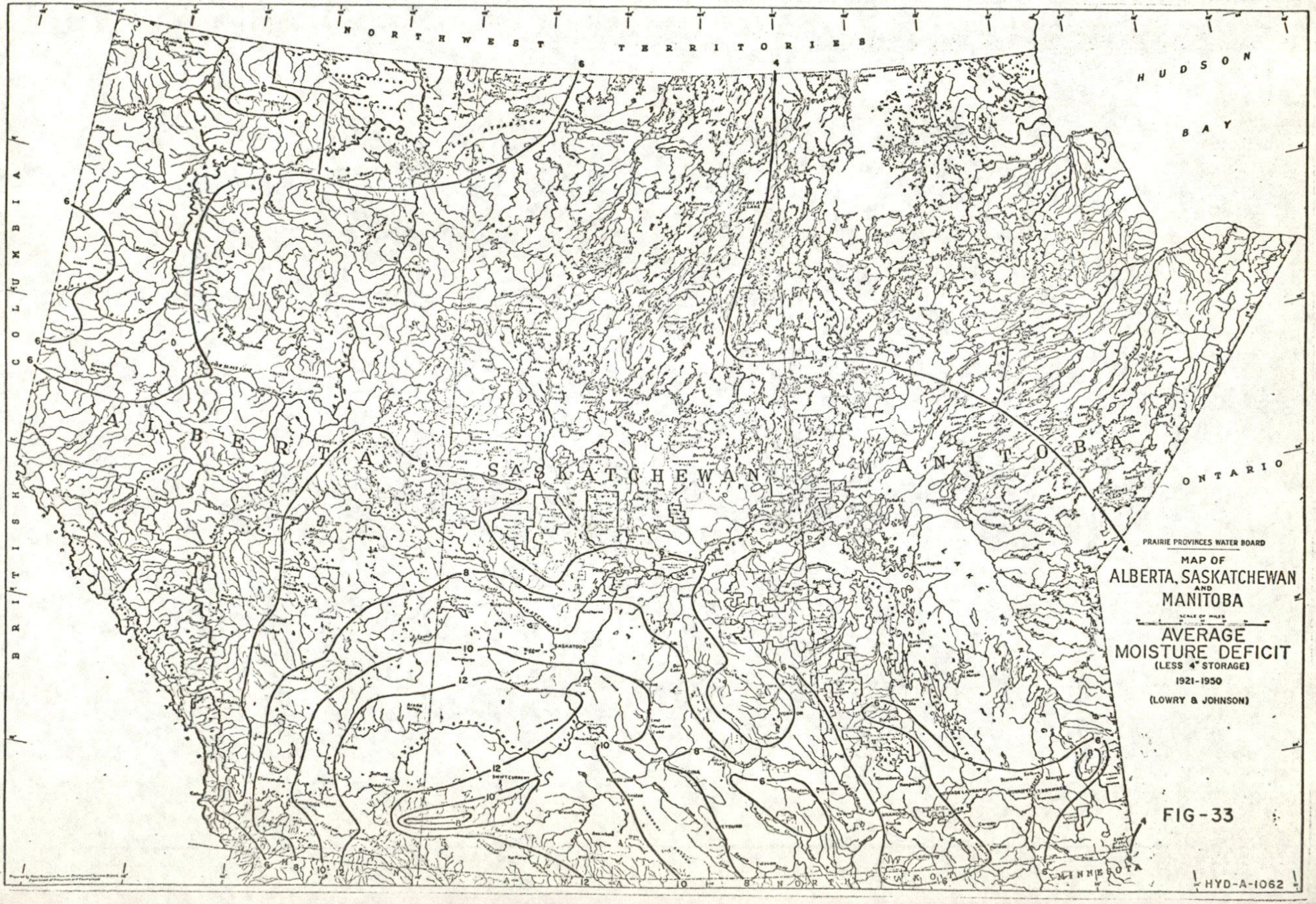
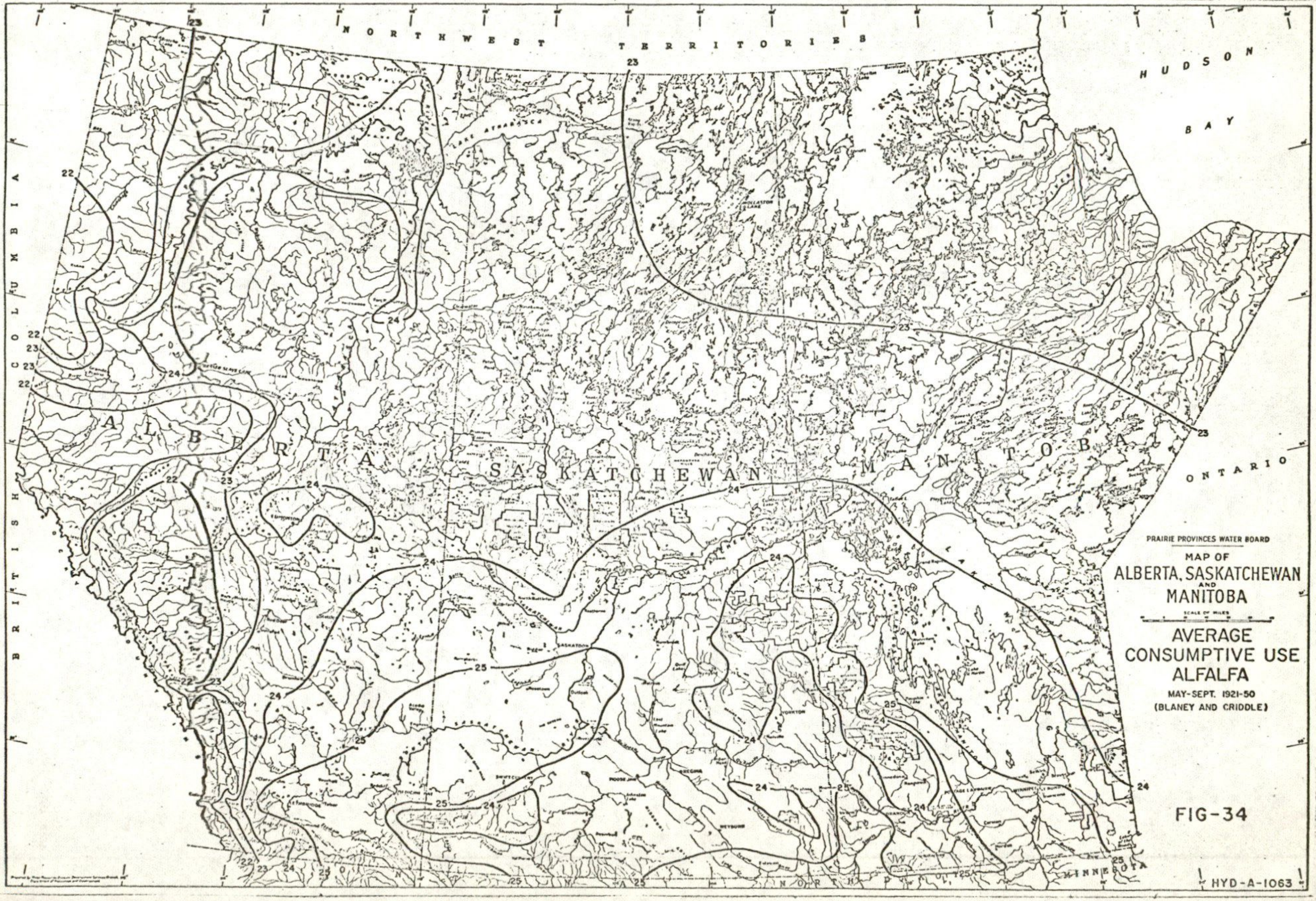


FIG-33

HYD-A-1062



NORTHWEST TERRITORIES
HUDSON BAY
BRITISH COLUMBIA
ALBERTA
SASKATCHEWAN
MANITOBA
ONTARIO
MONTANA
NORTH DAKOTA
MINNESOTA
SASKATOON
REGINA
MOOSE JAW
YORKTON
WEYBURN
PRAIRIE PROVINCES WATER BOARD
MAP OF
ALBERTA, SASKATCHEWAN
AND
MANITOBA
SCALE OF MILES
AVERAGE
CONSUMPTIVE USE
ALFALFA
MAY-SEPT. 1921-50
(BLANEY AND CRIDDLE)
HYD-A-1063

FIG-34

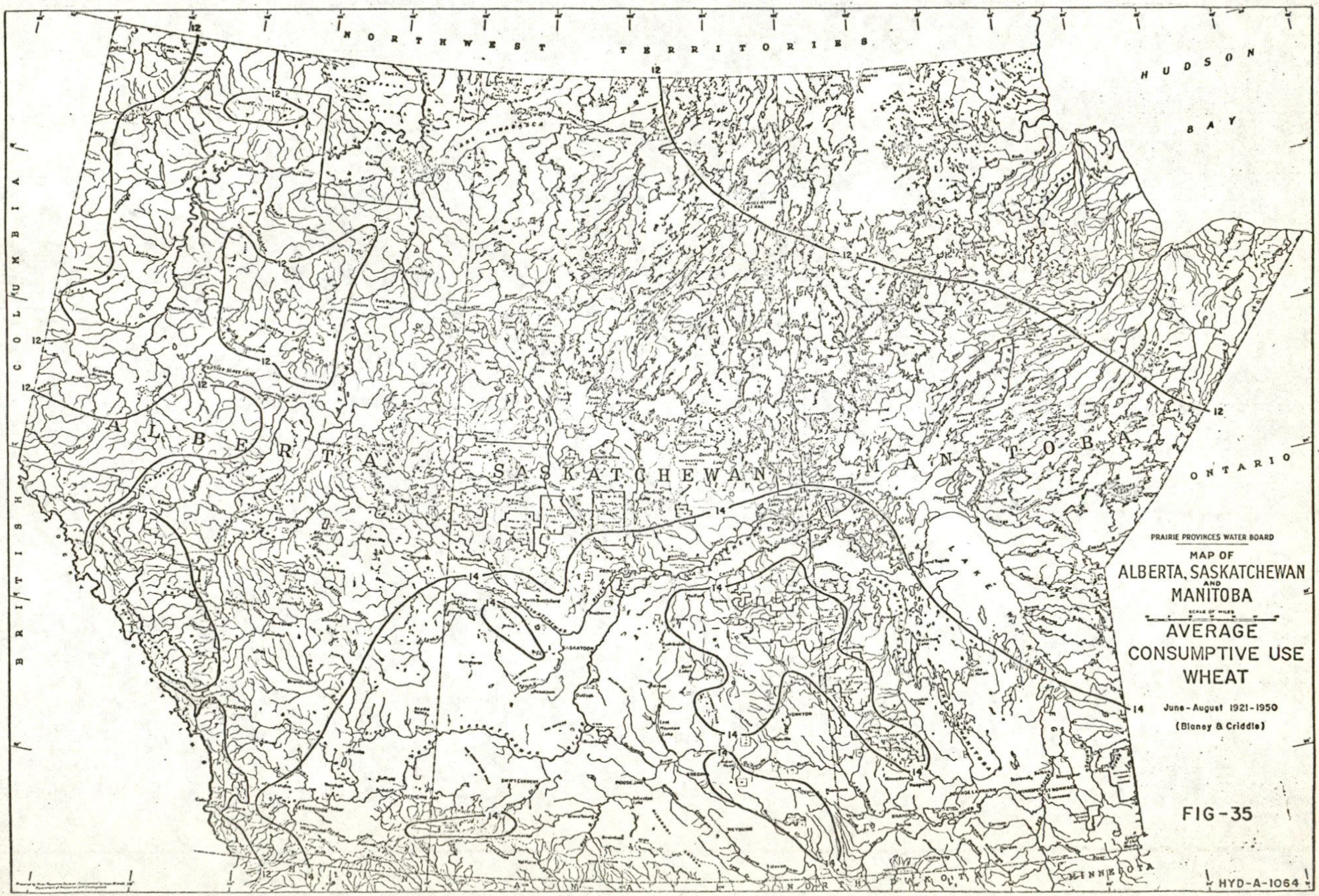
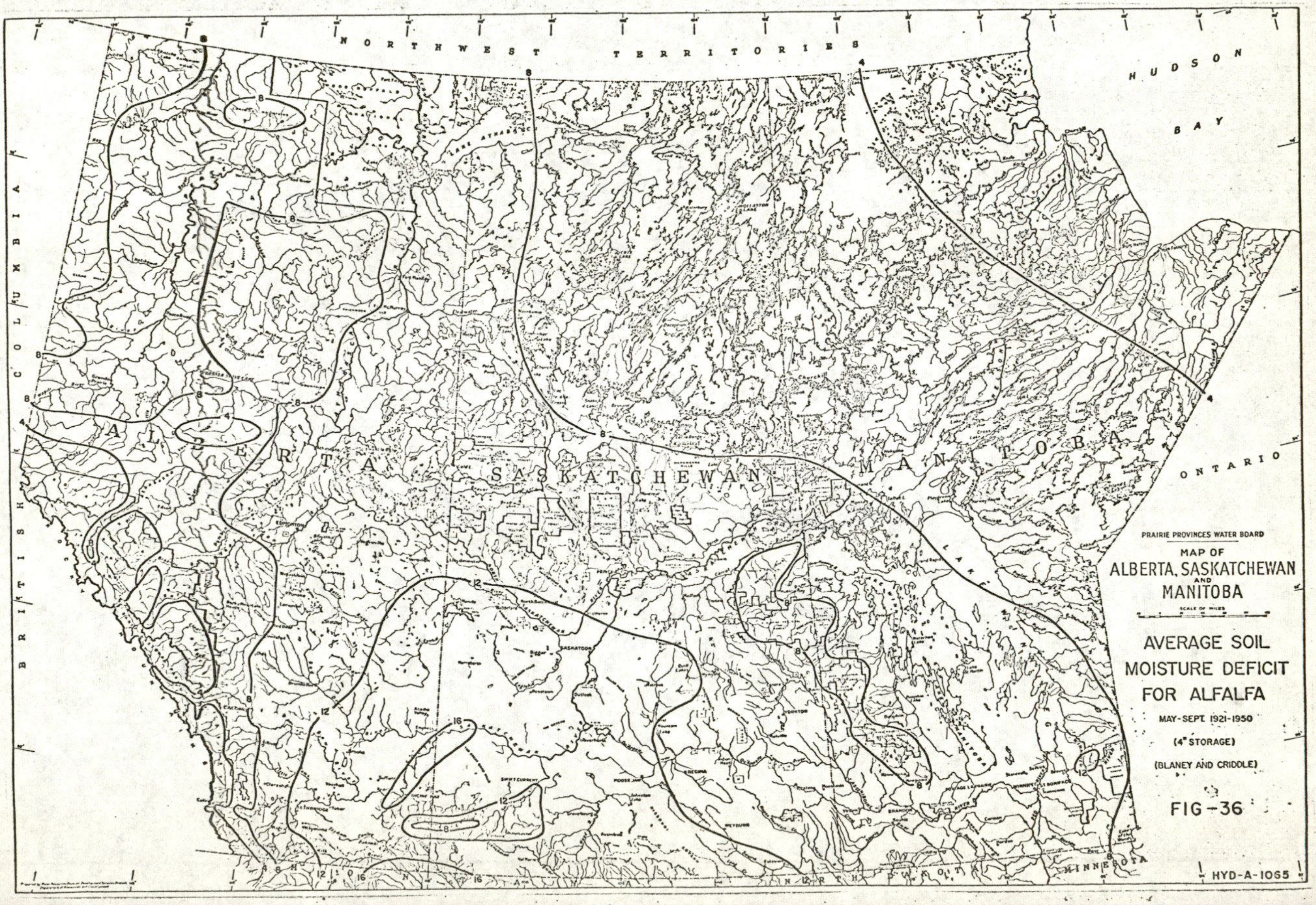


FIG-35

HYD-A-1064



PRAIRIE PROVINCES WATER BOARD

MAP OF ALBERTA, SASKATCHEWAN AND MANITOBA

SCALE OF MILES

AVERAGE SOIL MOISTURE DEFICIT FOR ALFALFA

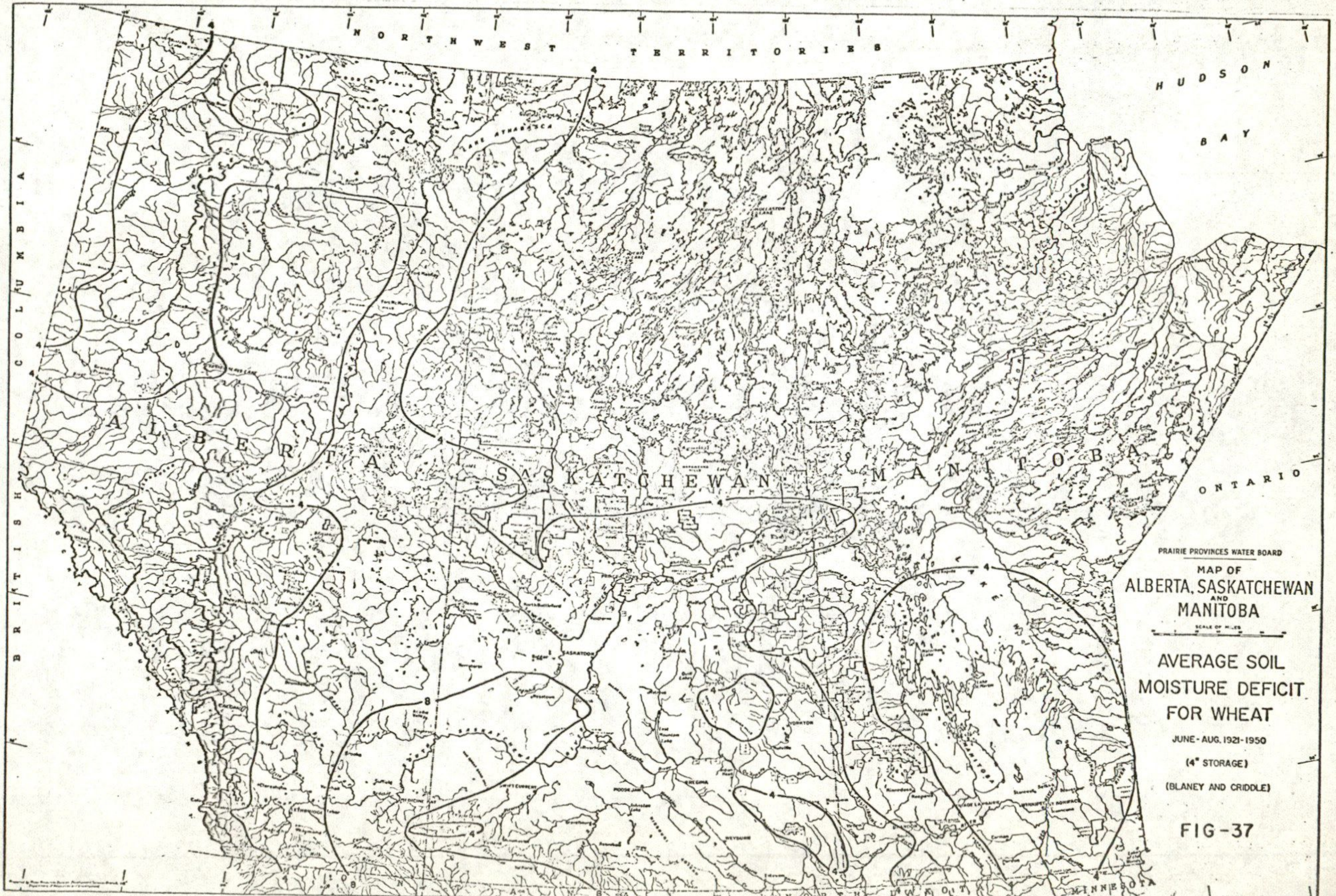
MAY-SEPT. 1921-1950

(4" STORAGE)

(BLANEY AND CRIDDLE)

FIG-36

HYD-A-1065



PRAIRIE PROVINCES WATER BOARD

MAP OF
ALBERTA, SASKATCHEWAN
AND
MANITOBA

AVERAGE SOIL MOISTURE DEFICIT FOR WHEAT

JUNE - AUG. 1921-1950

(4" STORAGE)

(BLANEY AND CRIDDLE)

FIG-37

HYD-A-1066

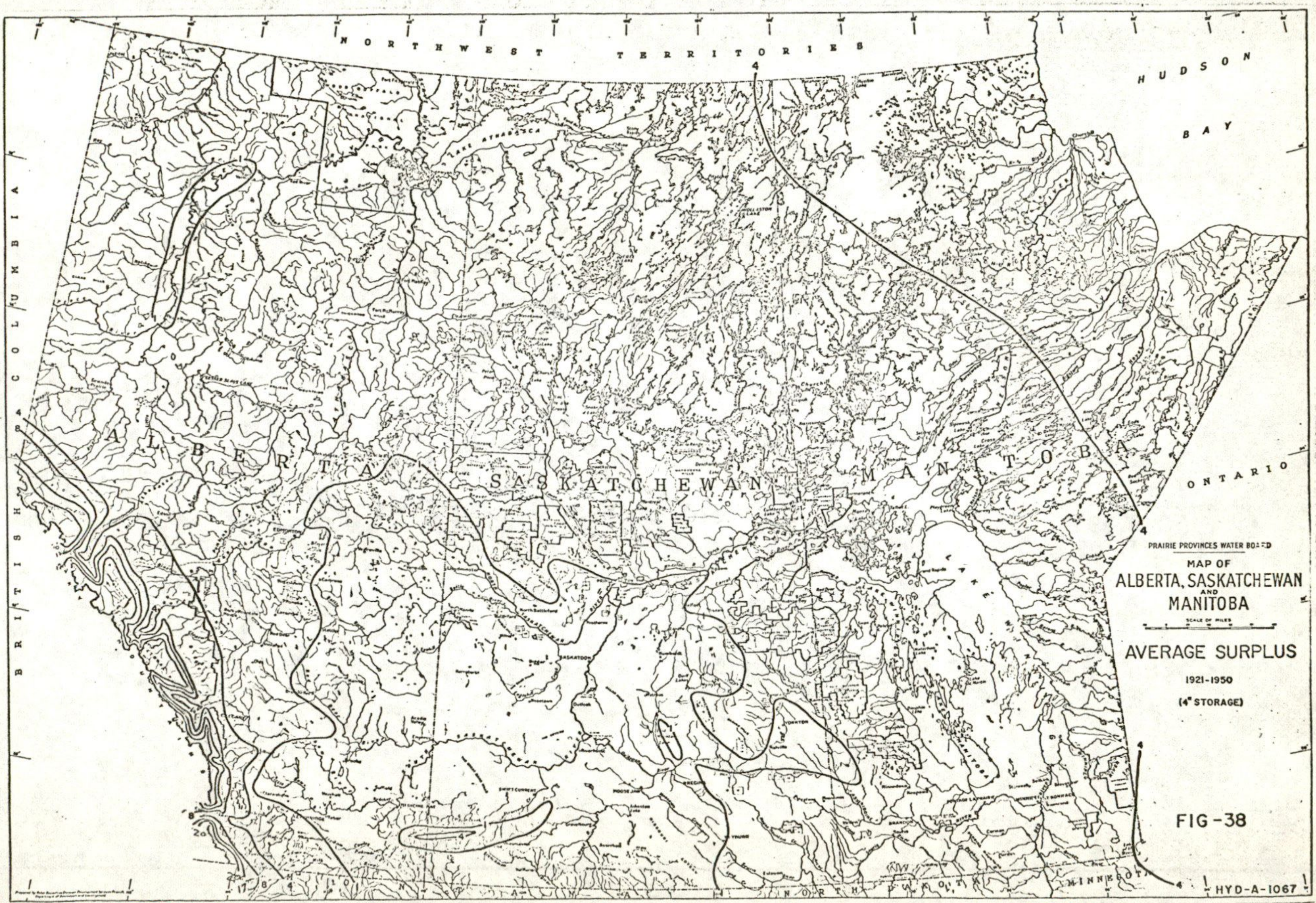

NORTHWEST TERRITORIES
HUDSON BAY
BRITISH COLUMBIA
ALBERTA
SASKATCHEWAN
MANITOBA
ONTARIO
LAKE ATHABASCA
SASKATOON
SWIFT CURRENT
MOOSE JAW
MINNESOTA
NORTH DAKOTA
PRAIRIE PROVINCES WATER BOARD
MAP OF
ALBERTA, SASKATCHEWAN
AND
MANITOBA
SCALE OF MILES
AVERAGE SURPLUS
1921-1950
(4" STORAGE)
HYD-A-1067

FIG - 38

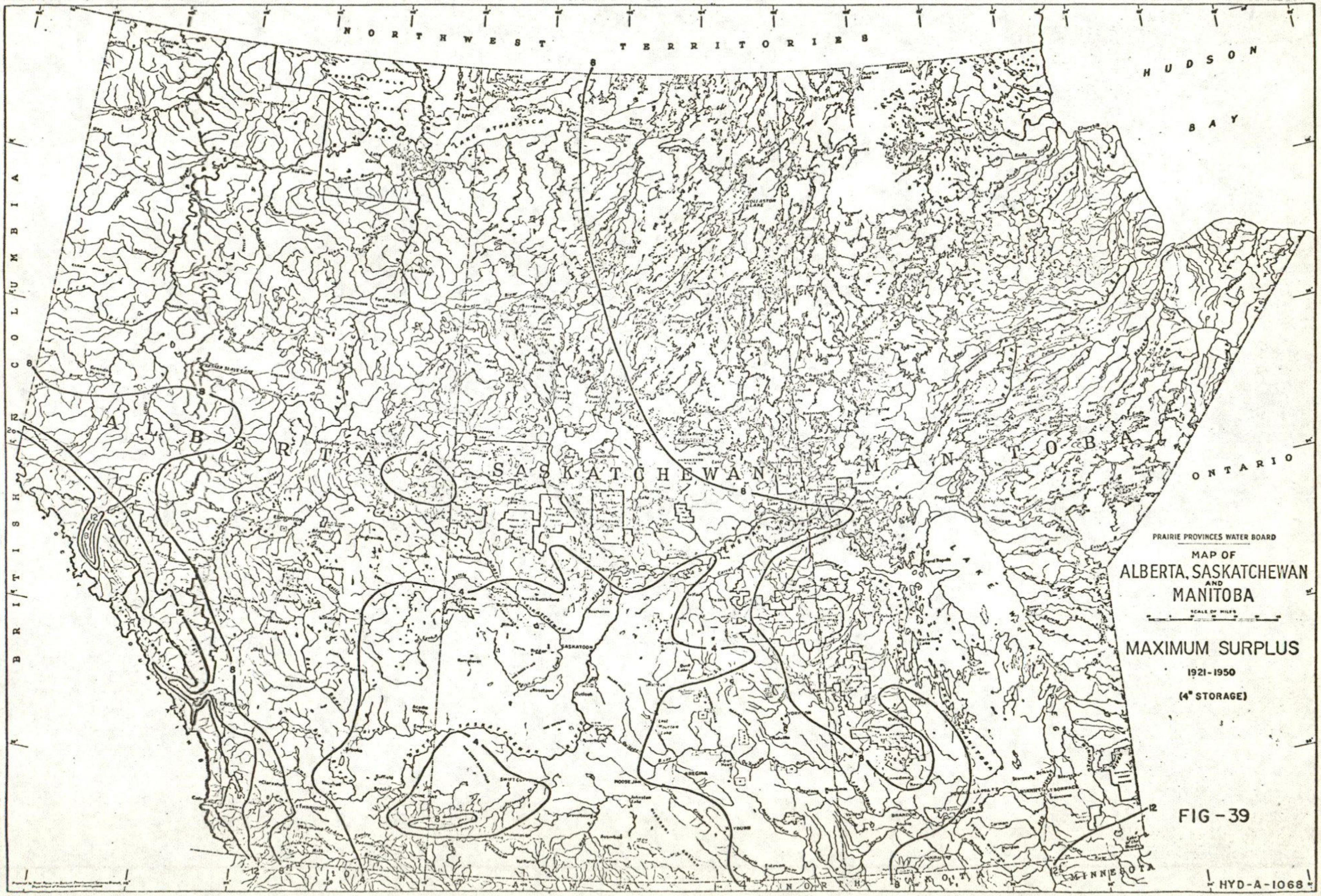


FIG-39

HYD-A-1068

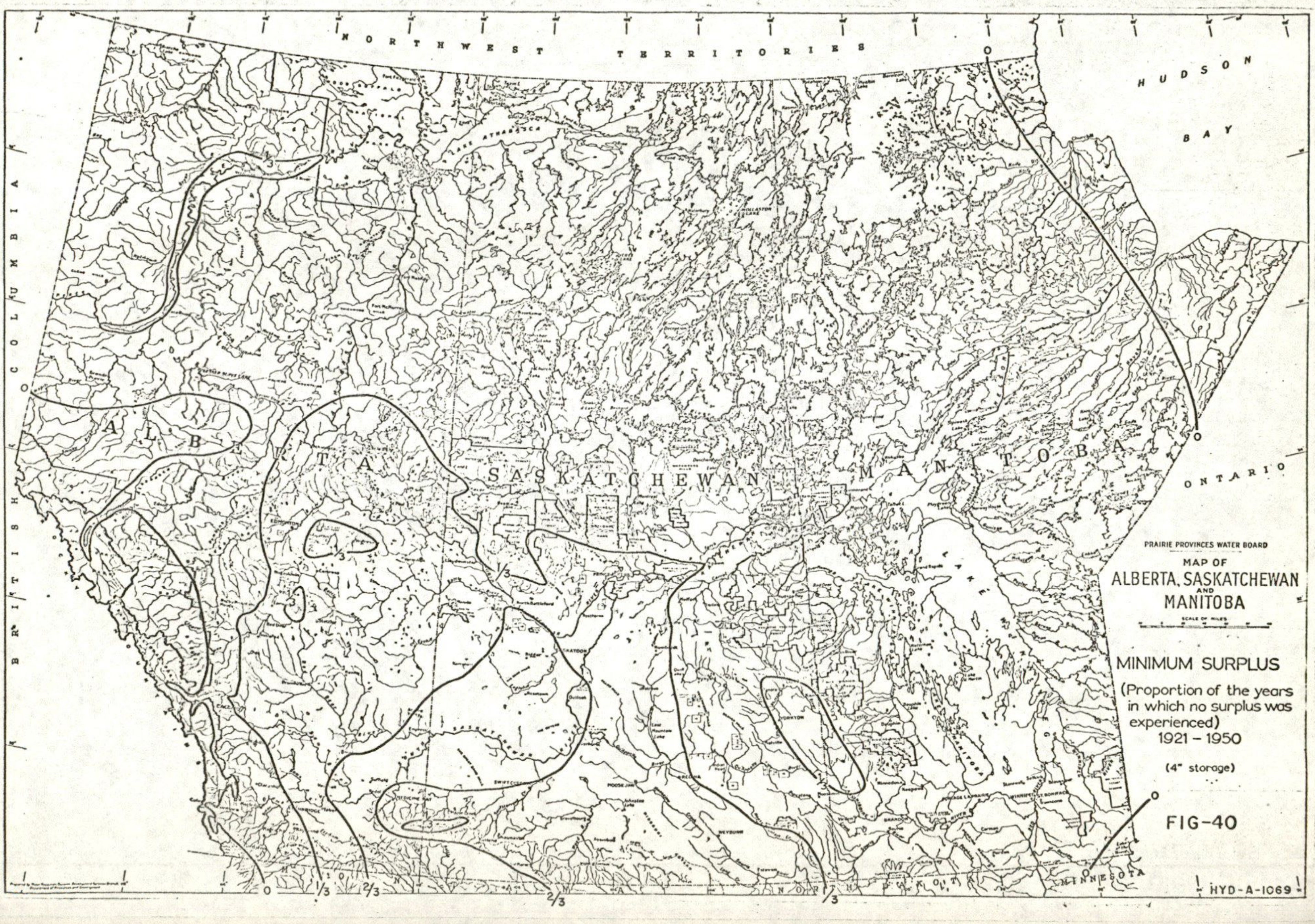
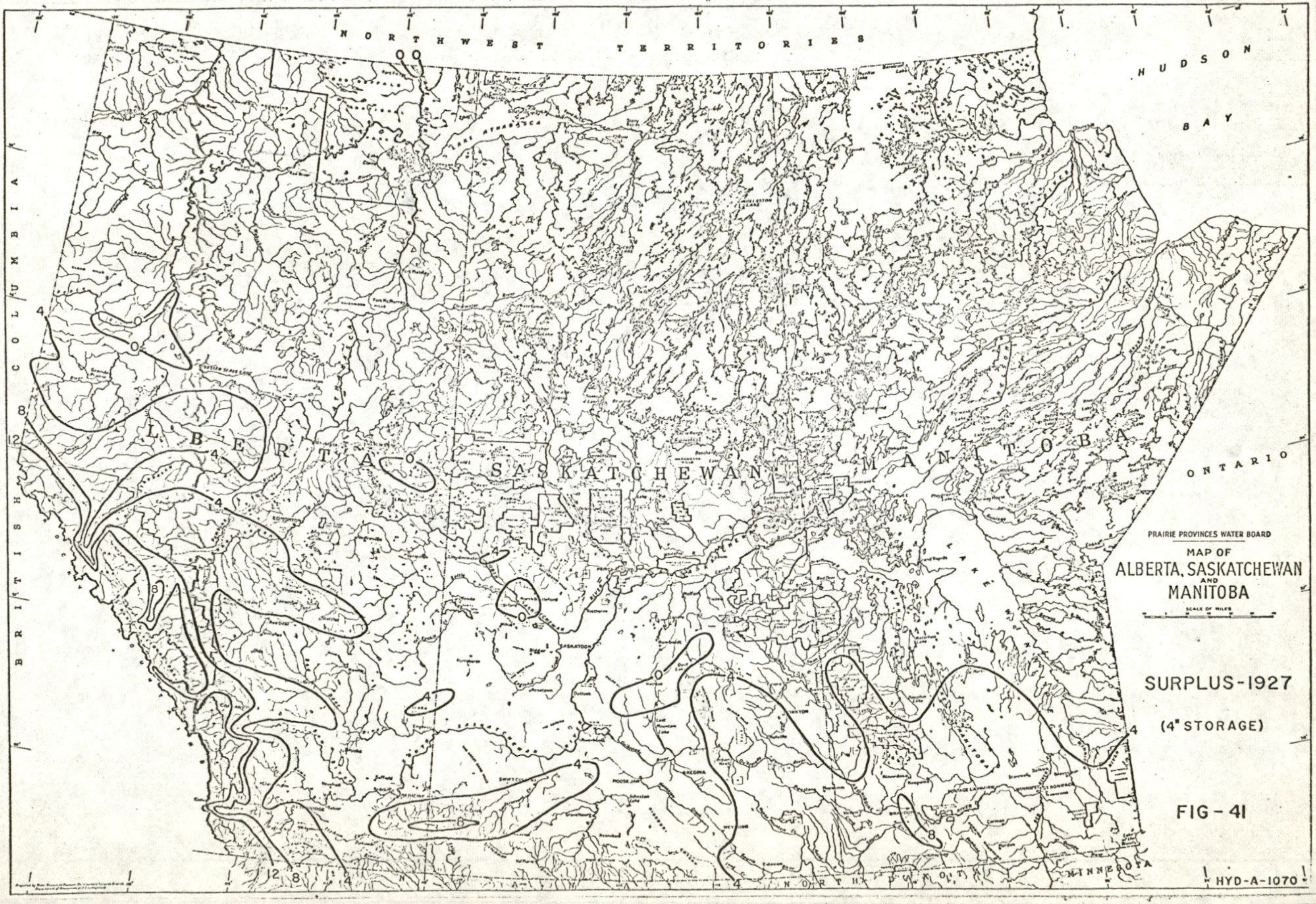


FIG-40

HYD-A-1069



SURPLUS-1927

(4" STORAGE)

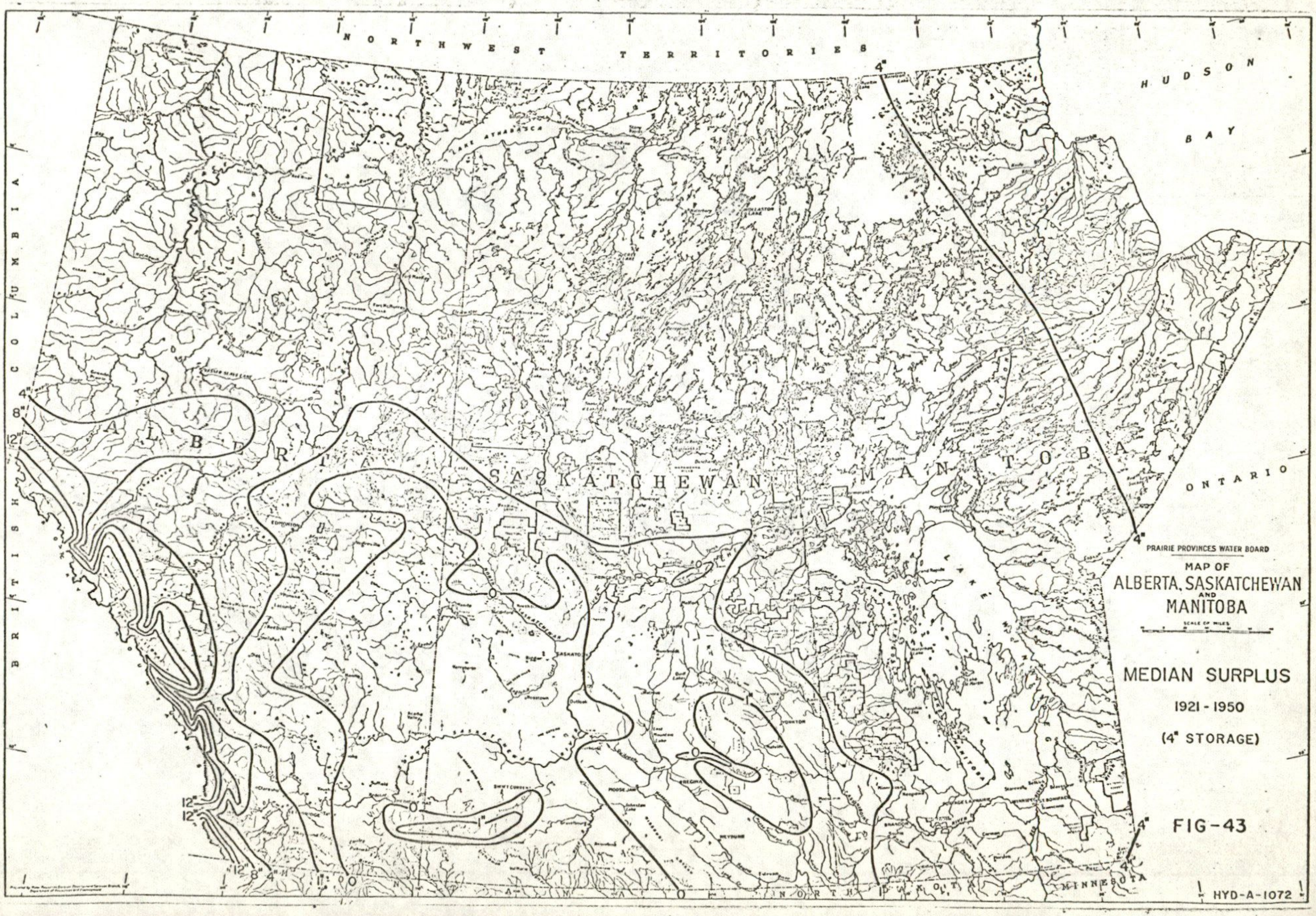
FIG-41

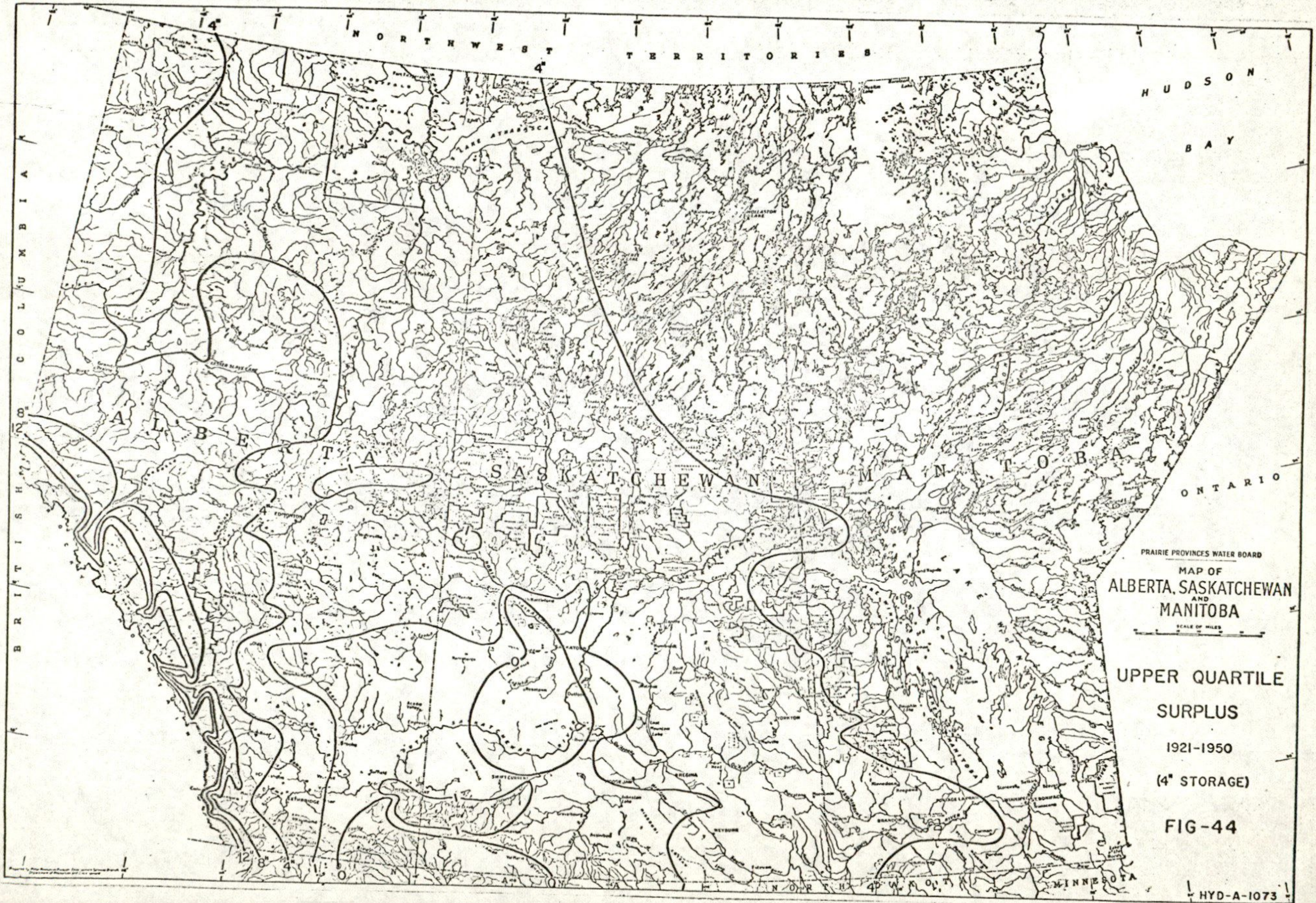
SURPLUS - 1936

(4" STORAGE)

FIG - 42

HYD-A-1071


NORTHWEST TERRITORIES
HUDSON BAY
ONTARIO
BRITISH COLUMBIA
ALBERTA
SASKATCHEWAN
MANITOBA
MINNESOTA
NORTH DAKOTA
PRAIRIE PROVINCES WATER BOARD
MAP OF
ALBERTA, SASKATCHEWAN AND MANITOBA
SCALE OF MILES
MEDIAN SURPLUS
1921 - 1950
(4" STORAGE)
4"
8"
12"
0
HYD-A-1072
FIG-43



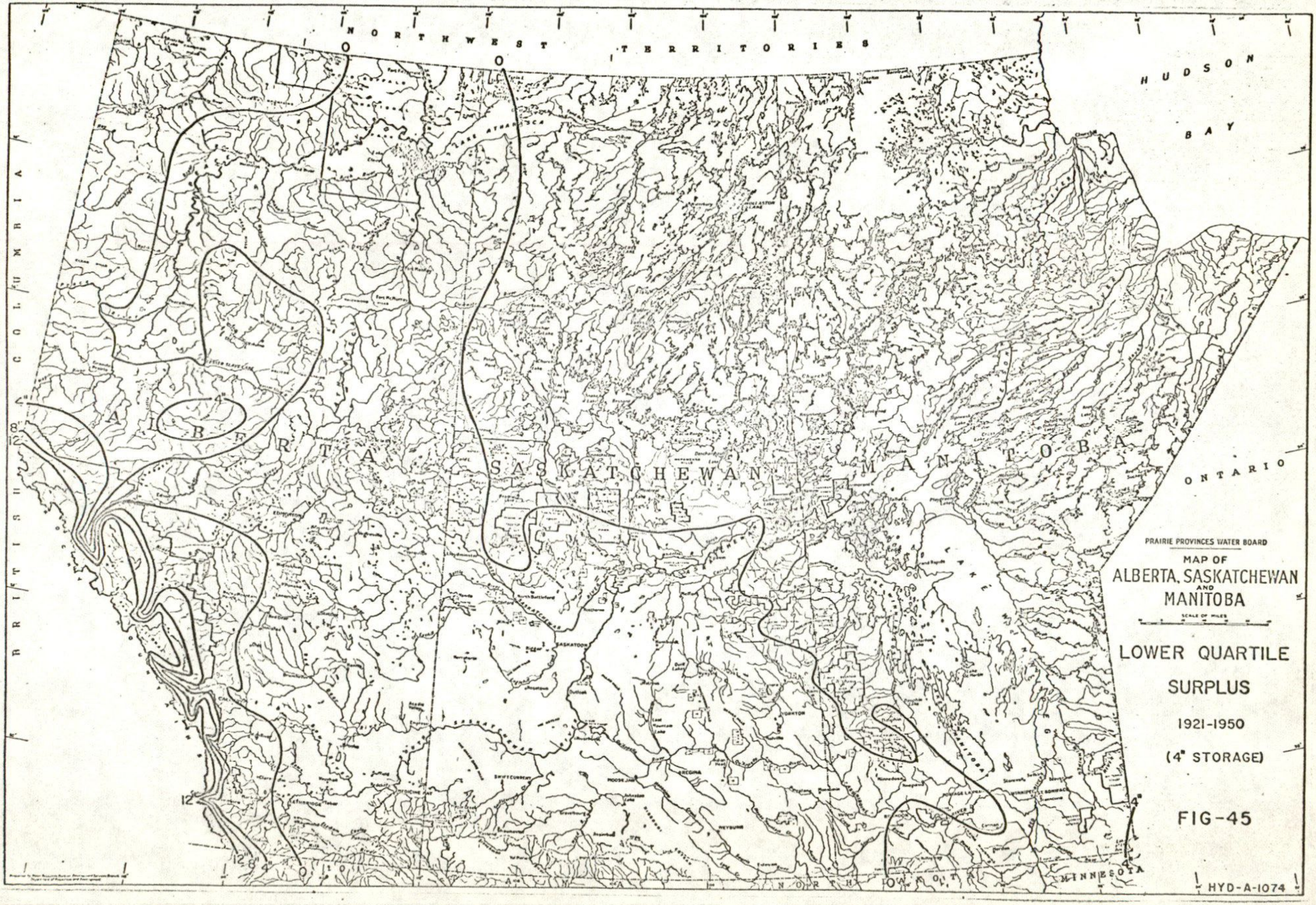
UPPER QUARTILE SURPLUS

1921-1950

(4" STORAGE)

FIG-44

HYD-A-1073


NORTHWEST TERRITORIES
HUDSON BAY
BRITISH COLUMBIA
ALBERTA
SASKATCHEWAN
MANITOBA
ONTARIO
MINNESOTA
NORTH DAKOTA
MONTANA
EDMONTON
SASKATOON
REGINA
MOOSE JAW
SWIFT CURRENT
YORKTON
PRAIRIE PROVINCES WATER BOARD
MAP OF
ALBERTA, SASKATCHEWAN AND MANITOBA
LOWER QUARTILE
SURPLUS
1921-1950
(4" STORAGE)
FIG-45
HYD-A-1074

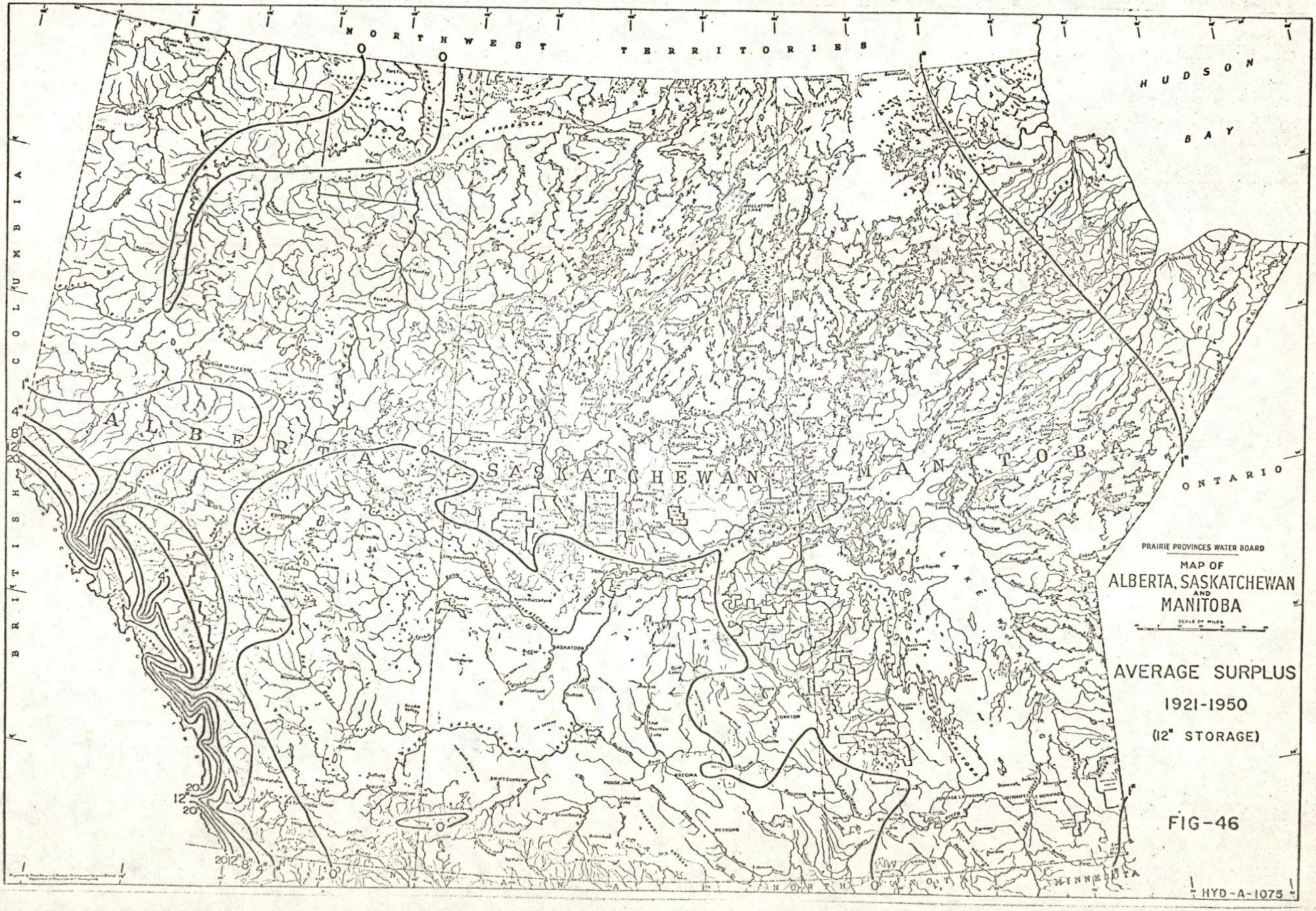
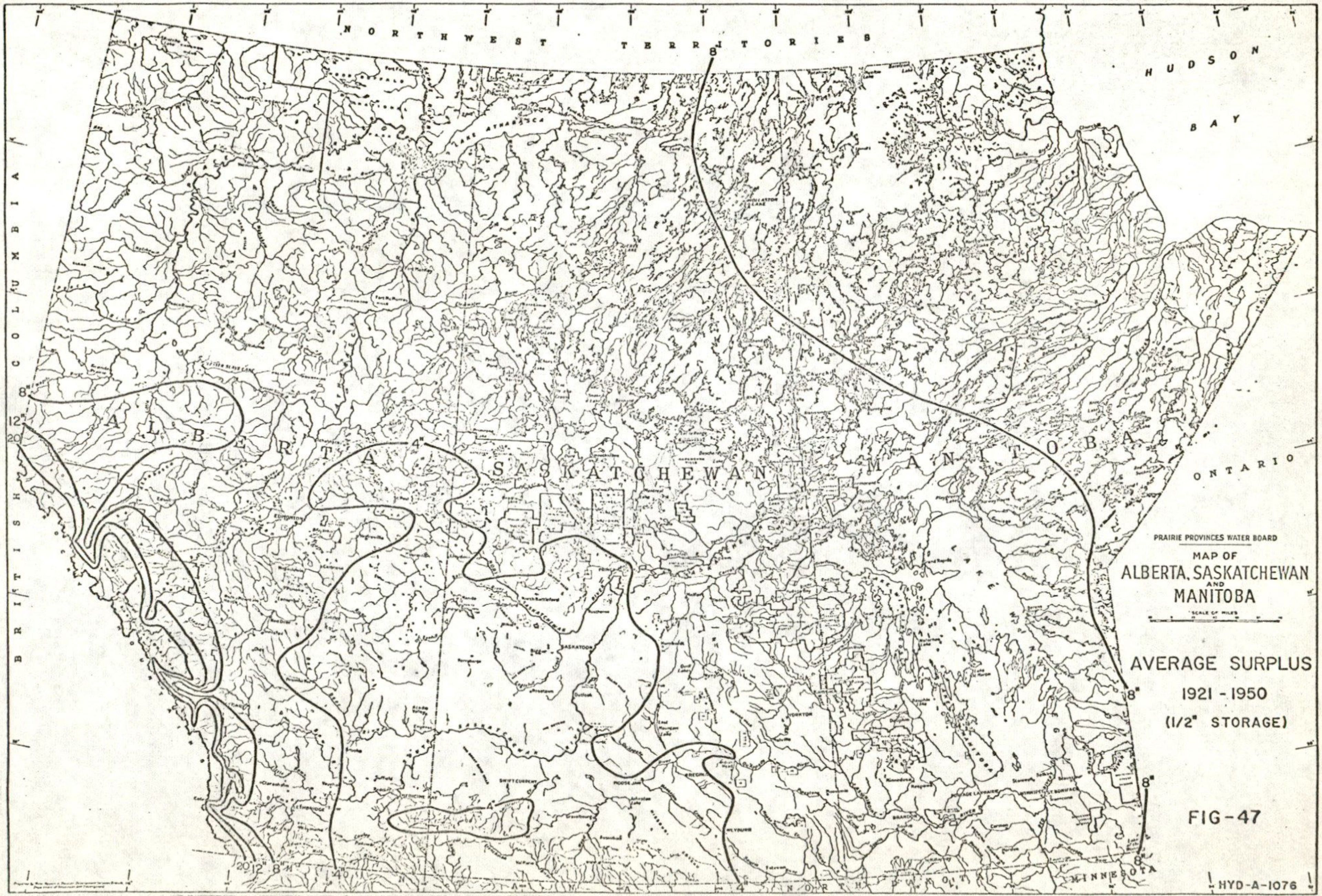


FIG-46

HYD-A-1075


NORTHWEST TERRITORIES
HUDSON BAY
BRITISH COLUMBIA
ALBERTA
SASKATCHEWAN
MANITOBA
ONTARIO
MINNESOTA
NORTH DAKOTA
SASKATOON
PRAIRIE PROVINCES WATER BOARD
MAP OF ALBERTA, SASKATCHEWAN AND MANITOBA
SCALE OF MILES
AVERAGE SURPLUS
1921 - 1950
(1/2" STORAGE)
8"
12"
20
4"
HYD-A-1076
FIG-47


NORTHWEST TERRITORIES
HUDSON BAY
BRITISH COLUMBIA
ALBERTA
SASKATCHEWAN
MANITOBA
ONTARIO
LAKE ATHABASCA
MINNESOTA
NORTH
8"
12"
4
PRAIRIE PROVINCES WATER BOARD
MAP OF
ALBERTA, SASKATCHEWAN
AND
MANITOBA
SCALE OF MILES
UPPER QUARTILE
SURPLUS
1921 - 1950
(1/2" STORAGE)
HYD-A-1077

FIG-48

PRAIRIE PROVINCES WATER BOARD

MAP OF
ALBERTA, SASKATCHEWAN AND MANITOBA

SCALE OF MILES

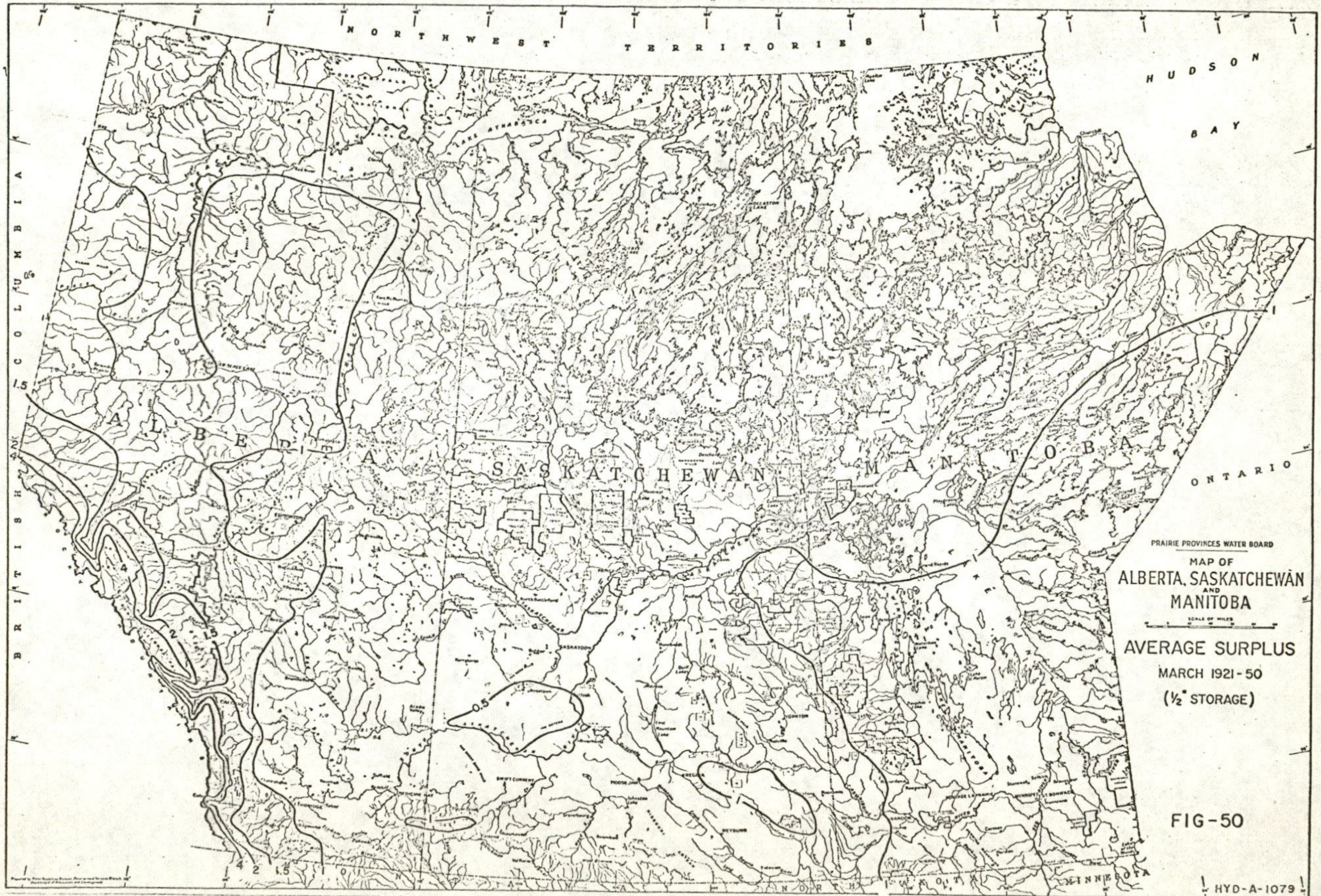
LOWER QUARTILE

1921-1950

(1/2" STORAGE)

FIG-49

HYD-A-1078



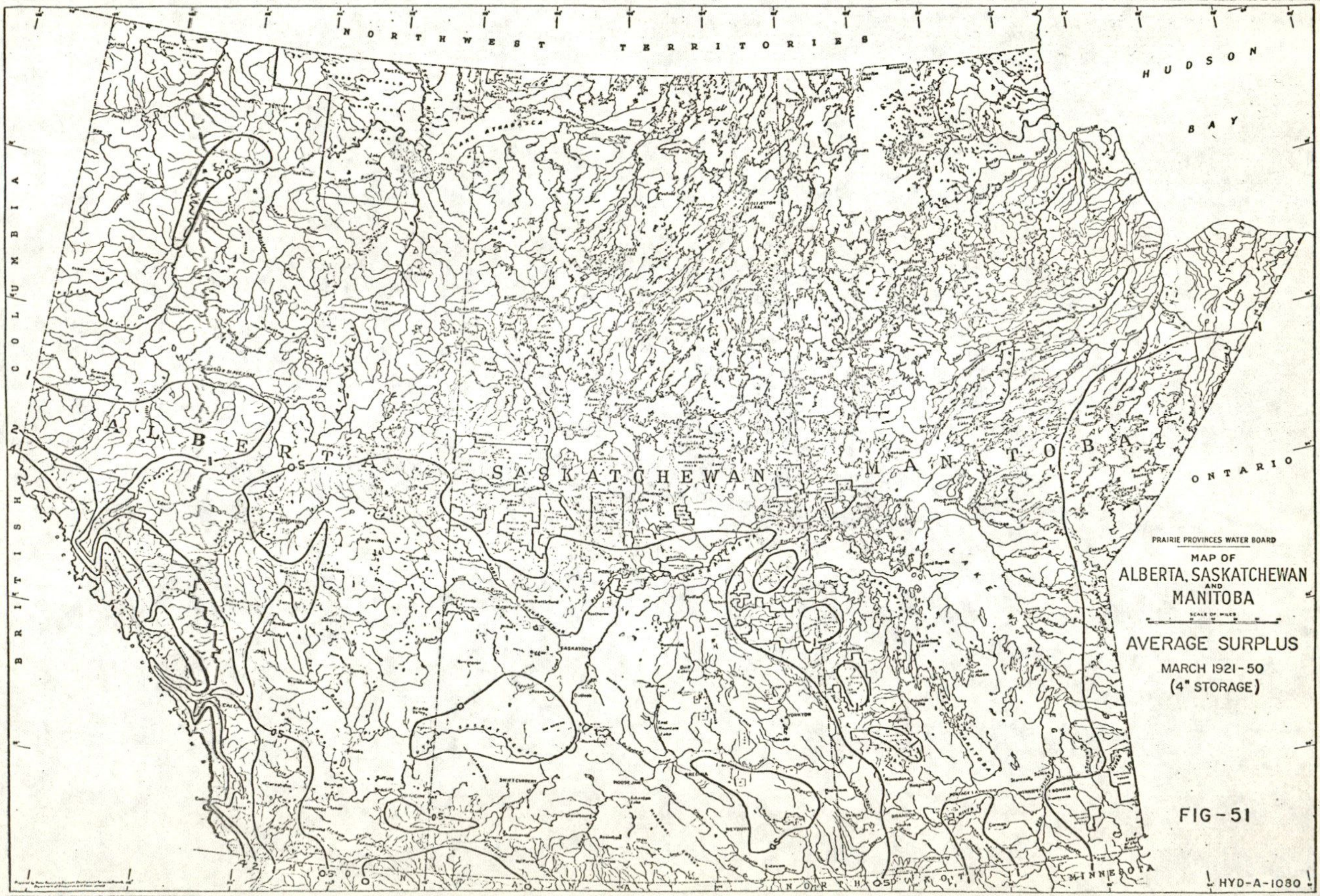
PRAIRIE PROVINCES WATER BOARD

MAP OF
ALBERTA, SASKATCHEWAN AND MANITOBA

AVERAGE SURPLUS
MARCH 1921-50
(½" STORAGE)

FIG-50

HYD-A-1079


NORTHWEST TERRITORIES
HUDSON BAY
BRITISH COLUMBIA
ALBERTA
SASKATCHEWAN
MANITOBA
ONTARIO
PRAIRIE PROVINCES WATER BOARD
MAP OF
ALBERTA, SASKATCHEWAN AND MANITOBA
SCALE OF MILES
AVERAGE SURPLUS
MARCH 1921-50
(4" STORAGE)
SASKATOON
MINNESOTA
NORTH DAKOTA
MONTANA
FIG-51
HYD-A-1080

PRAIRIE PROVINCES WATER BOARD

MAP OF
ALBERTA, SASKATCHEWAN AND MANITOBA

AVERAGE SURPLUS
APRIL 1921-50
(4" STORAGE)

FIG-52

HYD-A-1081


NORTHWEST TERRITORIES
HUDSON BAY
BRITISH COLUMBIA
ALBERTA
SASKATCHEWAN
MANITOBA
ONTARIO
MINNESOTA
EDMONTON
SASKATOON
SWIFT CURRENT
MOOSE JAW
YORKTON
BRANDON
PRAIRIE PROVINCES WATER BOARD
MAP OF
ALBERTA, SASKATCHEWAN
AND
MANITOBA
SCALE OF MILES
AVERAGE SURPLUS
MAY 1921-50
(4" STORAGE)
HYD-A-1082

FIG-53

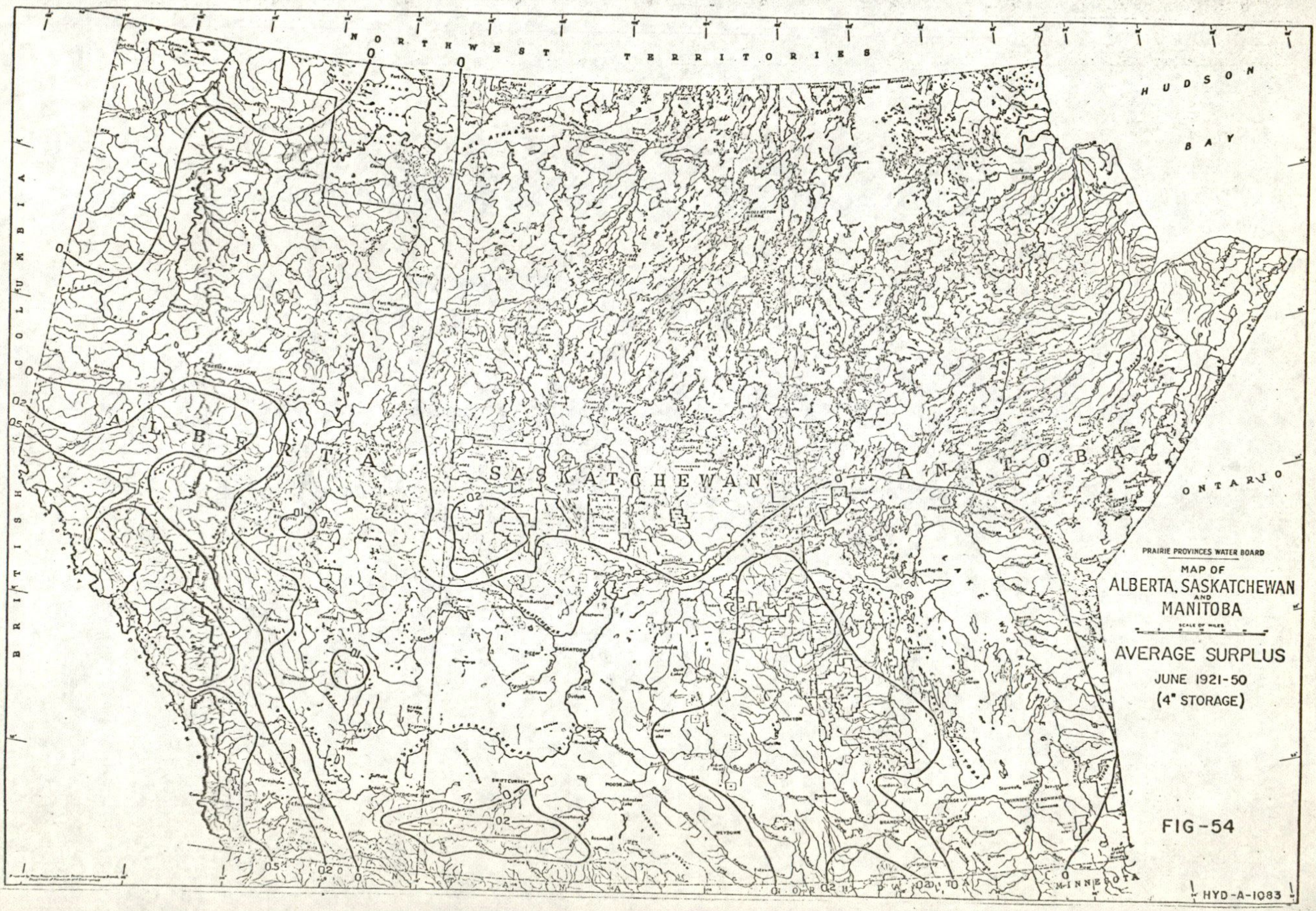


FIG-54

HYD-A-1083

PRAIRIE PROVINCES WATER BOARD

MAP OF
ALBERTA, SASKATCHEWAN AND MANITOBA

AVERAGE SOIL MOISTURE STORAGE
AT THE END OF APRIL 1921-50
(4" STORAGE)

FIG-55

HYD-A-1084

FIG-56

HYD-A-1085

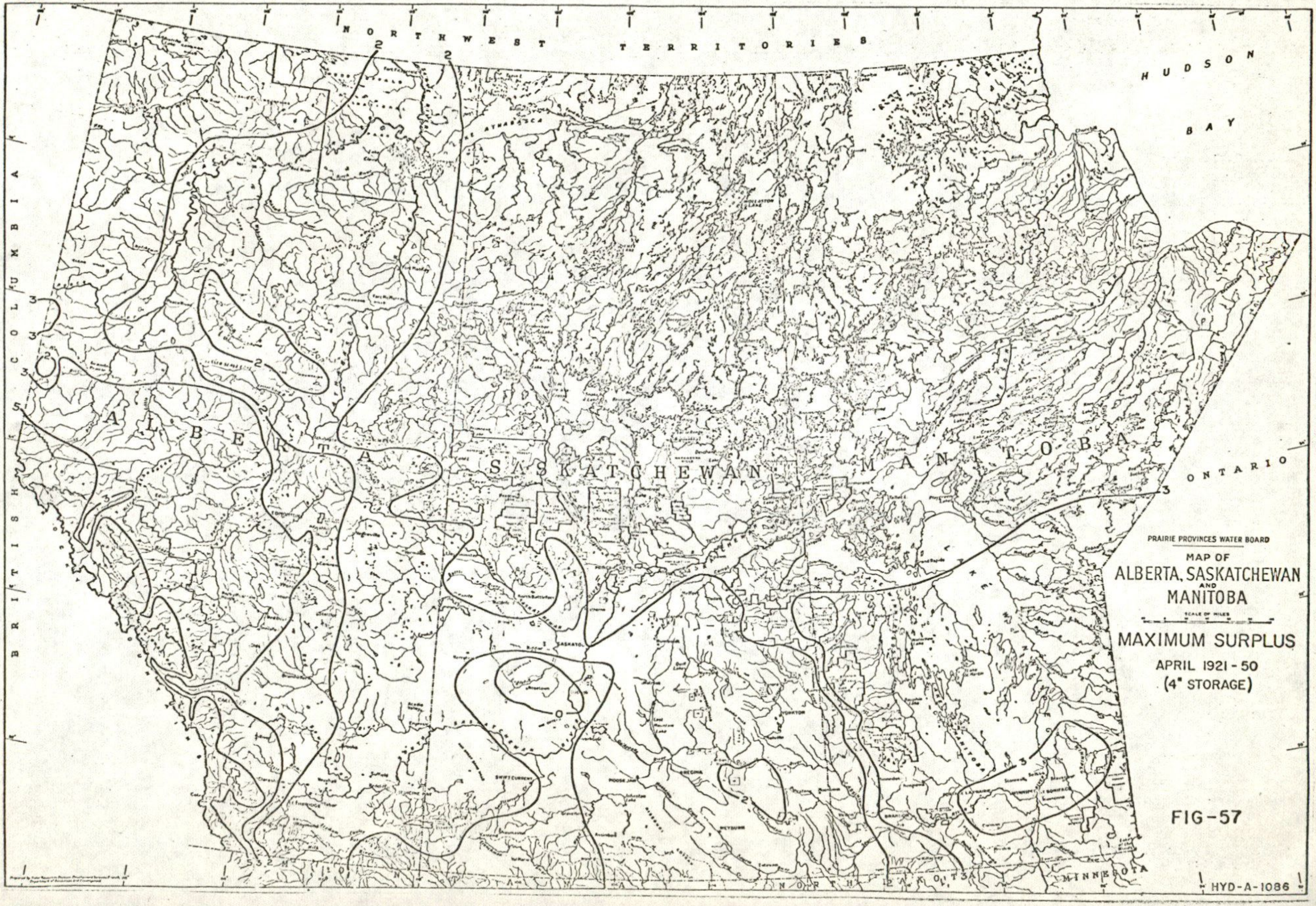


FIG-57

HYD-A-1086

PRAIRIE PROVINCES WATER BOARD

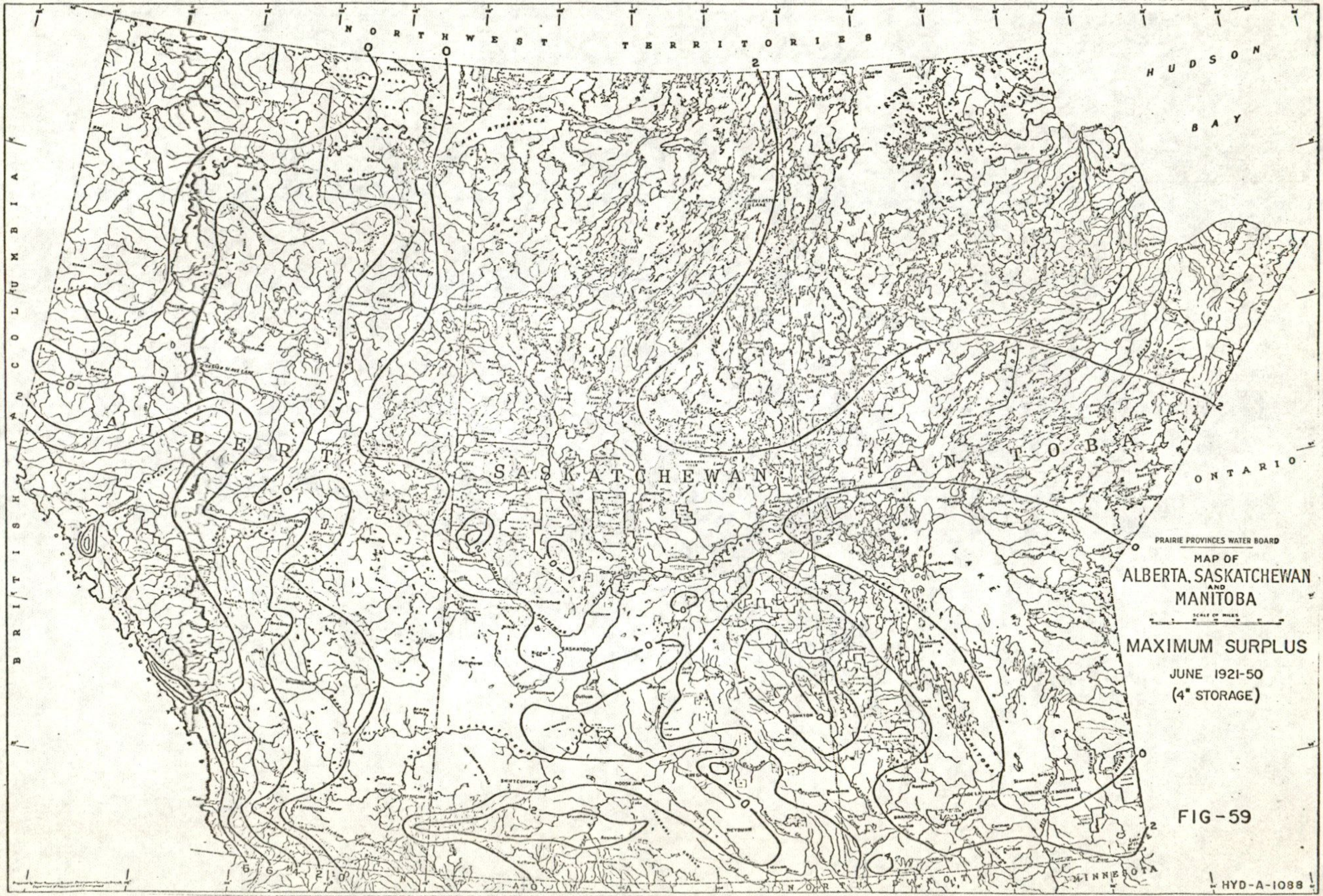
MAP OF
ALBERTA, SASKATCHEWAN AND MANITOBA

SCALE OF MILES

MAXIMUM SURPLUS
MAY 1921-50
(4" STORAGE)

FIG-58

HYD-A-1087


NORTHWEST TERRITORIES
HUDSON BAY
BRITISH COLUMBIA
ALBERTA
SASKATCHEWAN
MANITOBA
ONTARIO
MINNESOTA
PRAIRIE PROVINCES WATER BOARD
MAP OF
ALBERTA, SASKATCHEWAN AND MANITOBA
MAXIMUM SURPLUS
JUNE 1921-50
(4" STORAGE)
HYD-A-1088
FIG-59

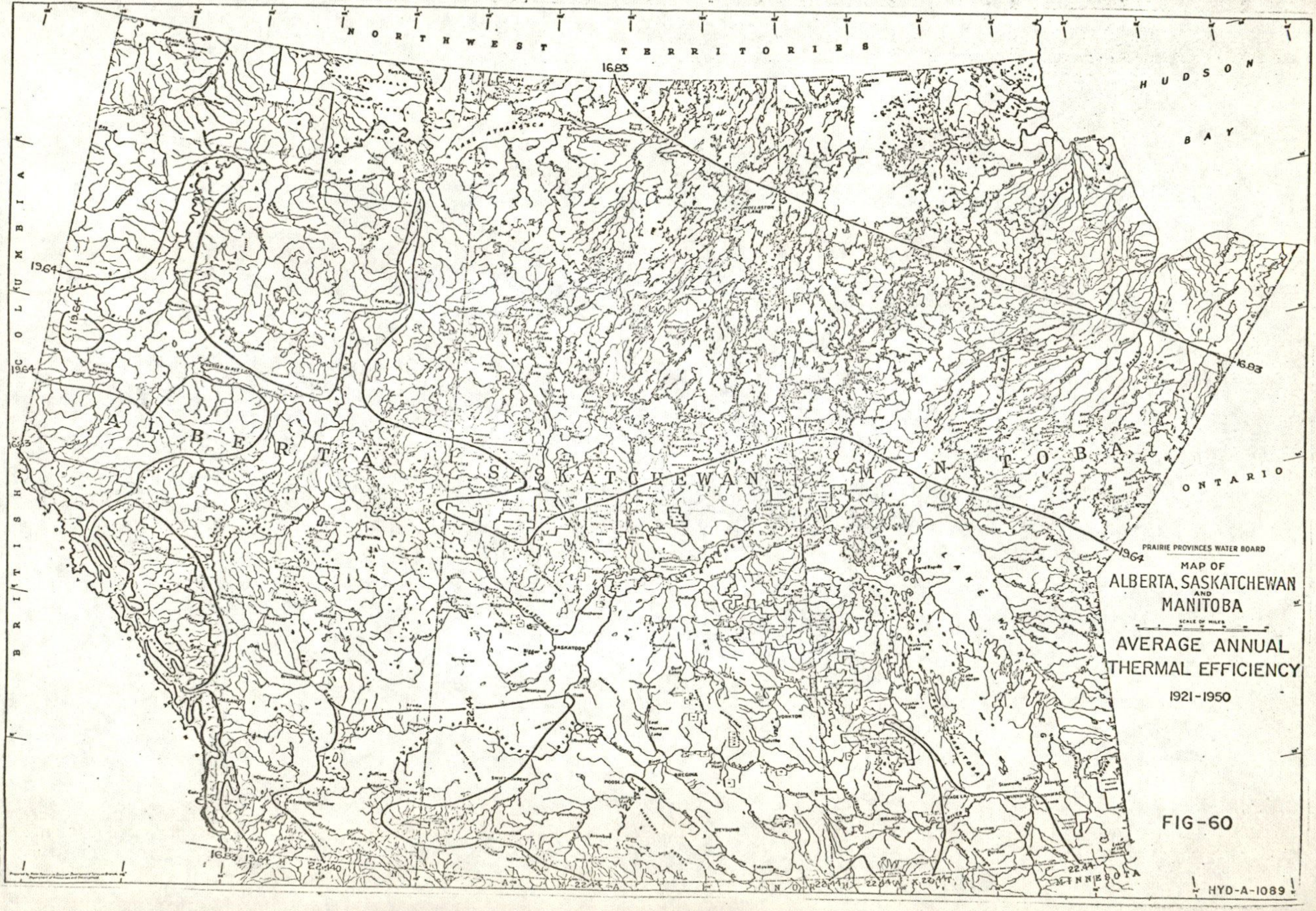
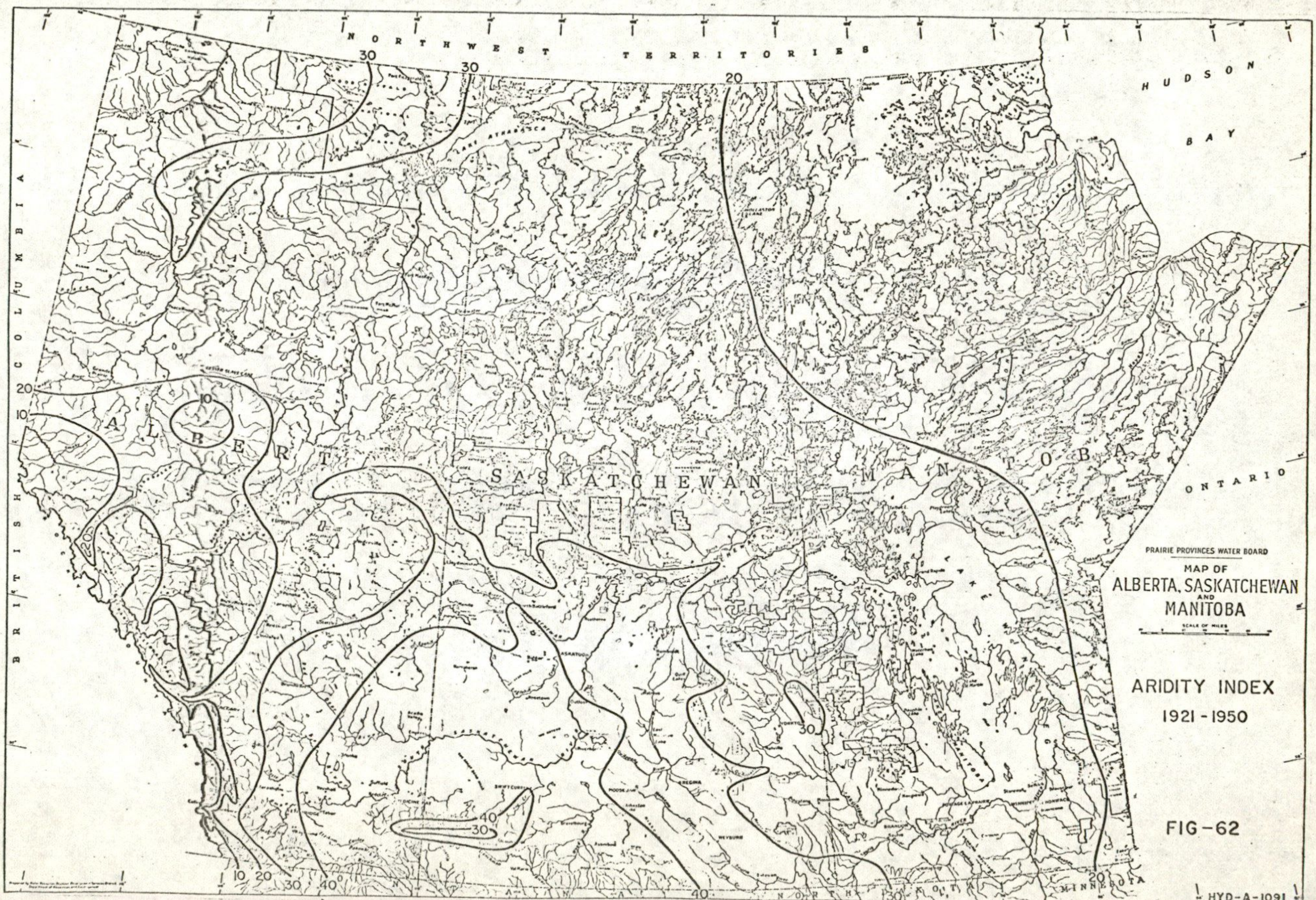

NORTHWEST TERRITORIES
HUDSON BAY
BRITISH COLUMBIA
ALBERTA
SASKATCHEWAN
MANITOBA
ONTARIO
MINNESOTA
16.83
19.64
22.44
SASKATOON
REGINA
MOOSE JAW
YORKTON
BRANDON
PRAIRIE PROVINCES WATER BOARD
MAP OF
ALBERTA, SASKATCHEWAN AND MANITOBA
AVERAGE ANNUAL THERMAL EFFICIENCY
1921-1950
HYD-A-1089

FIG-60

FIG - 61

HYD-A-1090



ARIDITY INDEX

1921 - 1950

FIG - 62

HYD-A-1091

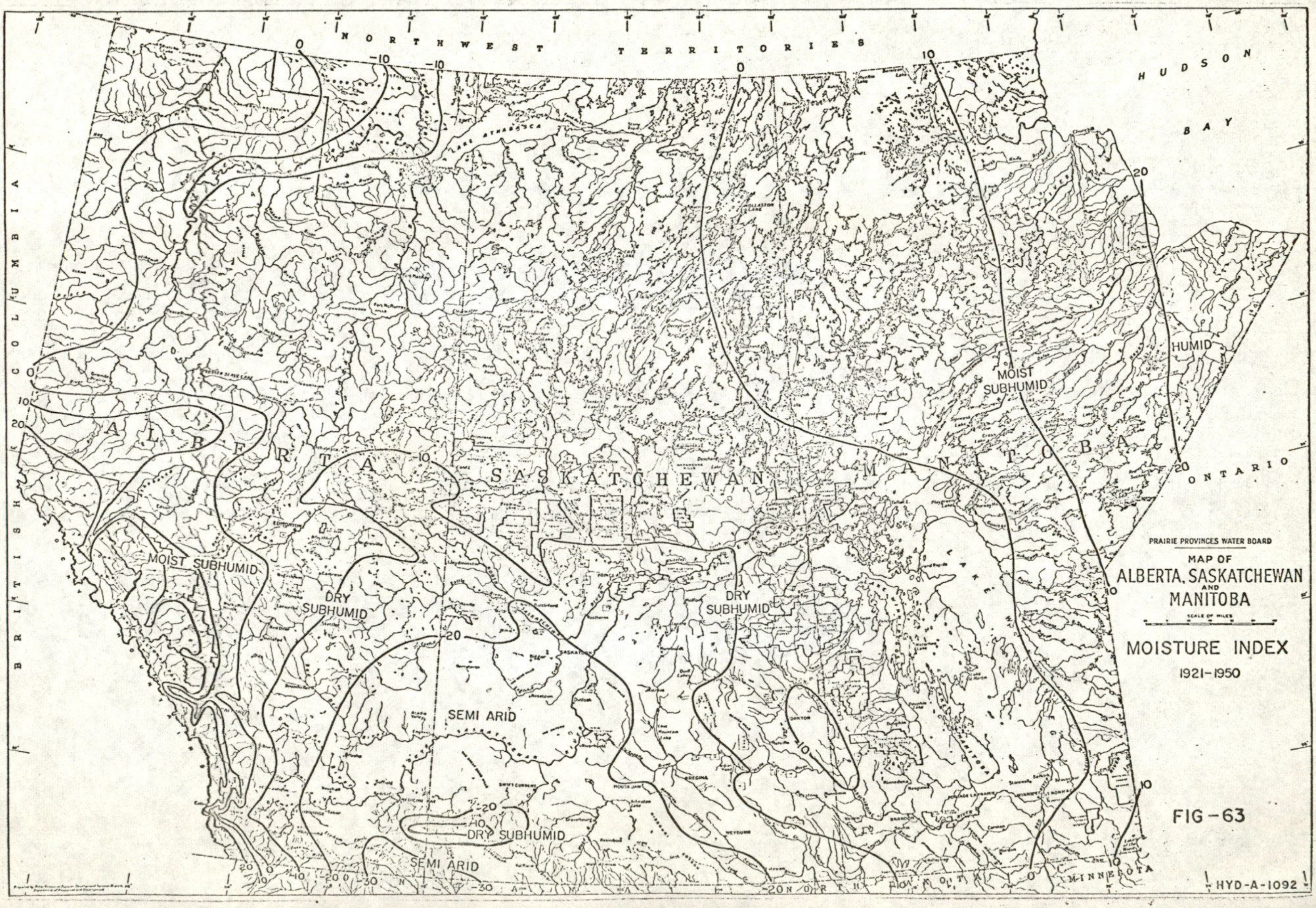
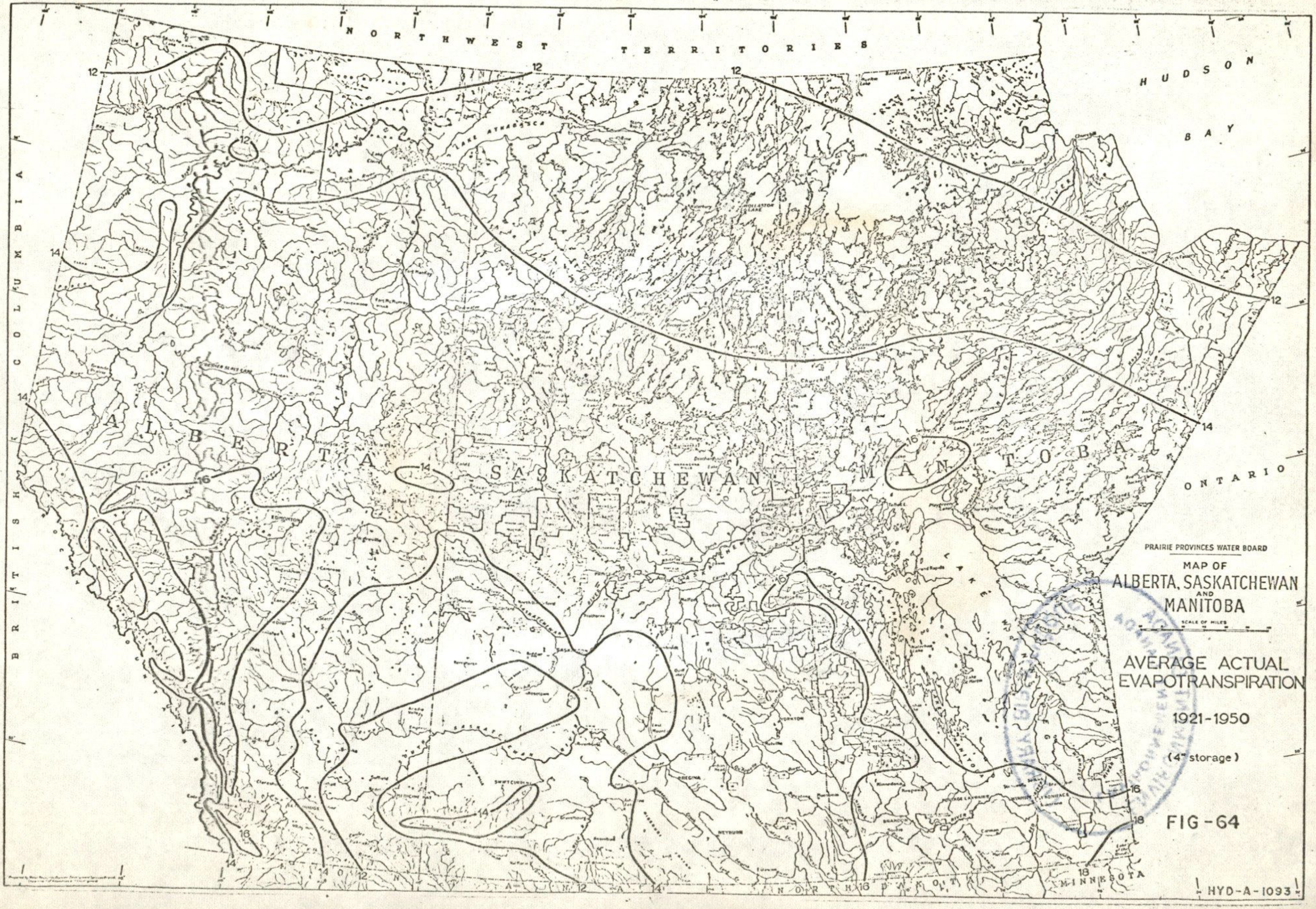

NORTHWEST TERRITORIES
HUDSON BAY
BRITISH COLUMBIA
ALBERTA
SASKATCHEWAN
MANITOBA
ONTARIO
MINNESOTA
LAKE ATHABASCA
MOIST SUBHUMID
HUMID
DRY SUBHUMID
SEMI ARID
PRAIRIE PROVINCES WATER BOARD
MAP OF
ALBERTA, SASKATCHEWAN AND MANITOBA
SCALE OF MILES
MOISTURE INDEX
1921-1950
HYD-A-1092

FIG-63


NORTHWEST TERRITORIES
HUDSON BAY
BRITISH COLUMBIA
ALBERTA
SASKATCHEWAN
MANITOBA
ONTARIO
NORTH DAKOTA
MINNESOTA
LAKE ATHABASCA
12
14
16
18
PRAIRIE PROVINCES WATER BOARD
MAP OF
ALBERTA, SASKATCHEWAN
AND
MANITOBA
SCALE OF MILES
AVERAGE ACTUAL
EVAPOTRANSPIRATION
1921-1950
(4" storage)
FIG-64
HYD-A-1093