ALBERTA OIL SANDS ENVIRONMENTAL RESEARCH PROGRAM

Synthesis of Surface Water Hydrology

Project WS 1.1.1

June 1979

Sponsored jointly by

Alberta ENVIRONMENT

Environment Canada Environnement Canada

15th Floor, Oxbridge Place
9820 - 106 Street
Edmonton, Alberta, Canada
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ALBERTA OIL SANDS ENVIRONMENTAL RESEARCH PROGRAM RESEARCH REPORTS

These research reports describe the results of investigations funded under the Alberta Oil Sands Environmental Research Program, which was established by agreement between the Governments of Alberta and Canada in February 1975 (amended September 1977). This 10-year program is designed to direct and co-ordinate research projects concerned with the environmental effects of development of the Athabasca Oil Sands in Alberta.

A list of research reports published to date is included at the end of this report.

Enquiries pertaining to the Canada-Alberta Agreement or other reports in the series should be directed to:

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SYNTHESIS OF SURFACE WATER HYDROLOGY

Project WS 1.1.1

AOSERP REPORT 60

This report may be cited as:

Neill, C.R., and B.J. Evans. 1979. Synthesis of surface water hydrology. Prep. for the Alberta Oil Sands Environmental Research Program by Northwest Hydraulic Consultants Ltd. AOSERP Report 60. 84 pp.

The Hon. J.W. (Jack) Cookson
Minister of the Environment
222 Legislative Building
Edmonton, Alberta

and

The Hon. John Fraser
Minister of the Environment
Environment Canada
Ottawa, Ontario

Sirs:

Enclosed is the report "Synthesis of Surface Water Hydrology".

This report was prepared for the Alberta Oil Sands Environmental Research Program though its Water System, under the Canada-Alberta Agreement of Feburary 1975 (amended September 1977).

Respectfully,

W. Solodzuk, P. Eng.
Chairman, Steering Committee, AOSERP
Deputy Minister, Alberta Environment

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Member, Steering Committee, AOSERP
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SYNTHESIS OF SURFACE WATER HYDROLOGY

DESCRIPTIVE SUMMARY

BACKGROUND:

A large number of raw hydrometric and meteorological data have been collected for the oil sands area. However, only limited analysis of some of these data had been conducted under Alberta Oil Sands Environmental Research Program (AOSERP) direction in two projects "Evaluation of Baseline Hydrometric and Water Quality Networks in the AOSERP Study Area" and "An Intensive Study of the Water Quality of the Muskeg River Watershed" (in preparation). Therefore, a need for a study elucidating the state of the surface water as well as its interactions with the atmospheric, land, and groundwater was discerned.

The intention of this project was to provide an overview and analysis of all accumulated data to the end of year three of AOSERP (31 March 1979) in order to provide advisors, researchers, and others in AOSERP with an understanding of the hydrological processes that operate in the study area. Detailed objectives for this project are found in the Appendix of the report.

EVALUATION:

This project has been completed in terms of the objectives set forth. The report has been reviewed by engineers and scientists in Alberta Environment, Environment Canada, and the University of Alberta, and the final report contains the authors' responses to review input. The conclusions of the report do not necessarily reflect the views of Alberta Environment or Environment Canada and the mention of trade names for commerical products does not constitute an endorsement or recommendation for use. The Alberta Oil Sands Environmental Research Program is pleased to accept the report,

"Synthesis of Surface Water Hydrology", as an important and valid document to receive wide distribution. The authors are thanked for their contribution.

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SYNTHESIS OF
SURFACE WATER HYDROLOGY

by

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for

ALBERTA OIL SANDS

ENVIRONMENTAL RESEARCH PROGRAM

Project WS 1.1.1

June 1979

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ABSTRACT

The drainage system of the study area consists of a number of rivers draining from the west and from the east into the Athabasca River north of Fort McMurray, as well as a few rivers which join the Athabasca near Fort McMurray and drain areas to the south and east. Runoff from within the study area itself contributes less than 10% of the average flow in the Athabasca River at the northern boundary of the study area. Roughly 60% of annual runoff occurs in the 4-month period April through July.

Runoff represents on the average only about 20% of the precipitation that falls on the area, the remainder being returned to the atmosphere by evaporation and transpiration. Although snowfall constitutes only about 30% of precipitation, its proportional contribution to runoff is generally much greater. On the east slopes of the Birch Mountains, runoff from rainfall appears to be remarkably small.

Although the spatial variability of average runoff over the study area is not well defined by available streamflow data, it is clear that there is a wide range, from perhaps 30 mm per year on the east slopes of the Birch Mountains to 160 mm per year south of Fort McMurray. These differences are due only in part to differences in precipitation, and must reflect to a greater degree differences in physiographic features that affect evapotranspiration.

Year to year variations in runoff are quite high for many of the rivers draining the study area. For example, annual flow volumes in the MacKay River have varied fourfold in only five years of records. In the Athabasca River, annual variations are much less, covering approximately a twofold range in a 20-year period.

Few data are available to permit analysis of interactions between surface water and groundwater. Observational well data indicate substantial recharge of groundwater following snowmelt and rainstorms. There are indications that on the east slopes of the Birch Mountains, substantial subsurface flow to the Athabasca River

may account in part for the low measurements of runoff in this area.

Features of the hydrologic regime that merit further investigation in relation to development impacts include the very low natural runoff in some areas, interactions between surface water and groundwater and the relationship of runoff characteristics to basin physiography and vegetal cover.

ACKNOWLEDGEMENTS

This study was funded by the Alberta Oil Sands Environmental Research Program, a joint Alberta-Canada program established to fund direct and co-ordinate research into the effects of oil sands development on renewable resources. The authors wish to acknowledge helpful advice and suggestions from program scientific personnel R.T. Seidner and A.S. Mann.

We also wish to acknowledge advice, information and assistance from the following persons and agencies:

D. Hackbarth, Alberta Research Council

Syncrude Canada Ltd., Edmonton

Water Survey of Canada, Calgary

C.R. Froelich, Alberta Environment

W. Griffiths, LGL Ltd.

B. Janz and other staff of Atmospheric Environment Service, Edmonton

Critiques of an interim report and of a final draft, by external reviewers engaged by program management, were found generally helpful. We apologize for the inability to deal fully with all criticisms and suggestions received.

The report was typed by S.M. Hiebert and diagrams were prepared by D.E. Jacobs, both of Northwest Hydraulic Consultants Ltd. A.L. Charbonneau acted as internal reviewer.

1. INTRODUCTION

1.1 OBJECTIVES AND SCOPE

The main objective of the study is to provide an overview and interpretation of the hydrometeorological information available to March 1978, and thereby explain so far as practicable the hydrological processes and relationships that operate in the study area of the Alberta Oil Sands Environmental Research Program (AOSERP), as defined in Figure 1. Subsidiary objectives are to identify problems in data utilization, and to assess future research needs in relation to potential development impacts on the surface water system. The present study is one of a series of Baseline States studies being prepared at the end of Year 3 for the Research Program: these studies are designed to describe current understanding of baseline states and to establish a conceptual framework for subsequent research. Later studies will be concerned more with impact and mitigation.

Terms of reference for the study are given in Section 9.1. The scope of the study is limited mainly to consideration of quantities of surface water flowing in the drainage systems of the study area, and of their interactions with atmospheric water and groundwater. Water quality, sedimentation, and groundwater hydrogeology are covered in other AOSERP reports. The impact of present and future developments on hydrological systems is not considered in depth in the present report. Sources of data are referenced, but data compilations are not included.

In general, data utilized for analysis were dated up to 31 December 1977 only, because 1977 was the last year for which full-year data were available at the time the analyses were carried out. In many cases, a selective approach had to be taken to analysis, for logistic reasons.

1.2 SURFACE WATER SYSTEM OF THE STUDY AREA

The main components of the surface water system in the study area, as illustrated in Figure 2, are as follows:

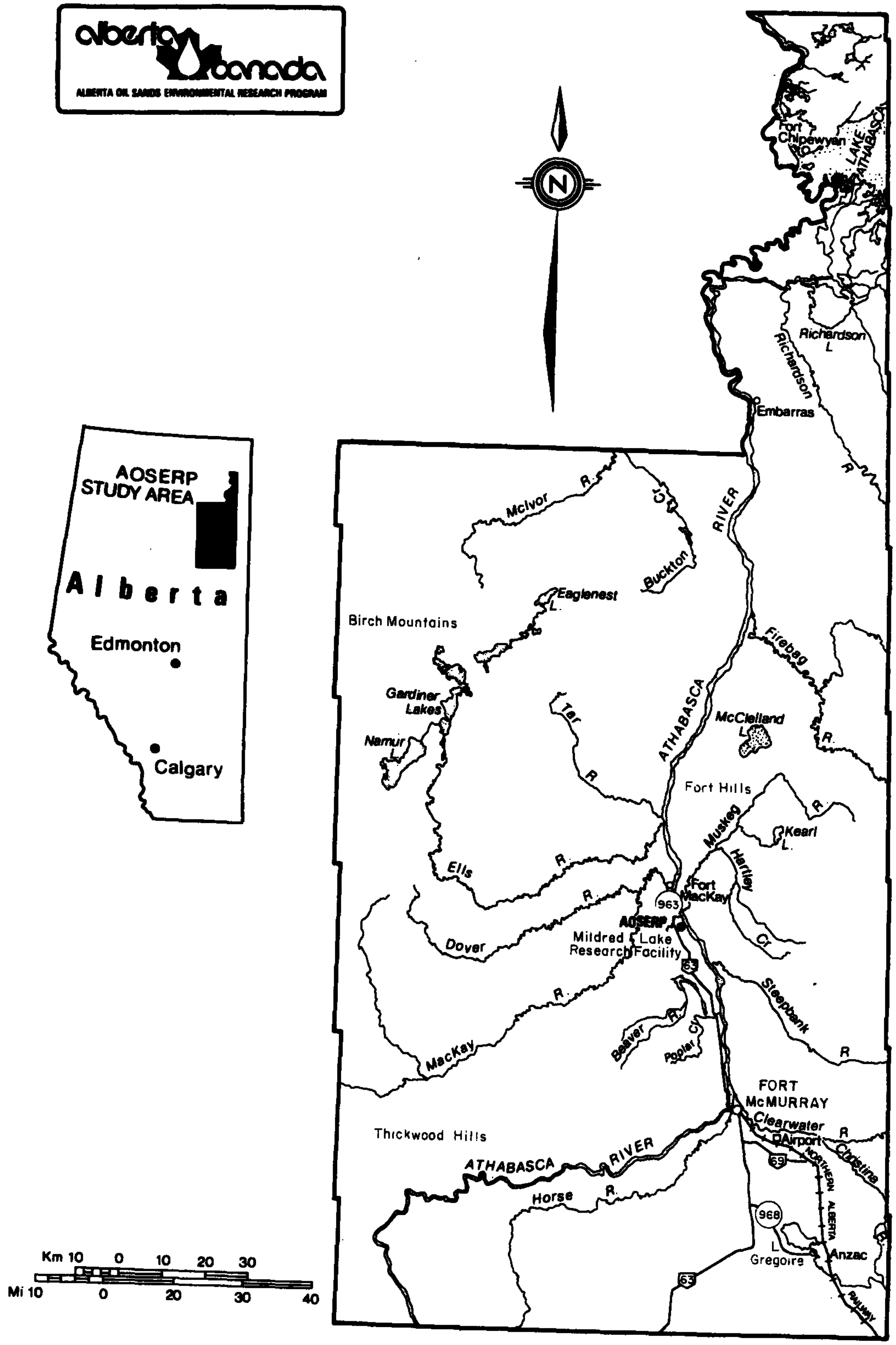


Figure 1. The AOSERP study area.

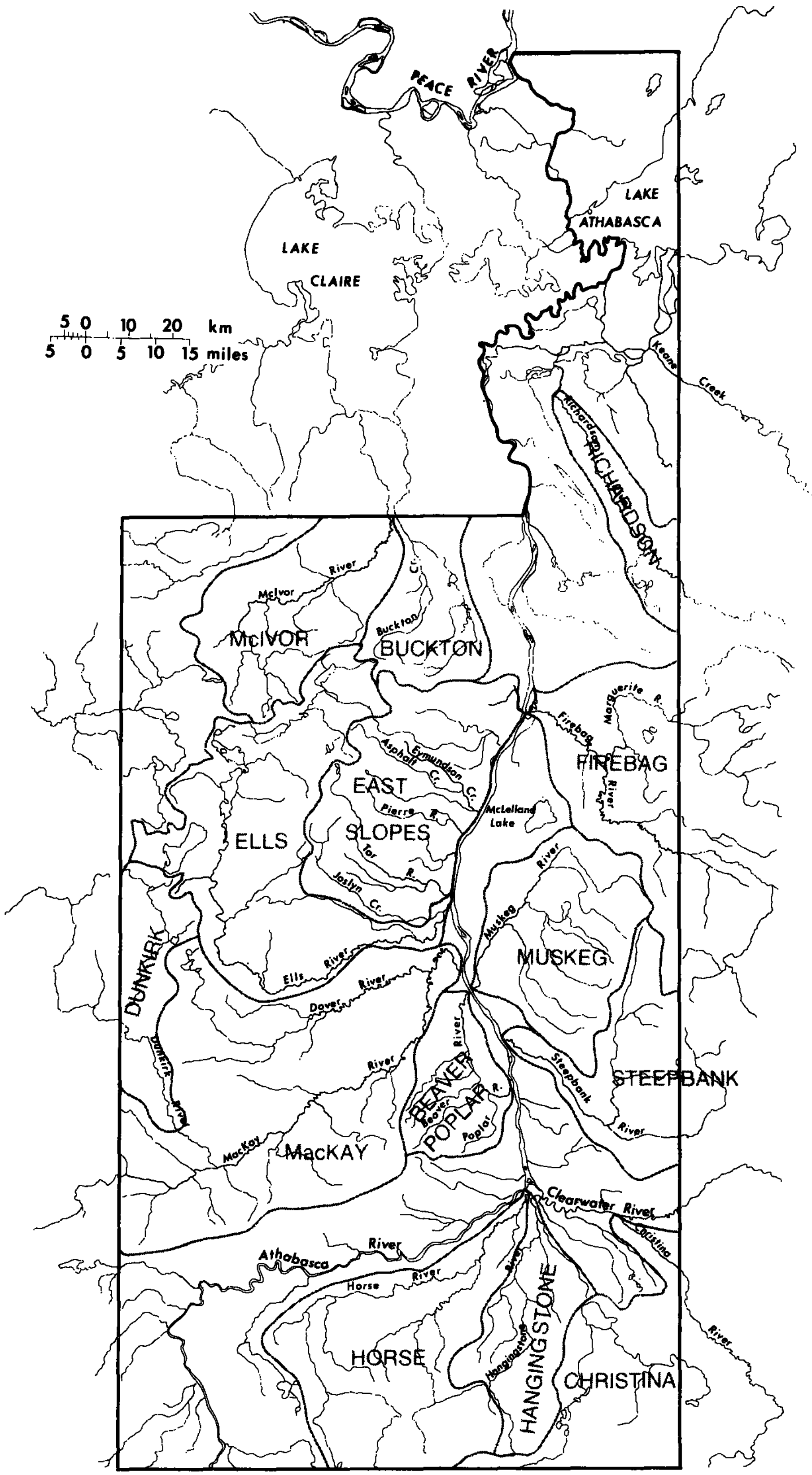
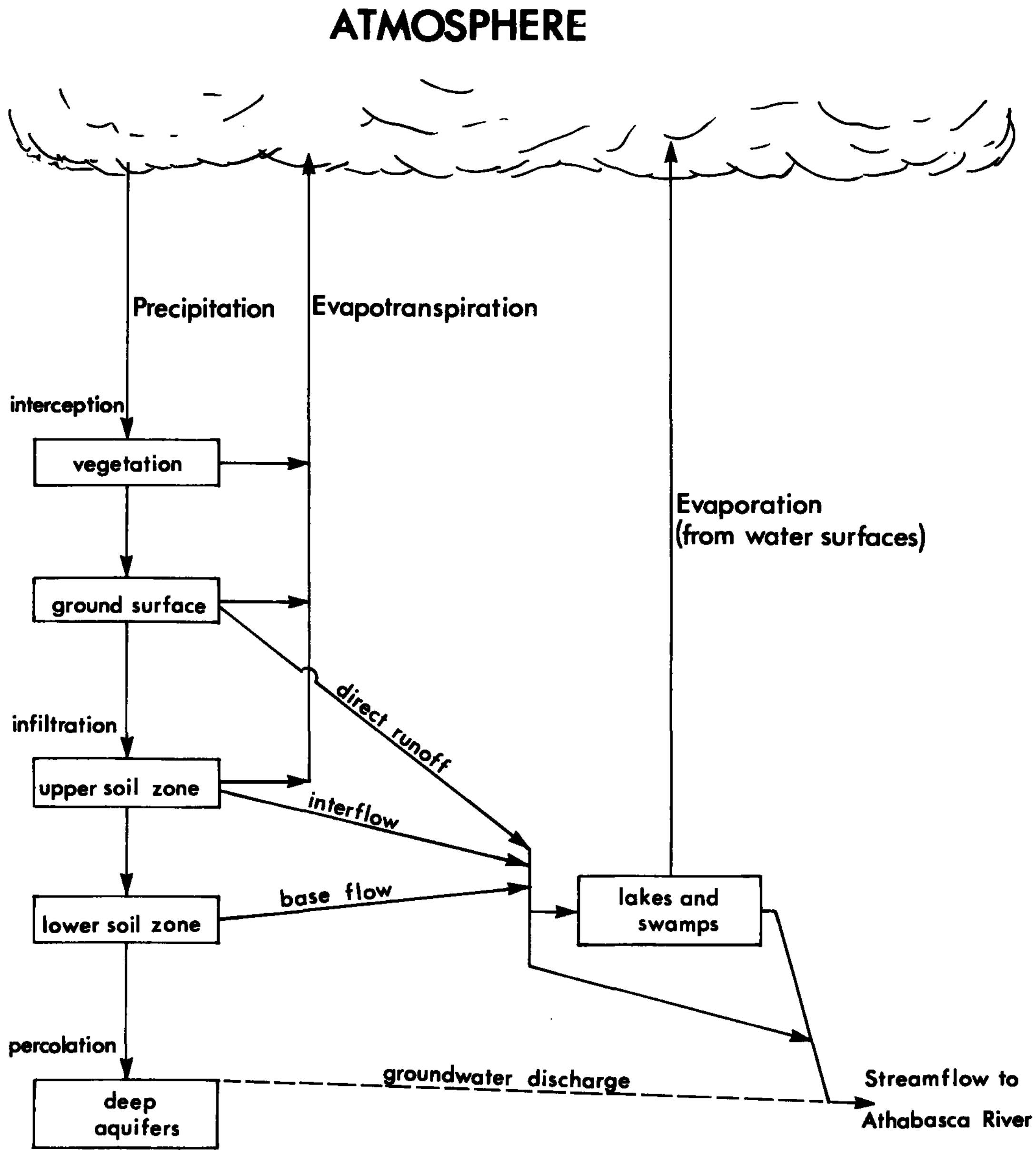


Figure 2. Surface water drainage system.

1. The Athabasca River, which enters the study area from the southwest and terminates in the Lake Athabasca and Peace-Athabasca Delta system at the north end. Its drainage area originates in Jasper National Park and covers a wide band of territory extending northeast to Lake Athabasca. The greater part of the river flow originates from the upper basin in the mountains and foothills;
2. The Clearwater River, which enters the study area from the east to join the Athabasca at Fort McMurray. Its flow originates mainly from northwestern Saskatchewan;
3. Tributary streams south of Fort McMurray, of which the most important within the study area are the Horse and Hangingstone rivers. A small part of the drainage area of the Christina River, a tributary of the Clearwater, lies within the study area;
4. Tributaries flowing from the west to the Athabasca River north of Fort McMurray. The most important are the MacKay, Beaver, and Ells rivers, with a number of smaller streams on the east slopes of the Birch Mountains;
5. Tributaries flowing from the east to the Athabasca River north of Fort McMurray. The most important are the Steepbank, Muskeg, and Firebag rivers. The upper parts of the Steepbank and Firebag drainage basins lie outside the study area; and
6. Rivers flowing north toward Lake Athabasca. The most important are the McIvor, Buckton, and Richardson rivers. Only parts of their basins lie within the study area.

A general concept of the hydrologic cycle, as it operates in the study area, is illustrated in Figure 3. As will be shown, surface runoff (streamflow) originating from drainage basins within the study area accounts for only a small fraction of the water that falls on the area. By far the greater part of precipitation is returned to the atmosphere by evaporation and transpiration.



NOTE

Water Balance Equation: Precipitation − (runoff + ground recharge + evapotranspiration)
= increase in storage

On long term basis, increase in storage = 0

Figure 3. Hydrologic cycle in the study area.

1.3 AVAILABILITY AND UTILITY OF HYDROMETEOROLOGICAL DATA

The principal data used in the study, in order of importance, are streamflow, precipitation, snow on ground, temperatures and evaporation. Availabity and utility of each category are discussed in sequence below.

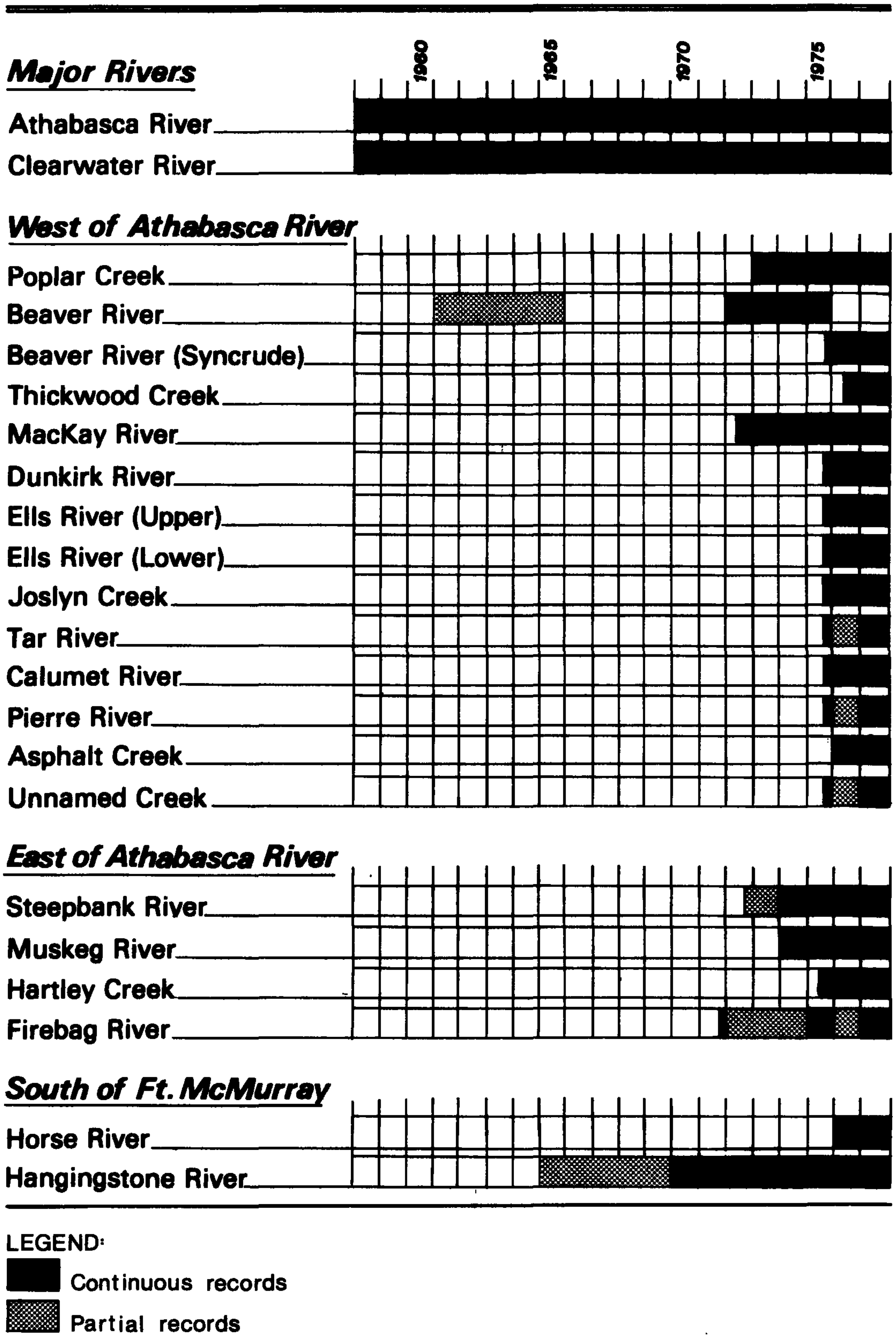
1.3.1 Streamflow

Statistical analysis of streamflow records normally requires some 20 to 30 years of data to give a reasonable picture of variability over the long term. As shown in Table 1, only two stations in the study area meet this standard: Athabasca River below Fort McMurray and Clearwater River above Fort McMurray, both gauged since 1957. For estimation of mean flows only, five years of record are usually acceptable. Six other rivers have been gauged for five years or more: Hangingstone, Poplar Creek, Beaver, MacKay, Firebag, and Richardson. Approximately 12 other rivers have data for 1976 and 1977 only. In addition, a downstream gauge on the Athabasca River at Embarras has records since 1971. To the north, some of the tributaries to Lake Athabasca and the delta system have records of reasonable length. Details of individual record periods are given in other AOSERP reports and will not be repeated here (Loeppky and Spitzer 1977; Yaremko and Murray in prep.).

Although the relatively long period records of the Athabasca and Clearwater rivers are of considerable hydrological interest, they do not represent runoff from the study area, but rather a large flow of water that originates from outside and passes through. Most of the basins draining the study area itself are represented by fairly short term records, many covering only two calendar years up to December 1977. It is these tributary streams that are likely to be of greater concern with regard to development impacts.

The quality of streamflow records is difficult to define. Published data compilations (Loeppky and Spitzer 1977; Warner and Spitzer 1979) indicate that discharge data for most of the larger rivers should be fairly reliable, although difficulties are evident with a

Table 1. Length of streamflow records.



few of the smaller basins where beaver dams and other phenomena have affected readings. Unexplained discrepancies exist, however, between Athabasca River data for Fort McMurray and Embarras, despite apparently good gauging conditions at both sites: differences in reported annual flows do not appear to check with tributary inflows and are sometimes negative (Table 2). Because of this, it is not possible to rely on differences between these two Athabasca River gauges to indicate the total inflow from the study area over periods of a year or less. Because the flows from the study area are small compared to flows in the Athabasca River, errors of only a few percent at the two Athabasca River gauges can invalidate the gauge records for this purpose.

Because many basins have been gauged only in 1976 and 1977, information on the spatial distribution of runoff from different parts of the study area is generally limited to these two years.

1.3.2 Precipitation

The meteorological data base in the study area is discussed in a climatology report (Longley and Janz 1978). The only long-term full-year precipitation records are for Fort McMurray, where a station has existed since 1908; in 1944 it was transferred from the town site to the airport. Other full-year records of reasonable length are for Embarras Airport (1943 to 1962) and Fort Chipewyan (1962 to present). Full-year data were also obtained at Stony Mountain, south of Fort McMurray, from 1957 to 1963.

Part-year precipitation data are available for approximately 20 forestry look-out towers established over the period 1951 to 1966. These data are mainly daily rainfall amounts for the months of May, June, July, and August, and with incomplete data for September. Rainfall during the four-month period May through August, on the basis of Fort McMurray data, amounts to about 75% of annual rainfall and to about 50% of annual total precipitation.

A series of 10 full-year automatic stations recording hourly precipitation data was established in 1976 under the AOSERP

Table 2. Comparison of reported annual flows in Athabasca River at Fort McMurray and Embarras.

Year	Fort McMurray (M)	Annual Flow Volumes in km^3 Embarras (E)	Difference (E-M)	Tributary Gauged Inflows Between (M) & (E)
1972	23.2	23.7	0.5	
1973	23.3	25.6	2.3	
1974	(26.6)	incomplete data		
1975	21.6	24.9	3.3	
1976	21.45	21.70	0.25	1.63
1977	24.17	23.55	-0.62	1.26
5-year average	22.7	23.9	1.2	

Notes

1. Gauged tributary inflows are tabulated for 1976 and 1977 only, because a large part of the inflow was not gauged prior to 1976.
2. Gauged tributary inflow reported for 1976 and 1977 represents approximately 80% of the tributary drainage area between Fort McMurray and Embarras.
3. Source of data: Loeppky and Spitzer 1977.

Meteorological Data Acquisition Program ('MAPS' stations). Some of these stations did not start reporting until the spring of 1977. The stations are mostly located adjacent to forestry look-outs.

For purposes of hydrological analysis, the utility of the precipitation data is limited by the following considerations:

1. Data are insufficient to establish the spatial variation of long-term average or 'normal' annual precipitation.[1] Longley and Janz (1978) presented a map of May to September precipitation normals, but not of full-year normals. The spatial distribution of snowfall is not well defined;
2. Spatial coverage of total annual precipitation is not available for the full 2-year period 1976 to 1977 for which good streamflow coverage is available; and
3. As noted by Longley and Janz (1978), information on short-duration rainfall intensity (less than 24-hour), over a reasonable period of years, is available only for Fort McMurray (from 1966).

1.3.3 Snow on Ground

A series of snow courses was established over the study area in 1975. Since then, isoline maps of snow water equivalent have been prepared by AES for late winter conditions. These data are useful hydrologically for examining the relationships between late winter snowpack and subsequent spring runoff.

1.3.4 Temperatures

Temperatures are of hydrologic interest in relation to snowmelt runoff and to evaporation and transpiration.

Temperature data available are more or less as outlined above for precipitation data, except that no temperature data were reported by forestry look-out towers before 1964.

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[1] Normals are defined by AES as mean values over the 30-year period 1941 to 1971. A tentative map of precipitation normals, prepared for this study, is referred to subsequently herein.

1.3.5 Evaporation

Daily pan evaporation has been measured during the summer at Mildred Lake since 1973 and at Birch Mountain since 1976. Atmometer[1] data have been recorded at McMurray since 1971, and intermittently at Edra and Richardson look-outs.

Hydrologically, the direct utility of evaporation measurements is limited to estimates of evaporation from lakes and reservoirs, and of potential evaporation from land surfaces. Actual evaporation from land surfaces reaches potential only where there is a non-limiting supply of soil moisture.

[1] Measures evaporation from a moist porous surface, instead of from an open water surface as in a pan.

2. BALANCE OF STREAM FLOWS THROUGH STUDY AREA

2.1 MEAN ANNUAL STREAMFLOW BALANCE

Mean annual balance of stream flows refers to the average volumes of water that pass through the study area and run off from its drainage basins each year. Variations from year to year are considered in Section 2.2. Volumes are expressed here in units of km^3/year.[1]

2.1.1 Derived Figures

The approximate mean annual flow balance is shown diagrammatically in Figure 4. The main flow inputs to the study area are 17.2 km^3/year from the Athabasca River above Fort McMurray and 4.3 km^3/year from the Clearwater River. The fraction of these flows derived from within the study area itself is quite small, probably not more than 0.4 km^3/year or about 2%. Contributions from the main tributaries south of Fort McMurray (Horse and Hangingstone) amount to about 0.4 km^3/year. North of Fort McMurray, west side tributaries contribute about 0.8 km^3/year and east side tributaries about 1.2 km^3/year, but about half of the latter figure originates from east of the study area boundary in the upper Firebag and Steepbank basins. In total, direct runoff to the Athabasca River from the land surface of the study area contributes only about 2.2 km^3/year on the average, or less than 10% of the flow at the northern boundary of the AOSERP study area. As will be shown in Section 2.2, however, this percentage is subject to considerable year to year variations.

As shown in Figure 4, the average outflow to the Slave River from Lake Athabasca is about 45.3 km^3/year. Direct contributions to the lake from the study area originate mainly from the upper parts of the McIvor and Buckton rivers and the lower parts of the Richardson and Maybelle rivers. The largest additional input to Lake Athabasca, 9.4 km^3/year, is from the Fond du Lac River in northeastern Saskatchewan.

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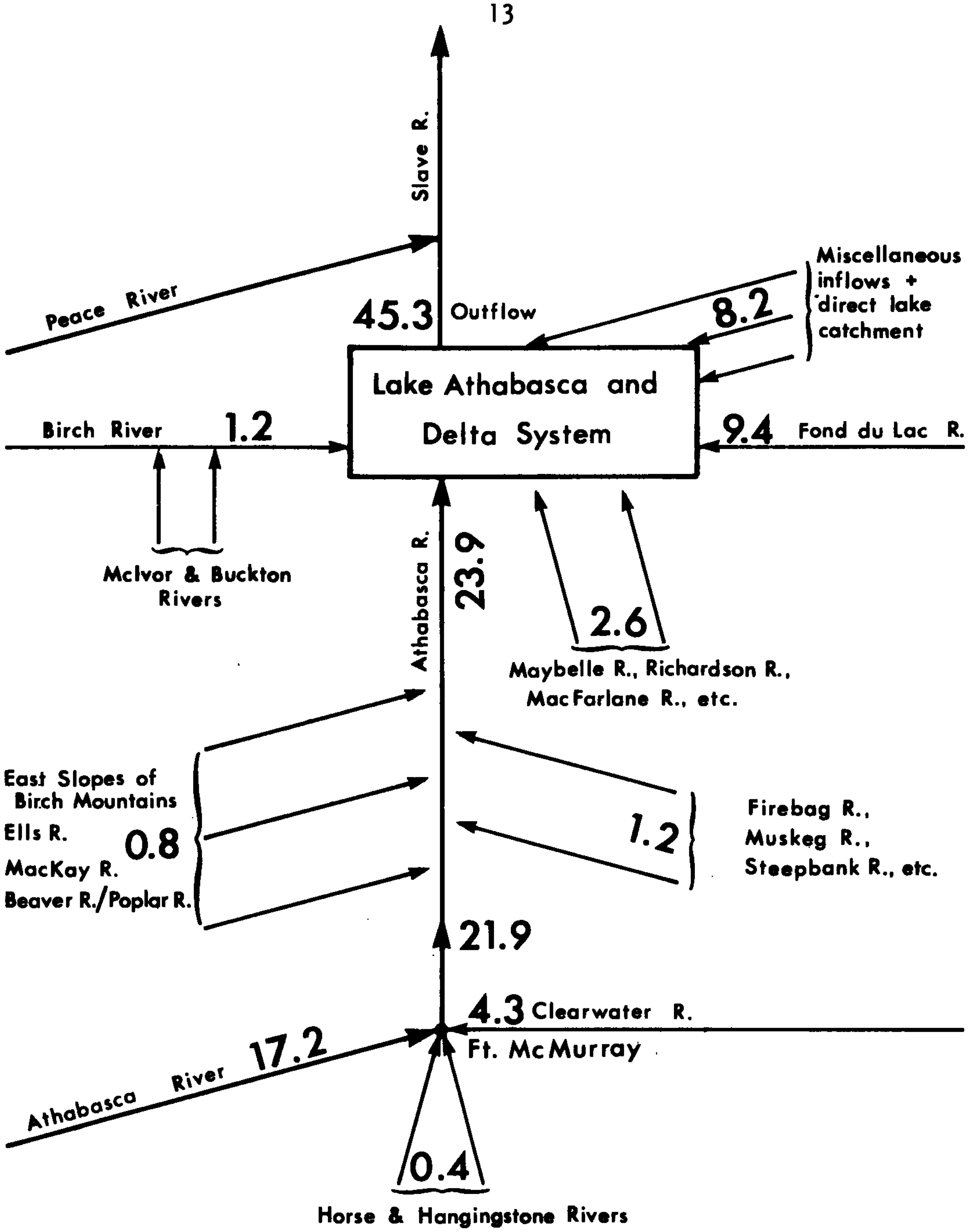
[1] An equivalent format would be units of $10^9 m^3$/year.



Athabasca River inflow to lake system: 17.2 + 0.4 + 4.3 + 0.8 + 1.2 = 23.9

Lake outflow to Slave River: 23.9 + 1.2 + 2.6 + 9.4 + 8.2 = 45.3

Units of km^3 ($= 10^9 m^3$)

Figure 4. Mean annual streamflow balance.

2.1.2 Sources of Derived Figures

The mean annual flow balance figures quoted above and illustrated in Figure 4 were derived as follows:

1. Athabasca and Clearwater rivers near Fort McMurray: figures are based on average annual flows over the 20-year period, 1958 to 1977. Athabasca River data, covering a much longer period farther upstream at the town of Athabasca, indicate that the period 1958 to 1977 is quite representative of the long term (Table 3);
2. Athabasca River near the mouth: the 1972 to 1977 gauge records at Embarras were ignored in deriving the quoted figures of 23.9 km^3/year, but in fact they agree with it, despite the year-by-year discrepancies discussed in Section 1.3;
3. Horse and Hangingstone rivers: figures are based on Hangingstone records, 1965 to 1977, and Horse records, 1975 to 1977, adjusted to the longer period by correlation;
4. West side tributaries north of Fort McMurray: approximately five years of data are available for the MacKay, Beaver, and Poplar basins, but other basins have data only for 1976 and 1977. After comparison of 1976 to 1977 data with those for longer periods, and consideration of annual precipitation figures, streamflow figures for 1976 to 1977 were increased by 25% where no earlier data were available. Allowance was made for ungauged areas on a proportional basis;
5. East side tributaries north of Fort McMurray: figures are based on approximately five years of data for the Firebag and Steepbank rivers, two years of data for the Muskeg River, and proportional allowance for smaller ungauged tributaries on the basis of drainage area; and

Table 3. Mean annual flow volumes in Athabasca River at Athabasca and near Fort McMurray

Period	No. of Years	At Athabasca km^3/yr	Mean Annual Flow Volumes: Above Fort McMurray[a] km^3/yr	Above Fort McMurray km^3/yr
1958-77	20	13.9	17.2	21.9
1914-30	17	13.1	-	-
1914-30 +1952-77	42	13.6	-	-

[a] Figures for above Fort McMurray were derived by deducting Clearwater, Horse, and Hangingstone river flows from measured flows below Fort McMurray.

6. Separate inflows to Lake Athabasca: figures are based on records except where indicated as ungauged. Ungauged areas were allowed for proportionally on the basis of drainage areas.

2.2 YEAR-TO-YEAR VARIABILITY IN STREAMFLOW BALANCE

Figure 5 shows a sequence of flow volumes covering the 20-year period 1958 to 1977 for the Athabasca River at Athabasca, the Clearwater River upstream of Fort McMurray, and the Athabasca River below the Clearwater confluence. Annual inflows to the study area from the upper Athabasca and the Clearwater rivers are poorly correlated, mainly because their principal sources of flow are far apart geographically. On the other hand, the short period data available for other streams in the study area indicate that fluctuations in their annual volumes parallel those of the Clearwater River fairly closely.

On the basis of these relationships, an approximate picture of the range of variation in the main flow balance components can be drawn up, as in Table 4. From this it appears that, over a 20-year period, tributaries to the Athabasca River within the study area (excluding the Clearwater River) contribute from 7% to 14% of the annual outflow to the delta. Over a 100-year period, the proportional contribution might be expected to range from about 5% to 16%.

2.3 MONTHLY STREAMFLOW BALANCES

Table 5 shows the average distribution of flow by months throughout the year for six rivers with adequate records. The highest month for the Athabasca River is July, but for many of the tributaries it is May. March is usually the lowest month for all streams. The table is based on published data for monthly flows, averaged over the period of record for each river (Inland Waters Directorate 1977).

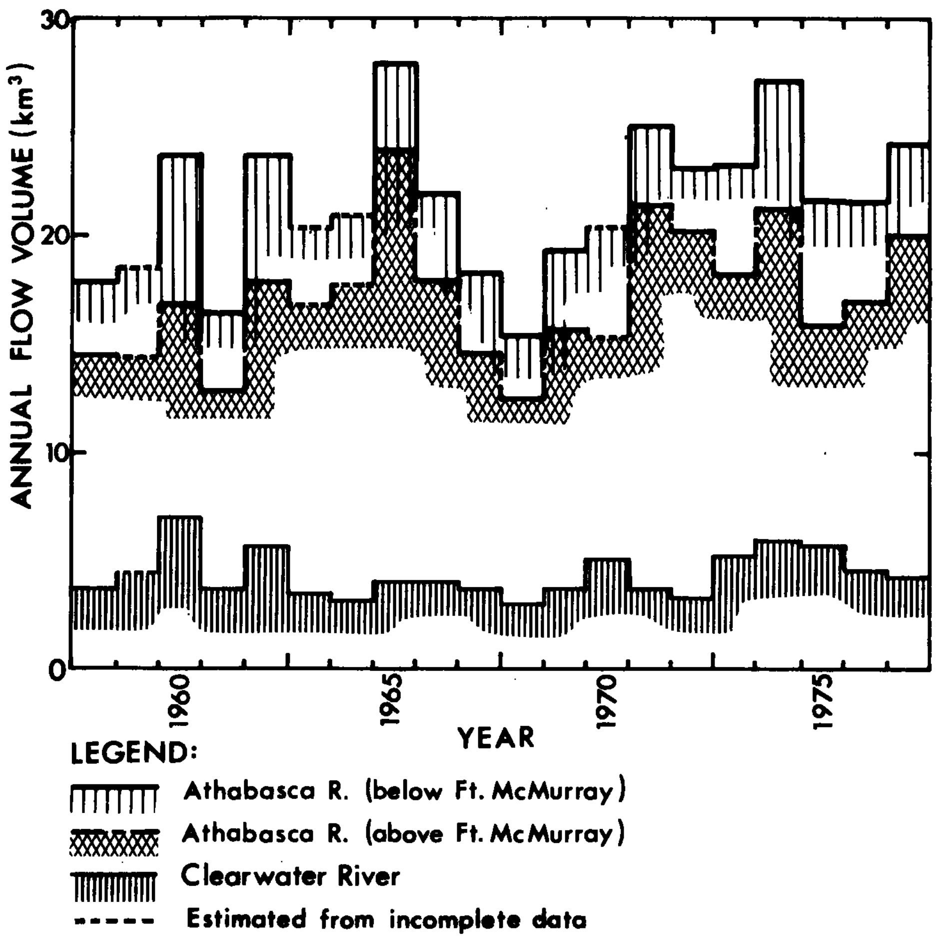


Figure 5. Sequence of annual flow volumes in Athabasca and Clearwater rivers.

Table 4. Variability in main components of annual streamflow balance.

Component	Mean	Annual Streamflow in km^3/year: Low Runoff Year in Study Area (1972)[a]	Annual Streamflow in km^3/year: High Runoff Year in Study Area (1960)[b]
Athabasca River above Fort McMurray	17.2	20.1	16.8
Clearwater River	4.3	3.1	6.8
Tributaries from study area (est'd)	2.4	1.7	3.7
Athabasca River at the delta	23.9	24.9	27.3
Percentage contribution of study area tributaries to Athabasca River at delta	10%	7%	14%

[a] 1972 was a year of below-average flow in the Clearwater River and comparatively high flow in the Athabasca River (see Figure 5).

[b] 1960 was a year of maximum flow in the Clearwater River and below-average flow in the Athabasca River below Fort McMurray (see Figure 5).

Table 5. Percentage of annual flow volumes by calendar months for selected rivers.

River	Percentage in Calendar Months Jan. to Dec. [a]											
	J	F	M	A	M	J	J	A	S	O	N	D
Athabasca	2	2	2	7	14	16	18	13	11	8	4	3
MacKay	0.5	0.5	-	19	17	22	15	9	8	5	2	1
Steepbank	1	1	1	12	17	11	15	12	16	10	3	1
Muskeg	1	1	1	15	17	10	16	8	14	12	4	1
Hangingstone	1	1	1	14	18	15	14	11	11	9	3	2
Clearwater	4	3	3	9	16	13	12	10	11	9	6	4

[a] The highest month is underlined in each case.

Variations in monthly streamflow balances have been analyzed for the following cases:

1. Month of July in an average year: Athabasca River at normal high flow;
2. Month of August in 1977, a year when the Athabasca River had high flows and local tributaries were low;
3. Month of April in 1975, a year when the Athabasca River had low flows and local tributaries were high; and
4. Month of March in an average year: all streams at normal low flow.

Results shown in Table 6 indicate that the proportional contribution by streams in the study area (exclusive of the Clearwater) to monthly flows at the mouth of the Athbasca River normally varies between 5% and 15%. Note, however, that part of this contribution originates from outside the study area.

The year-to-year variability of monthly flows in individual streams is considered further in Section 4.3.

Table 6. Selected monthly streamflow balances.

Component	Average Flow for the Month, m^3/s			
	July of Average Year	August 1977	April 1975	March of Average Year
Athabasca River above Fort McMurray	1270	930	260	115
Clearwater River	200	155	120	50
Tributaries from study area (partly est'd)	135	60	65	10
Athabasca River at the delta	1605	1145	445	175
Percentage contribution of study area tributaries to Athabasca River at delta	8%	5%	15%	6%

3. OVERALL WATER BALANCE: PRECIPITATION, RUNOFF AND EVAPORATION

Overall water balance refers to relationships between precipitation, streamflow, evapotranspiration, and groundwater recharge (Figure 3). As in the case of streamflow balances, it will be considered first in terms of the mean annual picture, then in terms of year-to-year variations.

3.1 MEAN ANNUAL WATER BALANCE

The basic water balance equation for a drainage basin over a stated period of time may be written as:

$$P = R + ET + G + \Delta S$$

where P = total precipitation
R = runoff
ET = evapotranspiration
G = groundwater leakage out of basin
ΔS = increase in storage

where all quantities are expressed in millimetres of water depth, averaged over the basin area. Evapotranspiration means the total return of water to the atmosphere by evaporation and sublimation from water and snow surfaces, and by evaporation and transpiration from vegetation and the ground.

For present purposes, it will be assumed that groundwater leakage out of the study area is negligible in relation to other components. In considering the mean balance over a period of years, it can be assumed that annual storage changes cancel out. The equation for mean annual balance then reduces to division of precipitation between runoff and evapotranspiration. Reservations concerning the groundwater leakage assumption are stated subsequently in Section 5.3, in relation to a part of the study area.

3.1.1 Information from the Hydrological Atlas of Canada (1978)

The recently published Hydrological Atlas of Canada contains four maps that are relevant to the water balance. A brief explanation of their sources and relationships is given below:

Map #3, Annual precipitation. Based essentially on station data adjusted to 'normal' 30-year period 1941 to 1970. One centimetre of new snow is taken as equivalent to 1 mm of precipitation.

Map #17, Mean annual lake evaporation. Based on limited evaporation pan measurements, extended by correlation with climatic data, and corrected for pan effects and station elevation.

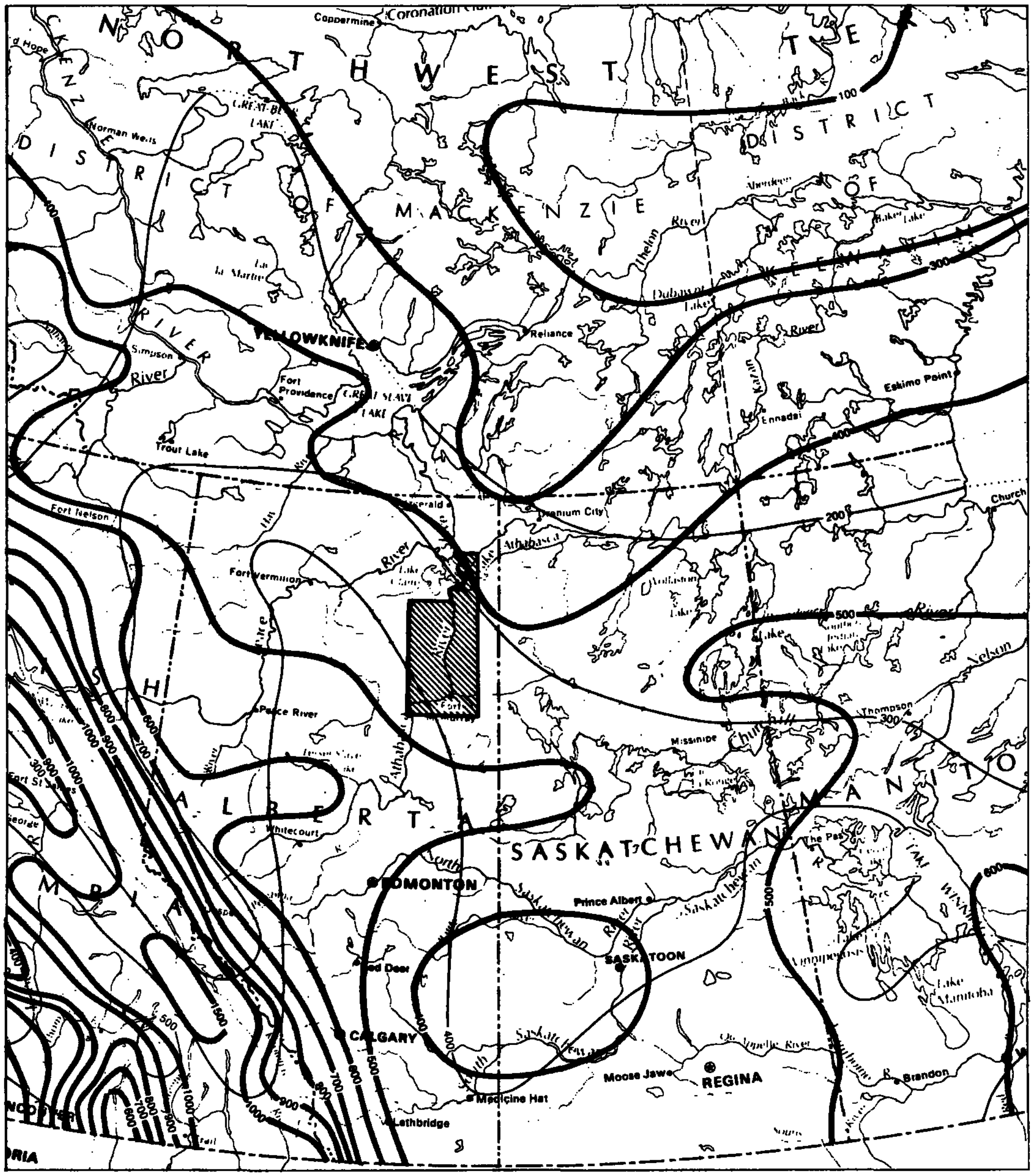
Map #24, Annual runoff. Based essentially on streamflow data, supplemented by synthesized data, and differentiated to indicate depth of runoff at point or from small areas.

Map #25, Water balance-derived precipitation and evapotranspiration. Explanations accompanying the map indicate that potential evapotranspiration was assumed approximately equal to lake evaporation (from Map #17). Actual evapotranspiration was then estimated by applying coefficients related to the nature of the terrain, ranging from 0.1 for bare rock and paved areas to 1.0 for open water and bog areas. An adjustment procedure was then applied to these estimates and to precipitation (from Map #3), to match "derived precipitation" with "derived evapotranspiration" and runoff (the latter according to Map #24). The "derived precipitation" figures therefore do not agree exactly with the precipitation figures of Map #3.

Approximate mean annual water balance data for Fort McMurray and the Athabasca Delta, based on Maps #17 and #25, are shown in Table 7 and Figure 6. The most notable feature is that indicated evapotranspiration amounts to 75% to 80% of precipitation in the study area; that is, only 20% to 25% of the precipitation runs off as streamflow. The Atlas map shows that no other part of Canada in the same latitudes as the study area has such a high ratio of evapotranspiration to runoff. The high ratio is presumbaly due to relatively high summer temperatures combined with long hours of sunshine, low atmospheric humidity, plentiful vegetation and considerable areas of open water and muskeg. In areas of open water and muskeg, actual evapotranspiration is likely to be close to potential for much of the time.

Table 7. Mean annual water balances based on Hydrological Atlas of Canada (1978).

Location	Derived Precipitation mm	Lake Evaporation or Potential Evapotranspiration (Atlas Map #17) mm	Mapped Actual Evapotranspiration (Atlas Map #25) mm	Runoff = Precipitation less Actual Evapotranspiration mm	Ratio of Runoff to Precipitation mm
Fort McMurray	460	510	370	90	0.20
Athabasca Delta	400	450	300	100	0.25



LEGEND

Study area ....

Mean annual precipitation 500

Mean annual evapotranspiration 500

NOTE

Fort McMurray : precipitation = 460 mm

evapotransporation = 370 mm

Figure 6. Water balance data from Hydrological Atlas of Canada.

3.1.2 Local Data for Study Area

The figures quoted in Table 7 are based on widespread data generalized on a regional basis. Table 8 summarizes the results of a check analysis based on local precipitation and runoff data for the study area. Explanations are as follows:

1. The first line of Table 8 is based on 1976 to 1977 data for all gauged basins in the study area draining into the Athabasca River north of Fort McMurray. Runoff and derived evapotranspiration figures for this 2-year period are probably somewhat below long-term means. Spatial average precipitation was estimated from incomplete data; and
2. The second line of Table 8 is for the Beaver River basin near Fort McMurray, over the 6-year period 1972 to 1977. Runoff and evaportranspiration averaged over this period are probably well above long-term means. The precipitation data in this case are recorded data for Fort McMurray, not adjusted to a water year basis in view of the longer period utilized.

Given the rather limited data used in these analyses, the results appear to support the indications of the Hydrological Atlas of Canada very well.

Detailed consideration is given in Section 4.1 to variations in the water balance between individual basins. The role of subsurface flow or groundwater leakage in some basins is discussed in 5.3

3.2 YEAR-TO-YEAR FLUCTUATIONS

3.2.1 Analyses

The possibilities of analyzing year-to-year fluctuations in the water balance are severely limited by scarcity of long-term streamflow data and of full-year precipitation data for stations other than Fort McMurray and Fort Chipewyan. It is necessary to make

Table 7. Annual water balances based on local data.

Basins	Years[a]	Estimated Mean Annual Precipitation P mm	Mean Annual Runoff R mm	Derived Mean Evapotrans. ET = P - R mm	Ratio of Runoff to Precipitation
(i) All gauged tributaries north of Fort McMurray	1976-77	440	80	360[b]	0.18
(ii) Beaver River[c]	1972-77	550	120	430	0.22

[a] Calendar years used for this table. See Table 9 for water year figures.

[b] See Section 5.3 of text for comments regarding groundwater leakage from certain basins.

[c] Refers to lower gauge operational until 1975. Runoff figures for upper gauge, 1976 to 1977, were adjusted to correspond to the greater drainage area.

the assumption that changes in water storage from year to year are relatively small; this may not be defensible in all cases.

Table 9 shows annual ratios of derived "actual" evapotranspiration to potential evapotranspiration based on evaporation measurements. Ratios vary from 0.66 to 1.00, and the correlation between the two data sets is weak. The potential figures show relatively little year-to-year variation; available energy for evapotranspiration does not vary so much from year to year as precipitation and runoff.

An empirical formula has been published by Turc (1954), relating evapotranspiration to precipitation on the basis of analyses of world-wide data. Although Turc's formula is intended to apply to mean annual figures, it is interesting to compare his result with the trend of the Beaver River data shown in Figure 7. Turc's formula may be written:

$$ET = P/(0.9 + P^2/L^2_t)^{0.5}$$

where ET = annual evapotranspiration, mm

P = annual precipitation, mm

$L_t = 300 + 25t + 0.05t^3$, where t = mean annual temperature, ^oC.

When an adjusted mean annual temperature of 5.4 ^oC is computed by taking below-zero months as having zero temperature, the formula gives the result ET = 0.71P. The annual data for the Beaver River shown in Figure 7 indicate an approximate relationship of ET = 0.776P.

Similar year-to-year correlations for the Hangingstone and MacKay rivers and for Poplar Creek (not reproduced here) result in similar trends but greater scatter. Part of the scatter is probably due to the fact that Fort McMurray precipitation is not generally valid for the Hangingstone and MacKay basins.

3.2.2 Computation of Evapotranspiration from Climatic Data

Attempts were made to check evapotranspiration estimates as quoted above by deriving estimates independently using a procedure

Table 9. Year-by-year water balances for Beaver River basin.

Year	Runoff Jan.-Dec. R	Fort McMurray Precip. Oct.-Sept. P	Derived Evapotrans. Jan.-Sept. ET = P - R	Recorded Gross Pan Evaporation E	Estimated Potential Evapotrans. PET = 0.7E[a]	Ratio ET/PET
	mm	mm	mm	mm	mm	
1972	133	613	500	832[b]	582	0.86
1973	164	733	569	810[b]	567	1.00
1974	126	576	390	707[c]	495	0.79
1975	139	564	425	711[c]	498	0.85
1976	129[d]	525	396	784[c]	549	0.72
1977	73[d]	403	330	711[b]	498	0.66
6-Year Average	124	559	435		531[e]	0.81

[a] Factor 0.7 is a "pan coefficient" applied to all recorded data in preceding column.

[b] Fort McMurray, based on atmometer data.

[c] Mildred Lake, based on pan data.

[d] Data estimated by proportional adjustment from new gauged area to previously gauged data.

[e] Hydrological Atlas of Canada (1978) indicates long-term average = 510 mm.

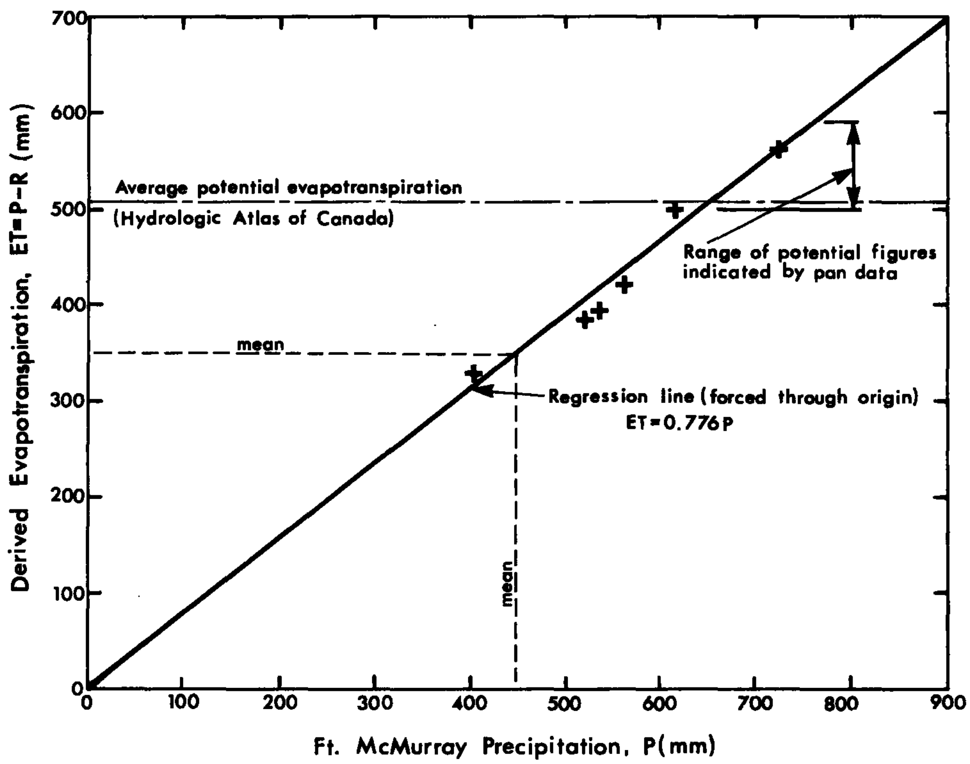


Figure 7. Derived evapotranspiration versus precipitation, Beaver River basin, 1972 to 1977.

proposed by Morton (1976). This procedure utilizes climatic data on monthly temperatures, humidity, hours of sunshine, and solar radiation. Preliminary results were not encouraging: although values computed by Morton's procedure yielded more or less the correct overall mean figure, year by year means did not correspond at all with the actual year by year fluctuations in derived evapotranspiration or recorded evaporation indicated by Table 9. For example, although both derived evapotranspiration and recorded evaporation were about 20% higher in 1972 than in 1974, Morton's procedure appeared to produce a slightly lower figure in 1972 than in 1974.

4. VARIABILITY OF RUNOFF IN SPACE AND TIME

The following sections consider how annual runoff, expressed as an average depth of water over a basin area, varies from one basin to another; how annual and monthly flows vary from one year to another; and how daily flows vary in different basins. The problem of estimating normal runoff patterns from the limited data base is also considered.

4.1 SPATIAL VARIABILITY OF ANNUAL RUNOFF

4.1.1 Data for 1976-77

As mentioned in Section 1.3.1, recorded data on the spatial variability of runoff throughout the study area are available for 1976 and 1977, when an extensive network of streamflow gauging stations was in operation. Table 10 summarizes the data on a calendar year basis. Figure 8 maps the annual runoff averaged for these two years, on the basis of calendar years 1 January to 31 December. It can be seen that there is quite a wide range of values, from a high of about 160 mm for the Hangingstone basin south of Fort McMurray, to a low of about 30 mm on the east slopes of the Birch Hills.

4.1.2 Relation of Spatial Variability to Precipitation and Other Factors

For years 1976 and 1977, approximate maps were drawn of the spatial distribution of precipitation over the study area, utilizing data from AES stations, look-out towers, and MAPS stations. Average precipitation values were then determined for various basins and groups of basins, for comparison with the runoff depths listed in Table 10. Results consolidated for the 2-year period are shown in Table 11. Both runoff and precipitation data refer to calendar years: a water year basis would be preferable, but there are difficulties in extending areal precpitation estimates back into 1975.

Table 11 shows that the variation in runoff depths between various parts of the study area is explained to only a minor degree by variation in total precipitation. For the most part, depths are

Table 10. Runoff from gauged basins in the study area, 1976 and 1977.

Drainage Basin	Drainage Area km^2	Annual Runoff Volumes 1976	1977	Av. 1976/77	Runoff Depth Av.1976/77 mm
		$10^6 m^3$			
West of Athabasca River					
Poplar	151	12.3	13.6	13.0	86
Upper Beaver	176	22.7	12.9	17.8	101
Dunkirk	1582	103.2	70.8	87.0	55
Thickwood[a]	170	(8.6)	8.6	(8.6)	(51)
Mackay-Dunkirk	3649	360	114.7	237.3	65
Upper Ells	1365	109.4	108.4	108.9	80
Lower Ells-Upper Ells	1110	58.3	27.2	42.8	38
Joslyn	248	18.6	8.1	13.4	54
Upper Tar[a]	97	(10.4)	10.4	(10.4)	(107)
Lower Tar	313	23.3	15.7	19.5	62
Calumet	181	5.6	1.8	3.7	21
Pierre	130	5.1	5.7	5.4	41
Asphalt	149	9.5	9.5	9.5	64
Unnamed	280	8.9	9.0	9.0	32
TOTAL	9194	724.6	383.8	554.3	Av. 60
East of Athabasca River					
Steepbank	1373	129.5	95.8	112.7	82
Hartley	368	24.2	20.1	22.1	58
Muskeg-Hartley	1092	41.4	52.9	47.1	43
Firebag[b]	6035	695.4	694.2	694.8	115
TOTAL	8864	890.5	864	876.7	Av. 99
South and East of Fort McMurray					
Horse	2181	293.5	231.8	262.7	120
Hangingstone	914	160.3	135.6	148	162
Christina	13,390	1553.6	1064.1	1308.8	98
Clearwater	17,172	2898	3091	2994.6	174
TOTAL	33,656	4905	4523	4714	Av.140

[a] Bracketed figures have been filled in where data are missing, to complete the table.

[b] Basin is largely outside the study area.

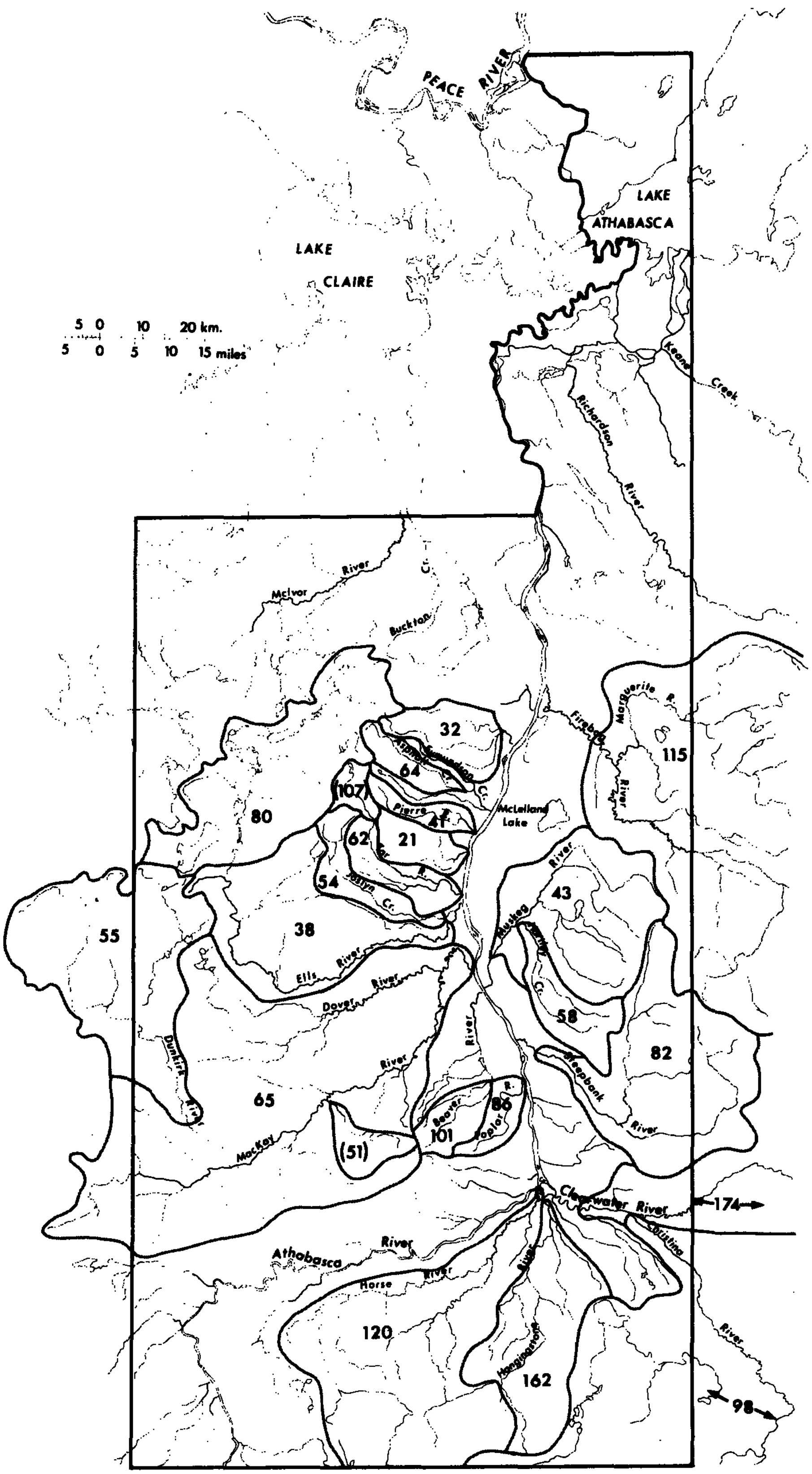


Figure 8. Spatial variability of annual runoff, 1976 to 1977. Bracketed figures indicate that the sub-basin is also included in the average for the surrounding larger basin. Units are mm/year, averaged 1976 to 1977.

Table 11. Spatial variation of runoff coefficients over the study area, 1976 to 1977.

Basin	2-Year Runoff (total) mm	2-Year Estimated Precipitation mm	Runoff Coefficient = Runoff/ Precipitation
West of Athabasca River			
Upper Beaver + Poplar	188	1000	0.19
Dunkirk	110	800	0.14
Mackay (less Dunkirk)	130	770	0.17
Upper Ells	160	870	0.18
Lower Ells (less Upper Ells)	77	750	0.10
Joslyn + Tar	112	810	0.14
Calumet + Pierre + Asphalt + Unnamed	74	890	0.08
East of Athabasca River			
Steepbank	180	820	0.22
Muskeg	95	770	0.12
Firebag	230	820[a]	0.28[a]
South of Fort McMurray			
Horse	240	1030	0.23
Hangingstone	323	1090	0.30

[a] Precipitation not well defined.

paralleled by variations in runoff coefficients, which range from less than 0.10 on the east slopes of the Birch Hills to 0.30 south of Fort McMurray. Other factors likely to be involved include the following:

1. Seasonal distribution of precipitation and division between rain and snow: higher proportions of summer precipitation are likely to reduce annual runoff;
2. Nature and density of vegetation: dense immature growth, creating a large evapotranspiration demand, is likely to reduce runoff;
3. Infiltration and storage capacity of soils: high storage capacity is likely to reduce runoff by withholding water for subsequent use by vegetation. This factor is linked to a degree with factor 2;
4. Prevalence of surface water in lakes, ponds and marshes: a high proportion of surface water may favour higher evaporation and thereby reduce runoff;
5. Topography: steep slopes with rapid runoff are likely to leave less water in the ground to be lost by evapotranspiration, and thereby favour higher runoff; and
6. Subsurface geology: water may pass out of some basins by subsurface flow to the Athabasca River, not being measured as basin runoff. This factor is further discussed in section 5.3.

A thorough analysis of all these factors would be heavily time-consuming, and has been considered outside the scope of the present study. In large part it implies development of a "model" to predict basin runoff from geographic factors and climatic data. Data from smaller sub-basins, not listed in Table 11, are important for such a development.

4.1.3 Estimation of Runoff Normals from 1976-77 Data

In considering to what extent the 1976-77 spatial runoff distribution of Figure 8 may represent the long-term pattern, the most useful long-term data are: (1) the precipitation data for Fort McMurray and Fort Chipewyan, and (2) the streamflow data for the Hangingstone River. The indications of these two sets of data are examined in turn below.

Table 12 and Figure 9 illustrate historical precipitation data in relation to 1976 and 1977 figures. A difficulty arises over defining long-term mean precipitation figures, because of the long-period fluctuations that are characteristic of many climatic records. In terms of the 1941 to 1970 normals quoted by Longley and Janz (1978), the 2-year period 1976 to 1977 was slightly high. In terms of more recent periods like 1951 to 1977 or 1961 to 1977, the period 1976 to 1977 was slightly low. On balance, precipitation for the 2-year period 1976 to 1977 does not appear to have been far from the long-term mean. A similar conclusion applies to the division of precipitation between rain and snow.

Table 13 compares 1976 to 1977 runoff data for the Hangingstone and Clearwater rivers with longer periods over which full-year data are available. For the Clearwater River basin (which lies mostly outside the study area), 1976 to 1977 runoff was equivalent to the 20-year average for 1958 to 1977. For the Hangingstone River, data are available since 1970 only, but the ratio of 1976 to 1977 average to 1970 to 1977 average is virtually the same for both rivers; it can therefore be expected that the relationship of 1976 to 1977 data to 20-year records would be similar.

As a third approach to the problem of estimating the mean runoff pattern, a tentative map of precipitation normals was prepared for the period 1941 to 1970 (Figure 10). In order to prepare the map, it was assumed that the proportion of annual precipitation, at look-out towers, that fell in months when records were not taken was similar to the proportion of Fort McMurray annual precipitation that fell in those months. The 1976 to 1977 runoff coefficients listed in Table 11 were then applied to the mapped precipitation normals to estimate runoff normals for various basins. Resulting basin runoffs were on average about 15% higher than the 1976 to 1977 data mapped on Figure 8.

Table 12. Comparison of 1976 to 1977 precipitation data for Fort McMurray and Fort Chipewyan with data for longer periods.

Statistic and Period	Annual Rainfall in mm		Annual Snowfall in cm		Annual Total Precipitation in mm[a]	
	Fort McMurray	Fort Chipewyan	Fort McMurray	Fort Chipewyan	Fort McMurray	Fort Chipewyan
Longer Periods						
Mean, 1951 to 1960	312	-	150	-	462	-
Mean, 1961 to 1970	318	(287)[b]	165	(134)[b]	483	(421)[b]
Mean, 1971 to 1977	370	275	195	149	531	419
Mean, 1951 to 1977	329		167		488	
Standard deviation, 1951 to 1977	86		56		95	
Coefft. of variation, 1951 to 1977	26%		34%		19%	
"Normal" 1941 to 1970[a]	305		140		435	368
1976 to 1977						
Annual, 1976	427	264	126	168	521	425
Deviation from 1951 to 1977 mean	+ 30%		- 25%		+ 7%	
Annual, 1977	285	273	164	100	404	368
Deviation from 1951 to 1977 mean	- 13%		- 2%		- 17%	
Mean, 1976 to 1977	356	268	145	134	462	396

[a]Up to 1972, total precipitation is computed on the assumption that 1 cm of snowfall = 1 mm precipitation. After 1972, total precipitation data are based on measured water equivalent of snow.

[b]Based on 1963 to 1970 data only.

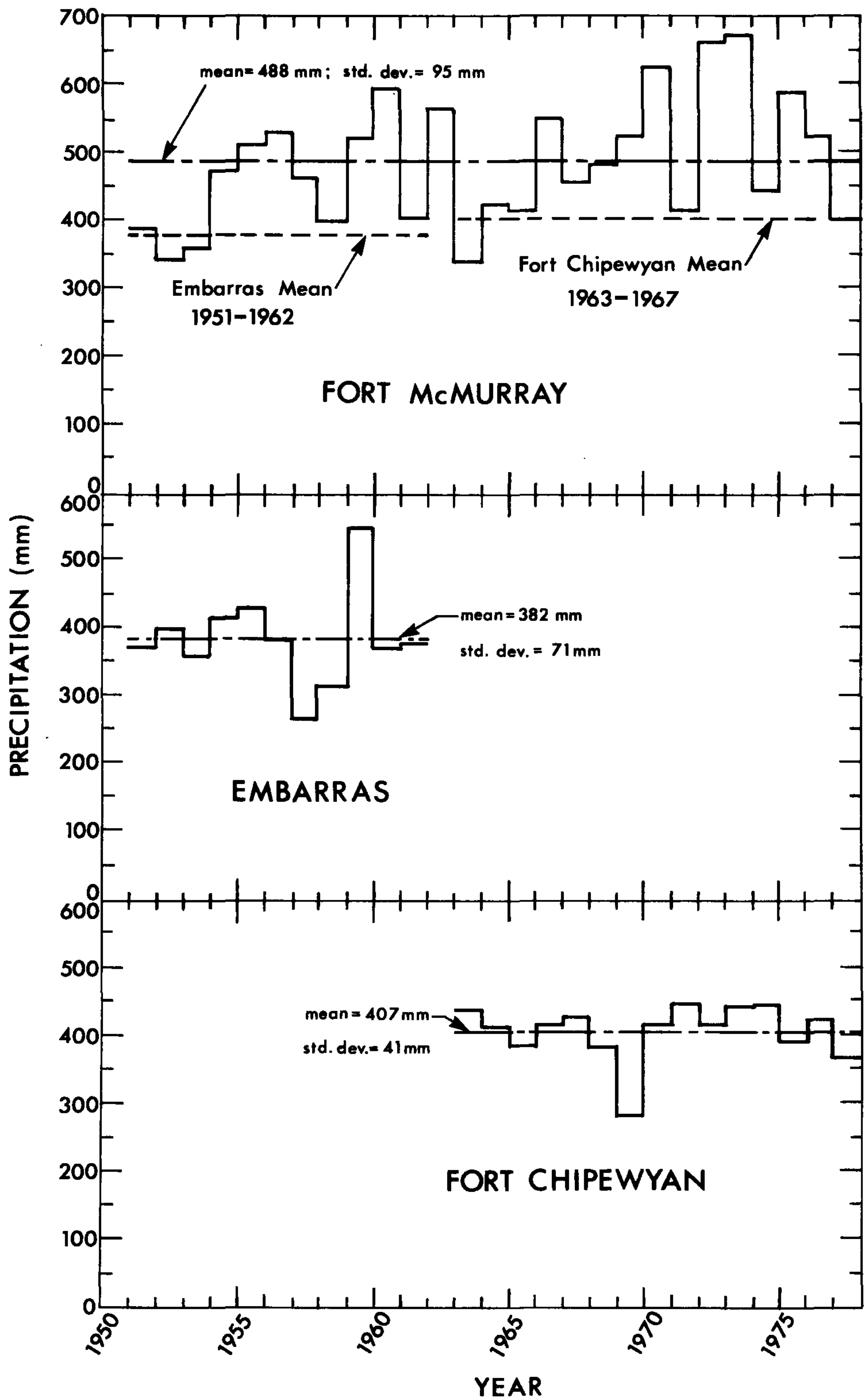


Figure 9. Variability of annual precipitation, 1950 to 1977.

Table 13. Comparison of 1976-77 runoff data for Hangingstone and Clearwater rivers with data for longer periods

Statistic and Period	Hangingstone River (D.A. = 914 km^2)		Clearwater River at Draper (D.A. = 30 600 km^2)	
	Runoff Volume km^3	Depth mm	Runoff Volume km^3	Depth mm
Longer Periods				
Mean annual, 1958-59	-	-	4.04	132
Mean annual, 1970-77	0.160	175	4.65	152
Mean annual, 1958-77	-	-	4.28	140
1976-77				
Annual, 1976	0.160	175	4.45	145
Annual, 1977	0.136	149	4.15	135
Mean annual, 1976-77	0.148	162	4.30	140
Ratios				
Ratio $\frac{\text{1976-77 mean}}{\text{1970-77 mean}}$	0.93		0.92	
Ratio $\frac{\text{1976-77}}{\text{1958-77}}$	-		1.00	

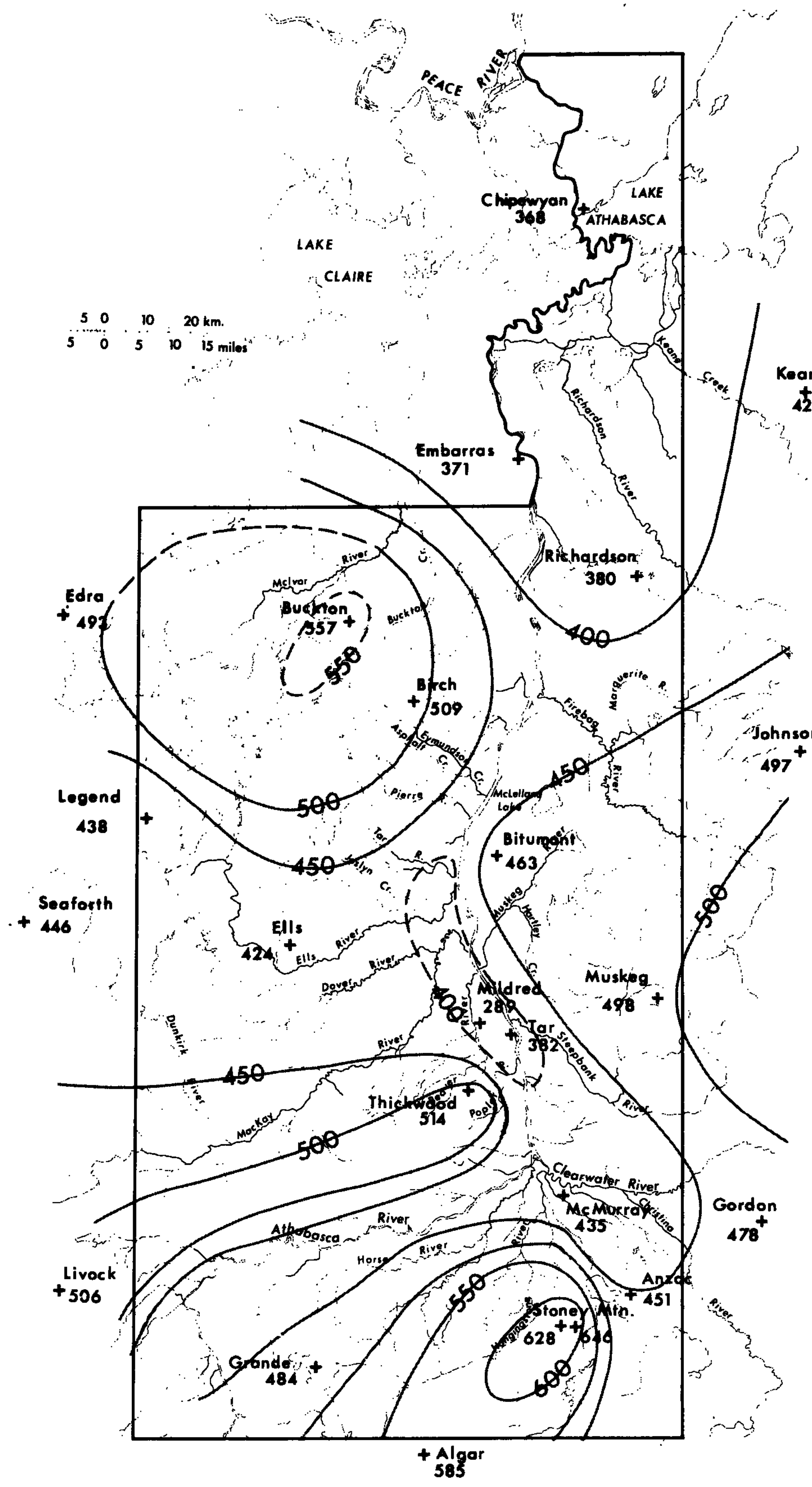


Figure 10. Tentative map of annual precipitation normals. Based on Fort McMurray data, 1941 to 1970, and adjustment of seasonal lookout tower data to full-year basis. (All measurements in mm/year).

In conclusion, available long-term data for precipitation and runoff in the region (which are poor in terms of spatial coverage) suggest that area-wide runoff data averaged over 1976 and 1977 should be fairly typical of long-term patterns. On the other hand, data for the MacKay and Steepbank Rivers, covering only about five years of record, suggest that 1976 and 1977 runoffs may have been considerably below average. On balance, Figure 8 can probably be accepted as giving a rough picture of the spatial distribution of mean annual runoff under existing conditions, with the understanding that normal figures are probably somewhat higher for most basins say by 10% to 20% on average.

4.2 YEAR-TO-YEAR VARIABILITY OF ANNUAL RUNOFF

4.2.1 Athabasca and Clearwater Rivers

Sequences of annual flow volumes in the Athabasca and Clearwater rivers were shown in Figure 5 for the gauged period 1958 to 1977. Basic statistics for these time series are listed in Table 14. The following points can be made.

1. Over the 20-year period, 1958 to 1977, highest annual volumes were about twice the lowest volumes;
2. It is reasonable to assume that annual volumes are basically distributed according to the normal law; and
3. The sequence of annual runoff volumes is essentially random; correlation between successive values is very weak and is of little statistical significance. In physical terms, this indicates no significant carry-over of water from year to year in the Athabasca and Clearwater basins.

4.2.2 Other Streams

Figure 11 shows sequences of gauged annual flow volumes for those other streams in the study area that have a few years of record. Means for the periods are shown. The sequences are too short to yield reliable estimates of variability over the long

Table 14. Variability of annual flow volumes, Athabasca and Clearwater rivers, for 1958 to 1977.

Statistic	Clearwater km^3/year	Athabasca Below Fort McMurray km^3/year	Athabasca Above Fort McMurray (by differences) km^3/year
Mean	4.3	21.5	17.2
Standard deviation	1.09	3.37	3.02
Minimum in period	2.9	15.3	12.4
Maximum in period	6.8	27.9	23.9
Range	3.9	12.6	11.5
Median	4.00	21.55	17.0
Predicted 100-year low[a]	1.6	13.0	9.6
Predicted 100-year high[a]	6.8	29.6	24.5
Autocorrelation coefficient for 1-year lag[b]	+0.08	+0.15	-

[a] Based on assumption that annual flow volumes are normally distributed.

[b] Values indicate very weak correlations between successive annual flow volumes.

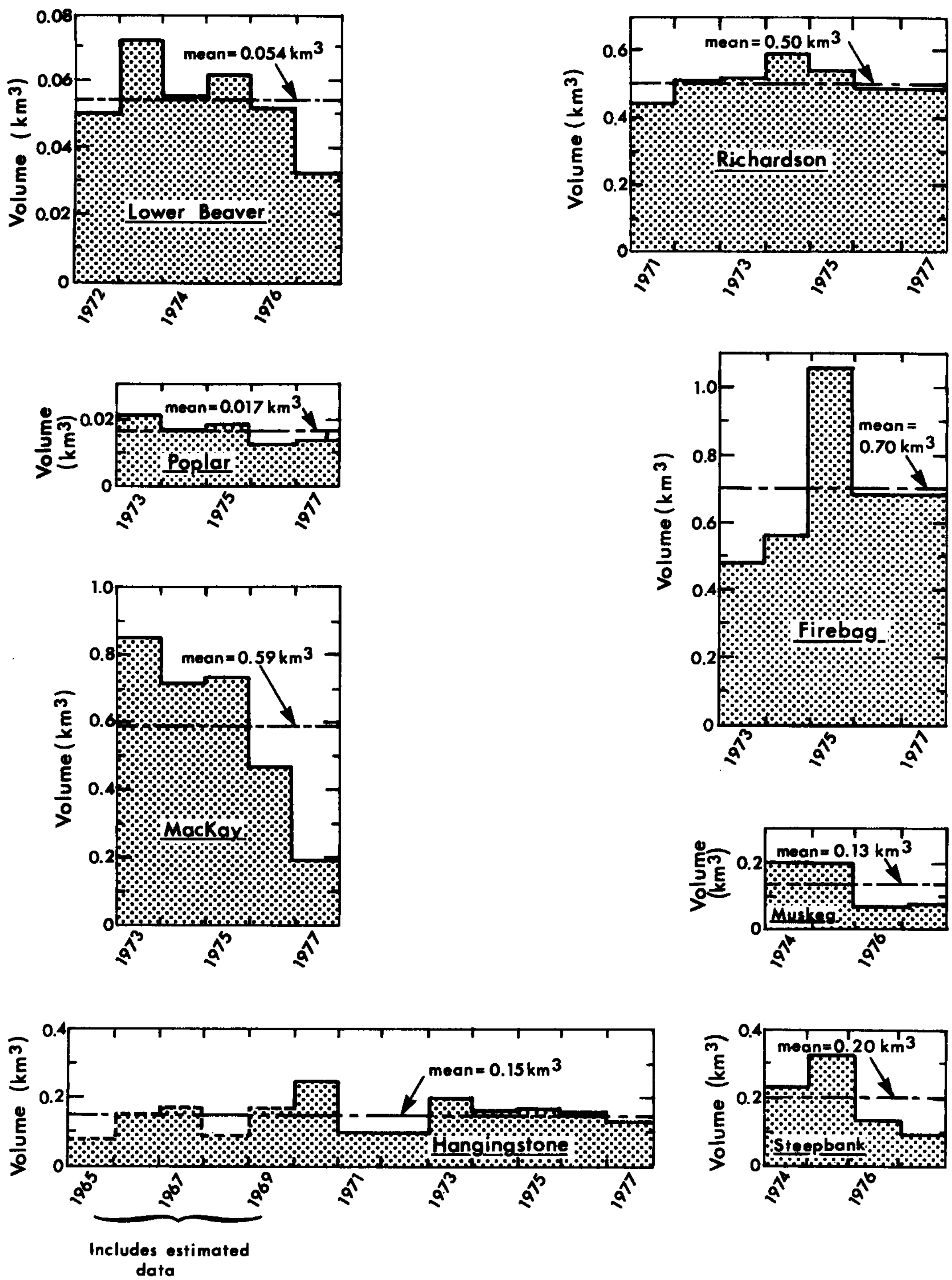


Figure 11. Sequences of annual flow volumes in streams draining study area.

terms. For the MacKay River, an attempt was made to generate a synthetic series of flow volumes for the years 1950 to 1972 on the basis of (1) a regression equation linking gauged volumes with Fort McMurray precipitation, for 1973 to 1977, and (2) a random component based on the scatter in the regression relationship. Table 15 shows estimated statistics based on the synthetic series and on the short gauged series. These figures should be treated with some scepticism.

It is clear that the year-to-year variability in annual runoff for some basins in the study area is quite high, yield in high years being many times greater than yield in low years. It was shown in Section 3.2 (covering year to year fluctuations in the water balance) that data for the Beaver River basin (for which Fort McMurray precipitation can be assumed reasonably representative) give good correlation between runoff and precipitation. On the other hand, it appears from Figure 11 and Table 15 that there are other streams, such as the MacKay River, where factors other than precipitation excercise an important influence on annual runoffs, because the wide fluctuations in annual runoffs cannot be explained by fluctuations in precipitation alone.

4.3 YEAR-TO-YEAR VARIABILITY OF MONTHLY FLOWS

The distribution of mean flows by calendar months was illustrated in Table 5 for six rivers with a few years or more of records. For the same rivers, Table 16 shows statistics on the year-to-year variability of average flows in selected months; March, May, June, and October.

Table 16 indicates that except in the low flow winter months, there is a high year-to-year variability in flows for a given calendar month. Streams with only a few years of records typically show a range of from 40% to 200% of the mean, for the months of May, June, or October. Over a 20-year period, a range of 25% to 300% of the mean might be expected on many of the rivers draining the study area, for any of the open-water months.

Table 15. Estimated variability of MacKay River annual runoff volumes.

Statistic	Recorded Data 1973-77 km^3/year	Synthetic Data 1950-72 km^3/year
Mean	0.59	0.50
Standard deviation	0.27	0.25
Low for period	0.18	0.09
High for period	0.85	1.05

Table 16. Year to year variability of selected monthly flows.

Month and River	No. of Years	Mean Monthly Flow[a] m^3/s	Standard Deviation % of Mean	Recorded High approx. % of Mean	Recorded Low approx. % of Mean
March (low flows)					
Athabasca	20	168	18%	135%	70%
MacKay	5	0.4	-	160%	40%
Steepbank	4	0.5	-	120%	85%
Muskeg	4	0.4	-	110%	85%
Hangingstone	8	0.35	32%	130%	40%
Clearwater	20	52	16%	135%	75%
May (High flows)					
Steepbank	4	13	-	195%	45%
Muskeg	4	8	-	250%	30%
Hangingstone	13	11	55%	180%	17%
Clearwater	20	263	33%	140%	50%
June (High flows)					
Athabasca	20	1375	25%	140%	60%
MacKay	5	47	-	335%	20%
October (Intermediate flows)					
Athabasca	21	607	24%	140%	60%
MacKay	6	13	-	200%	25%
Steepbank	5	7	-	240%	35%
Muskeg	4	6	-	195%	55%
Hangingstone	13	4.7	50%	165%	45%
Clearwater	21	144	39%	170%	50%

[a] Average flow for the month, averaged again over the number of years listed in column 2.

4.4 VARIABILITY OF DAILY FLOWS AND FLOW-DURATION RELATIONSHIPS

The sequential pattern of daily flow fluctuations is well illustrated by the daily flow tables and hydrographs contained in AOSERP Report 18 (Loeppky and Spitzer 1977). An example, for the MacKay River in 1976, is shown in Figure 12; the logarithmic discharge scale on the hydrograph tends to under-emphasize the extreme variation in daily discharges by scaling down the higher values. For this particular example, Table 17 lists autocorrelation coefficients for various lag periods: correlation is very high between successive daily flows, but effectively disappears for flows more than a week or two apart. In simple terms, this means that the flow on a particular day is highly dependent, in most cases, on the flow the day before, but is virtually independent of the flow several weeks before. In more strict terms, this last statement is not correct for the winter season when low flows persist for several months.

The statistical distribution of daily flows can be shown by flow-duration curves which plot, for a given period, the percentage of time when flow exceeded or fell short of a given value. Such curves are shown in Figure 13 for six rivers; they are based on the available full-year records for each river up to the end of 1976. To take an example, the curve for the MacKay River indicates that for 90% of the time, over a period of years, the flow can be expected to exceed 0.5 m^3/s; conversely, for 10% of the time it can be expected to be less than this value. Such curves are useful when considering water supply, fishery requirements, etc.

Table 18 lists statistics of maximum and minimum daily flows for six rivers with a few years of record. The wide spread between maximum and minimum flows is not always appreciated by lay persons.

WATER SURVEY OF CANADA
JAN 28 1977 PAGE 13
CALGARY, ALTA.

HANGINGSTONE RIVER AT FORT MC MURRAY

STATION NO. 07CD004

(PRELIMINARY) DAILY DISCHARGE IN CUBIC FEET PER SECOND FOR 1976

DAY	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	DAY
1	18.0 B	9.0 B	7.5 B	30.0 B	121	42.0 E	254	210 E	1720	138	90.0 B	22.0 B	1
2	17.5 B	8.7 B	7.6 B	34.0 B	101	41.2	209 E	184	1400	129	89.0 B	22.0 B	2
3	17.3 B	8.5 B	7.7 B	40.0 B	84.5	46.0	163	172	1200	197 E	88.0 B	21.0 B	3
4	17.1 B	8.2 B	7.8 B	48.0 B	75.3	46.0	145	140	1070	264	87.0 B	21.0 B	4
5	17.0 B	8.0 B	8.0 B	70.0 B	73.0	41.3 E	116	119	876	246	86.4 B	20.0 B	5
6	16.8 B	7.6 B	8.3 B	100 B	65.4	36.6	106	106	753	246	86.0 B	20.0 B	6
7	16.7 B	7.3 B	8.6 B	108 B	59.7	33.8	96.4 E	139 E	1180	253	84.0 B	19.3 B	7
8	16.5 B	7.0 B	9.0 B	188 B	55.9	39.6	86.8	172	1340 E	280	82.0 B	18.0 B	8
9	16.3 B	6.7 B	9.4 B	240 B	54.2 E	44.4	86.8	154	1500	288	80.0 B	18.0 B	9
10	16.2 B	6.6 B	9.8 B	270 B	52.4	47.6	126 E	143	1250	334 E	78.0 B	17.0 B	10
11	16.1 B	6.6 B	10.0 B	300 B	57.8	52.4	166	135	1070	380	75.0 B	17.0 B	11
12	16.0 B	6.5 B	10.5 B	329 B	59.7	50.8	181	124	876	405	72.0 B	16.0 B	12
13	15.6 B	6.6 B	11.0 B	280 B	65.4	55.3 E	273	114	725	415	69.0 B	16.0 B	13
14	15.3 B	6.7 B	11.5 B	245 B	61.6	59.7	485	111	662	380	66.0 B	16.0 B	14
15	15.0 B	6.7 B	12.0 B	235 B	59.7	71.1	545	89.1	578 E	355	62.0 B	15.0 B	15
16	14.6 B	6.8 B	12.5 B	230 B	57.8 E	61.6	460	63.5	494	330 E	58.0 B	15.0 B	16
17	14.3 B	6.8 B	13.0 B	220 B	55.9	55.9	420	67.4 E	440	305 E	55.0 B	14.0 B	17
18	14.0 B	6.9 B	14.0 B	215 B	57.8	47.6	354	71.4 E	395	280	52.0 B	14.0 B	18
19	13.8 B	6.9 B	14.5 B	210 B	65.4	41.2	318	75.3	362 E	260	50.0 B	14.0 B	19
20	13.5 B	7.0 B	16.0 B	200 B	67.3	43.6 E	258	69.2	328	239	46.0 B	14.0 B	20
21	13.0 B	7.0 B	17.0 B	184	93.7	46.0	217	63.5	294 E	162 B	43.0 B	14.0 B	21
22	12.6 B	7.0 B	18.0 B	151	82.2	55.9	204	57.8	260	135 B	40.0 B	14.0 B	22
23	12.3 B	7.1 B	19.0 B	162 E	75.3	49.2	169	49.2	246 E	124 B	37.0 B	13.0 B	23
24	12.0 B	7.1 B	20.0 B	172	63.5	63.5	166	47.6	232 E	113 B	34.0 B	13.0 B	24
25	11.8 B	7.2 B	21.0 B	175	59.7	137	145 E	273	218 E	102 B	31.0 B	13.0 B	25
26	11.5 B	7.2 B	22.0 B	169	57.8	246 E	124	700 E	204 E	104 B	29.0 B	13.0 B	26
27	11.0 B	7.3 B	23.0 B	145	54.0	354	137	1750 E	190 E	100 B	27.0 B	13.0 B	27
28	10.6 B	7.4 B	24.0 B	124	49.2	386	135 E	4500	176 E	98.0 B	25.0 B	12.0 B	28
29	10.3 B	7.5 B	25.0 B	121	42.8	341	132	3500 E	162	96.0 B	24.0 B	12.0 B	29
30	10.0 B		26.5 B	119	44.4	285	250	2600 E	153	94.0 B	23.0 B	12.0 B	30
31	9.8 B		28.0 B		42.8		235	1960		91.0 B		12.0 B	31
TOTAL	447.5	209.9	452.2	5114.0	2016.2	2921.3	6759.0	17960.0	20354	6943.0	1768.4	490.3	TOTAL
MEAN	14.3	7.2	14.6	170	65.0	97.4	218	579	678	224	58.9	15.8	MEAN
AC-FT	878	416	897	10100	4000	5790	13400	35600	40400	13800	3510	973	AC-FT
MAX	18.0	9.0	28.0	329	121	386	545	4500	1720	415	90.0	22.0	MAX
MIN	9.8	6.5	7.5	30.0	42.8	33.8	86.8	47.6	153	91.0	23.0	12.0	MIN

SUMMARY FOR THE YEAR 1976
MEAN DISCHARGE, 179 CFS
TOTAL DISCHARGE, 130000 AC-FT
MAXIMUM DAILY DISCHARGE, 4500 CFS ON AUG 28
MINIMUM DAILY DISCHARGE, 6.5 CFS ON FEB 12

B-ICE CONDITIONS
E-ESTIMATED

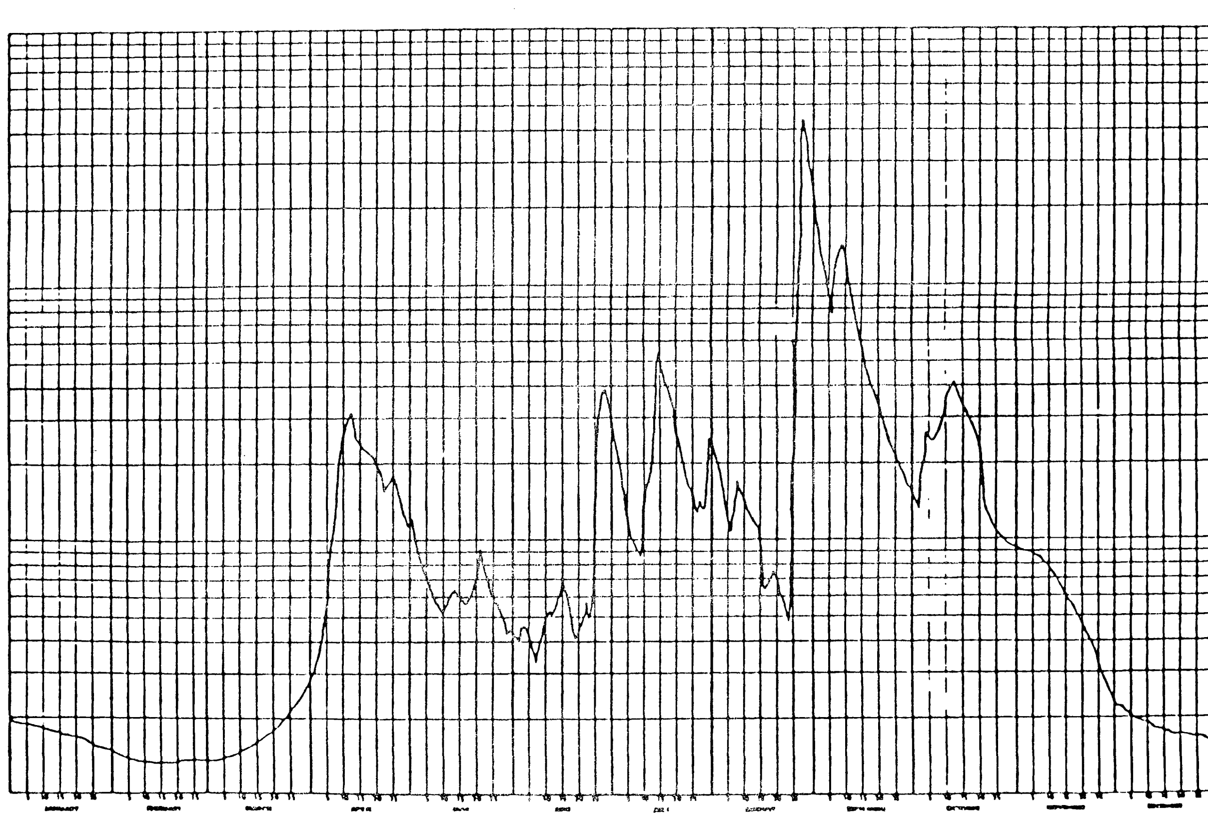


Figure 12. Example daily flow table and hydrograph (reproduced directly from Loeppky and Spitzer 1977, without conversion to metric units).

Table 17. Correlation between daily flows for various lag periods, MacKay River, 1976.

Lag Interval Days	Autocorrelation Coefficients Full Year (366 days)	1 Apr-30 Nov (244 days)
1	0.97	0.96
2	0.89	0.87
5	0.62	0.55
10	0.37	0.26
15	0.21	0.15
20	0.08	0.04

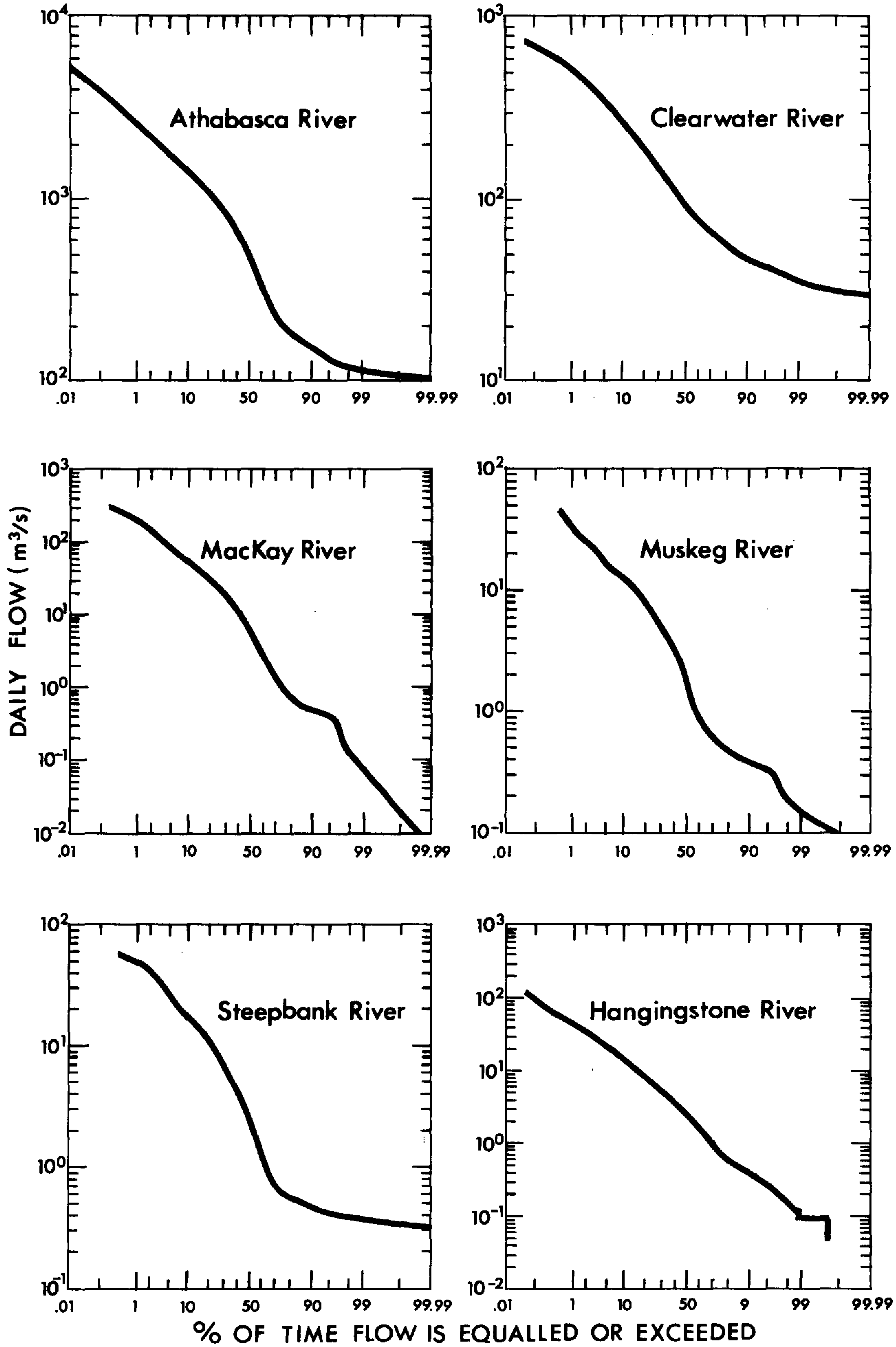


Figure 13. Flow-duration curves for six rivers.

Table 18. Variability of daily streamflows.

River	Mean Flow	Average Annual		Extreme Recorded	
		Max.	Min.	Max.	Min.
	m^3/s	m^3/s		m^3/s	
Athabasca	690	2660	140	4790	47
Clearwater	136	500	43	790	30
Hangingstone	5	60	0.4	135	0
Beaver	2	30	0.2	54	0
Mackay	22	180	0.3	306	0
Firebag	34	70	9	99	7

5. RESPONSE OF STREAMFLOW TO SNOWMELT AND RAINFALL

The following sections consider, for streams draining the study area, the relationship of runoff volumes and hydrograph patterns to meteorological factors, specifically volumes and rates of snowmelt and rainfall.

5.1 RESPONSE TO SNOWMELT

5.1.1 Volumetric Runoff Coefficients

Of the two years of good spatial coverage available for analysis (1976 and 1977), only 1976 was found amenable to fairly reliable interpretation of snowmelt runoff coefficients. For 1976, a map is available from AES showing contours of snow water equivalent on the ground at 18 March, and hydrographs for many streams show a fairly clear snowmelt response starting about the end of March, peaking about mid-April, and receding to the early part of June, when rainfall response begins to be evident. Typical examples are shown in Figure 14.

Snowmelt runoff coefficients were estimated by the following procedure:

1. Volume of snow water equivalent on the ground in each basin at the start of melt was computed from the AES map of 18 March 1976, which shows contours of equivalent depth of water;
2. Volume of snowmelt runoff in each basin was computed from the area under the appropriate part of the streamflow hydrograph, as indicated in Figure 14. In general, the hydrograph recession was projected down as a more or less straight line (on the semi-logarithmic plot) from the mid-April peak to the latter part of June, discounting subsequent rises identifiable as due to rainfall. Base flow during the snowmelt period was not deducted in order to compensate for cutting off the recession at the end of June; and
3. Snowmelt runoff coefficient was estimated as volume

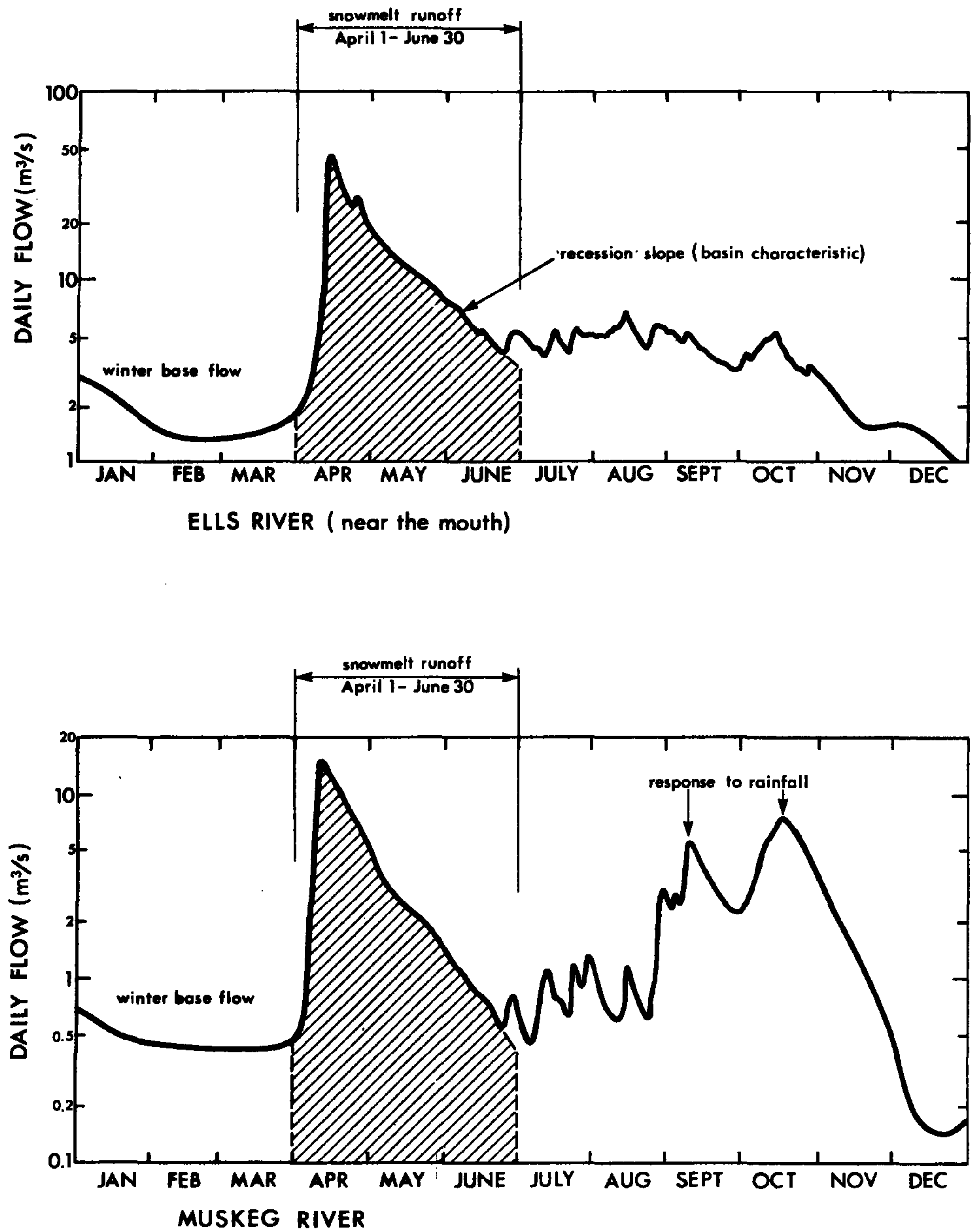


Figure 14. 1976 streamflow hydrographs showing response to snowmelt and rainfall.

of runoff divided by volume of snow water equivalent on ground. Results are shown in Table 19. These coefficients are likely to be high because some precipitation during the snowmelt period was neglected in computing snowmelt runoff from the hydrographs.

Overall, computed snow on the ground averaged about 100 mm of water equivalent, and computed runoff from snow averaged about 33 mm, that is 33%. Runoff coefficients for individual basins range from less than 20% to over 50%.

Attempts to apply a similar analysis to 1977 data were frustrated by the light winter snowpack, and difficulties of distinguishing between runoff from snowpack melt and runoff from substantial precipitation that occurred during the snowmelt period.

The quoted snowmelt runoff coefficients appear remarkably low. Presumably, most of the 'lost' snowmelt is stored in the soil and subsequently utilized by vegetation or evaporated directly. As indicated in Section 5.1.2 below, however, losses to the atmosphere from the snowpack probably constitute a signficant part of the total loss to runoff.

The 1976 snowmelt runoff coefficients of Table 19 may be compared with the overall runoff coefficients of Table 11. It is seen that on the west side of the Athabasca River, 1976 snowmelt runoff coefficients are considerably greater than overall runoff coefficients for 1976-77. East of the Athabasca River and south of Fort McMurray, the two sets are remarkably similar.

5.1.2 Losses of Water From Snowpack

Successive surveys of snow water equivalent were made prior to the snowmelt period in January, February and March 1978. Data supplied by AES suggest that between 24 February and 24 March, losses averaged about 20 mm of water equivalent, but may have been considerably higher at some stations. With reference to the snowmelt runoff coefficients listed in Table 19, therefore, it is possible that a significant part of the 'lost' water is returned directly

Table 19. 1976 snowmelt runoff coefficients.

Basin	Drainage Area	Average Depth of Snow Water Equiv. on 18 Mar., mm	Total Snow Water Equiv. 10^6 m^3	Total Snowmelt Runoff Hydrograph 10^6 m^3	Apparent Runoff Coefficient = = column 5/column 4
West Side					
Mackay (less Dunkirk)	3649	74	270	152	0.56
Dunkirk	1582	95	150	62	.41
Lower Ells (less Upper Ells)	1121	107	120	46	.38
Upper Ells	1365	114	156	54	.35
Joslyn	248	97	24	13.4	.56
Calumet	181	88	16	4.4	.28
Asphalt	149	88	13	3.4	.26
Unnamed	280	88	25	4.4	.18
TOTALS & MEANS,W. SIDE	8575	90	774	340	.44
East Side					
Steepbank	1373	113	155	44	.28
Muskeg	1456	109	159	29	.18
Firebag	6087	131	797	220	.28
TOTALS & MEANS,E. SIDE	8916	125	1111	293	.26
South					
Horse	2150	52	112	26	.23
Hangingstone	914	79	72	20	.28
TOTALS & MEANS, S.	3064	60	184	46	.25
GRAND TOTALS & MEANS	20555	101	2069	679	.33

to the atmosphere from the diminishing snowpack.

The question of water losses from snow appears to be a relatively neglected topic in the hydrologic literature. According to Gartska (1964), quoting the U.S. Corps of Engineers, losses in middle latitudes in early spring can be assumed at about 13 mm per month for hydrologic computation purposes. Data from Finland (Lemmela 1972), at a latitude 3^{o} north of Fort McMurray, indicate an average figure of 12 mm per month during late March and early April, and considerably higher rates in some years. There is therefor some reason to accept the indications of the 1978 snow surveys.

5.1.3 Peak Flows Due to Snowmelt

Table 20 lists peak flow rates and rates of runoff (per km^2 of basin area) for the snowmelt runoff of April 1976. Peak runoff rates range from 0.007 to 0.058 $m^3/s/km^2$. The reasons for the wide range have not been ascertained.

Examination of the April 1976 snowmelt hydrograph for the MacKay River (Figure 15) indicates that significant snowmelt runoff was associated with daily maximum temperatures at Fort McMurray in excess of about $10^{o}C$. On 12 April, the day of peak runoff, the temperature at Fort McMurray reached a high for the month, of $24^{o}C$. A subsequent decline to $4^{o}C$ on 17 April was accompanied by a dip in the hydrograph recession curve. A later gradual rise to $22^{o}C$ on 28 April stemmed the rate of streamflow decline only slightly, presumably because of diminishing areas of snow cover.

Further analysis of snowmelt runoff could be done by application of simulation techniques. For example, snowmelt runoff in a particular basin could be estimated for a range of snowpack and spring weather conditions.

5.2 RESPONSE TO RAINFALL

5.2.1 Volumetric Runoff Coefficients

A computation of rainfall runoff coefficients for 1976 is shown in Table 21. Rainfall amounts on each basin were determined

Table 20. Peak snowmelt runoff rates, April 1976.

Basin	Drainage Area km^2	Streamflow Peak m^3/s	Peak Rate of Runoff $m^3/s/km^2$	Date
West Side				
Dunkirk	1582	30.9	0.020	21 April
Lower Ells	2476	49.9	0.020	14 April
MacKay	5230	209.3	0.040	12 April
Upper Ells	1365	16.1	0.012	17 April
Joslyn	248	14.4	0.058	14 April
Tar	313	14.5	0.046	9 April
Calumet	181	3.7	0.021	15 April
Asphalt	149	3.6	0.024	13 April
Unnamed	280	3.0	0.011	15 April
East Side				
Steepbank	1373	17.1	0.012	15 April
Muskeg	1456	14.2	0.010	12 April
Firebag	6087	60.9	0.010	20 April
South				
Horse	2150	14.4	0.007	11 April
Hangingstone	914	9.3	0.010	12 April

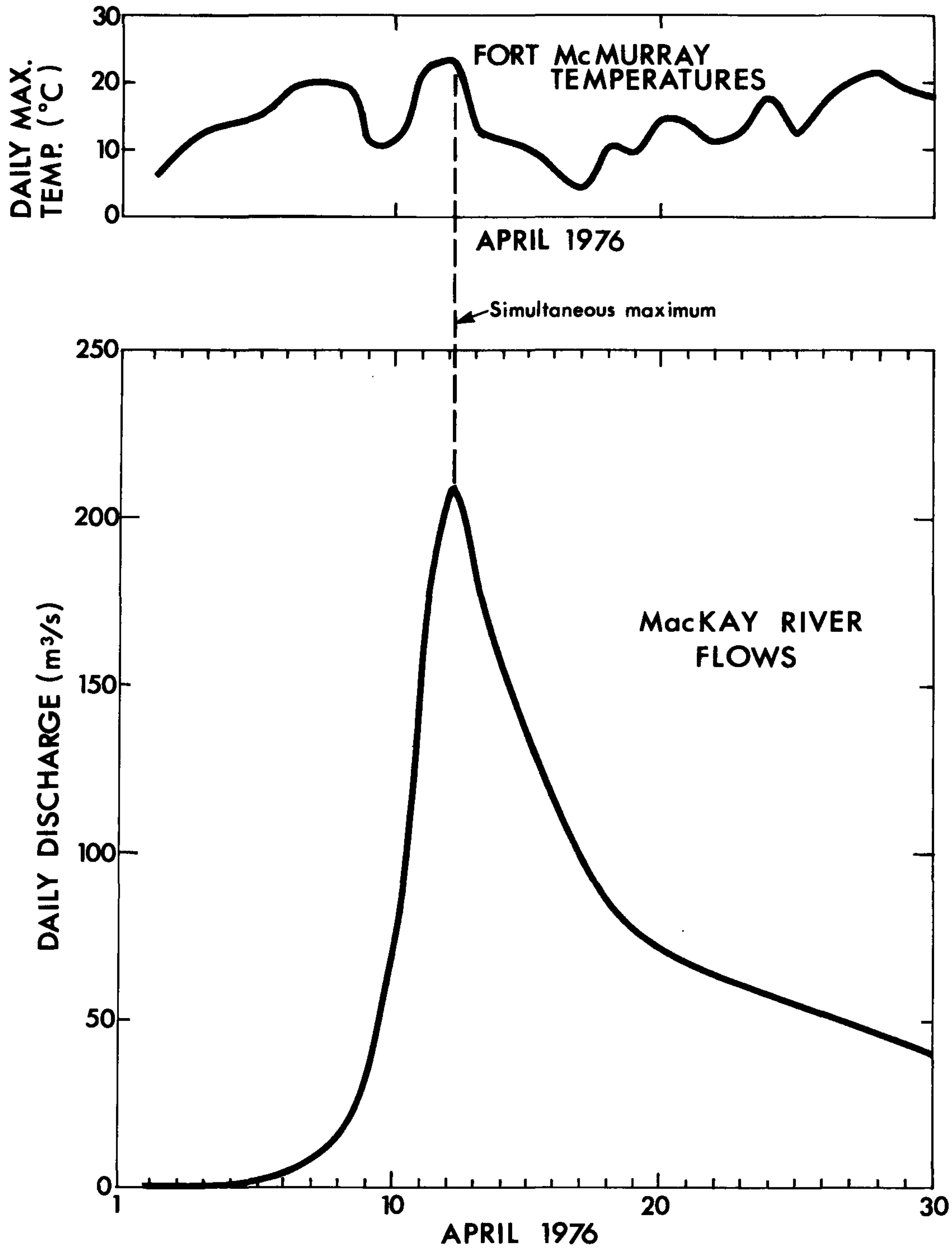


Figure 15. Air temperatures and snowmelt runoff, MacKay River, April 1976.

Table 21. Rainfall runoff coefficients, May to October 1976.

Basin	Drainage Area	Av. Basin Rainfall 1 May to 31 Oct mm	Av. Basin Rainfall 1 May to 31 Oct $10^6 m^3$	Rainfall Runoff From Hydrographs $10^6 m^3$	Apparent Runoff Coefficient
West Side					
Mackay (less Dunkirk)	3649	377	1375	204	0.15
Dunkirk	1582	300	475	40	0.08
Lower Ells (less Upper Ells)	1121	295	331	13	0.04
Joslyn	248	290	72	5.0	0.07
Calumet	181	295	53	1.2	0.02
Asphalt	149	320	48	6.1	0.13
Unnamed	280	330	92	3.9	0.04
TOTALS & MEAN, WEST SIDE			2446	273.2	0.11
East Side					
Steepbank	1373	365	501	82	0.16
Muskeg	1456	305	444	33	0.07
Firebag	6087	310	1887	366	0.19
TOTALS & MEAN, EAST SIDE			2832	481	0.17
South					
Horse	2150	435	935	264	0.28
Hangingstone	914	475	434	138	0.32
TOTALS & MEAN, SOUTH			1369	402	0.29

by preparing a map of rainfall isohyetals for the period 1 May to 31 October. Rainfall runoff was determined by subtracting previously identified snowmelt runoff (Table 19) from reported streamflows for the period 1 April to 31 December 1976. It is evident that except in the Firebag, Horse, and Hangingstone basins, measured runoff from rainfall is generally very low: on the east slopes of the Birch Mountains it appears to be only about 5%. On the west side of the Athabasca River generally, rainfall coefficients appear to be much lower than snowmelt runoff coefficients (Table 19), but east of the river and south of Fort McMurray the two sets are not remarkably different.

5.2.2 Peak Flows Due to Rainfall

During the 2-year period 1976-to 1977, for which good coverage of precipitation and streamflow data is available, two substantial rainstorms occurred within the study area. The first storm occurred on 25 to 26 August 1976; isohyetals mapped by Froelich (1977) and by Mann (1978) show that it was centred over the Horse and Hangingstone basins south of Fort McMurray, and that precipitation at the centre exceeded 100 mm. The second storm occurred on 1 to 3 July 1977; isohyetals mapped by Longley and Janz (1978) show that it was centred at Birch Mountain in the upper part of the Unnamed Creek basin, and that precipitation at the centre again exceeded 100 mm.

Table 22 lists some statistics regarding runoff volumes and hydrograph characteristics resulting from these rainstorms, in each case for three drainage basins close to the storm centre. In the case of the August 1976 storm near Fort McMurray, runoff coefficients (computed as volume of direct runoff divided by volume of rainfall) range from 17% to 36% and are fairly close to seasonal rainfall runoff coefficients listed in Table 21. In the case of the July 1977 storm, runoff coefficients for Unnamed, Asphalt and Calumet basins appear remarkably low, but are not grossly out of line with seasonal figures listed in Table 21.

The extremely low runoff resulting from rainfall on the east slopes of the Birch Hills is probably due to the nature of the

Table 22. Streamflow response to rainstorms.

River	Date of Rainfall	Estimated Basin Basin Average Precipitation mm	Storm Duration Days	Assumed Duration of Storm Runoff Days	Basin Av. Runoff mm	Runoff Coefficient	Time from Middle of Rainstorm to Hydrography Peak Days	Ratio of Peak to Average Runoff
Hangingstone	25 to 26 Aug. 1976	115	2	13	44	0.36	2	3.6
Beaver (above Syncrude)	26 Aug. 1976	93	1	8	26	0.28	2	2.8
Steepbank	26 Aug. 1976	70	1	21	12	0.17	3	2.0
Unnamed	2 to 3 July 1977	95	2	12	3.2	0.034	3	3.2
Asphalt	2 to 3 July 1977	90	2	11	8	0.09	2.5	2.1
Calumet	2 to 3 July 1977	75	2	13	1.5	0.02	3	Double Peak

subsoil. A surficial geology map (Research Council of Alberta, 1971) shows extensive areas of sand deposits in the lower parts of these basins. Presumably most of the rainfall runoff infiltrates the sand, whereas under snowmelt conditions runoff is higher because the subsoil is still frozen or saturated. Runoff infiltrating the sand probably travels as subsurface flow to the Athabasca River.

5.3 INTERACTION WITH GROUNDWATER

The only field investigation conducted so far on subsurface flow systems and rates of subsurface flow was a special study in the Muskeg River basin. This was designed to distinguish between shallow groundwater, muskeg and surface runoff components of streamflow on the basis of chemical characteristics (Schwartz 1979). For purposes of the present study, the possible interactions between surface and subsurface response to snowmelt and rainfall have been inferred indirectly from the network of observational wells maintained by Alberta Research Council.

At the time of writing a forthcoming Alberta Research Council report on hydrogeology was not yet available, however a short tabulation of data on water level changes and estimated soil porosities was provided by Dr. D. Hackbarth following a discussion on the subject of interactions. These data show that wells in some localities, where the water table is typically 2 or 3 m deep, experience water level rises of up to 1.5 m following snowmelt in spring. On the basis of soil porosity of 5%, which appears to be a typical figure at the level of the water table, the corresponding loss of water on the ground would be up to 75 mm. This figure corresponds closely to the differences between snow water equivalent and snowmelt runoff shown for some basins in Table 19. Assuming a snow water equivalent of 100 mm, and snowmelt runoff of 25% or 25 mm, the depth of water available for groundwater recharge would in fact be 75 mm.

Similar water well rises have been observed following rainstorms. For example, a well in the Calumet basin rose about 0.6 m following the rainstorm of 2 to 3 July 1977, for which runoff data are listed in Table 22. Assuming 5% to 10% porosity (estimated by Alberta Research Council) the corresponding depth of water on the ground would be 30 to 60 mm. Based on Table 22, the apparent 'loss' of precipitation was over 70 mm, but a substantial part of this might be accounted for by surface detention and evaporation.

In the case of the Calumet and other small basins on the east slopes of the Birch Hills, it appears to be a reasonable hypothesis that there is a substantial subsurface flow downslope to the Athabasca River. If this is so, there may be significant impact implications with respect to in situ oil recovery developments. There seems to be a strong case for field investigation of subsurface flow systems in certain parts of the study area, using tracers or other appropriate methods.

In relation to the overall water balance discussed in previous sections of the report, it seems reasonable to suppose that evapotranspiration from the east slopes basins is not greatly different from other parts of the study area, and that the extremely low runoff coefficients found for these basins reflect mainly ungauged groundwater leakage. On this basis, the computed evapotranspiration figure quoted in Table 8 for "all gauged tributaries north of Fort McMurray" would be slightly high.

6. MAXIMUM AND MINIMUM FLOWS

The following sections consider available data on annual maximum and minimum flows, and the prediction of maxima and minima beyond the range of recorded experience.

6.1 MAXIMUM FLOWS

6.1.1 Maximum Flow Data

Table 23 summarizes a limited amount of data on maximum flows for eight rivers with three to 20 years of records. Comments are as follows:

1. The mean annual flood based on data is listed for each river. This is the average, over the period of record, of the maximum flows reported each year. For six stations it is based on instantaneous maxima; for the other two it is based on daily maxima, instantaneous values not being available;
2. Values are listed for a mean flood coefficient computed as (mean annual flood) divided by (drainage area)$^{0.8}$. In general, mean annual floods increase as the 0.8 power of drainage area, other factors being equal. Values of this coefficient therefore indicate the relative intensity of annual floods among basins of different areas. The Hangingstone basin has the highest value (0.24), and the Firebag and Muskeg the lowest values (0.07 and 0.08). Using Table 23, values could be estimated reasonably for many of the other basins in the study area, by consideration of physiographic factors affecting the coefficient. For the anomalous small basins on the east slopes of the Birch Hills, however, several years of data from a representative basin would be advisable; and
3. An estimated 20-year flood based on statistical analysis (log-normal distribution) is shown for those stations with five years or more of record, and ratios

Table 23. Maximum flows.

River	Drainage Area (DA) km^2	No. of Years of Record	Mean Annual Flood (MAF) m^3/s	Flood Coefft. $(MAF)/(DA)^{0.8}$	Maximum Recorded m^3/s	Estimated 20-Year Flood m^3/s	Ratio 20-Year to Mean
Athabasca (below Fort McMurray)	133 000	20	2720	0.22	4786	4430	1.63
Clearwater	30 600	19	520	0.13	728	860	1.65
Poplar Ck.	151	5	7.8	0.14	17.8	17.5	2.2
MacKay	5 230	5	190	0.20	306	740[a]	3.9[a]
Steepbank	1 373	4	38	0.12	62	(95)	(2.5)[b]
Muskeg	1 456	4	26	0.08	43	(65)	(2.5)
Firebag	6 035	3	78[c]	0.07	99	(195)	(2.5)
Hangingstone	914	13	57[c]	0.24	135	140	2.5

[a] Figure considered too high, because 5-year sample is probably unrepresentative.

[b] Bracketed figures are based on assumed ratios to mean flood.

[c] Daily value: all others are instantaneous maxima.

of this value to the recorded mean flood are shown. Bracketed 20-year flood figures listed for other stations were derived by applying assumed ratios to the listed mean floods.

6.1.2 Regional Flood Analysis

A regional flood analysis, utilizing data from 13 stations both inside and outside the study area, was conducted on behalf of Syncrude Canada Ltd., in connection with development of Lease 17 and the associated diversion of the Beaver River (Syncrude Canada Ltd. 1975). Basically the analysis involved plotting mean annual floods against drainage area, and plotting 'normalized' flood frequency curves in which floods of various frequencies were expressed as ratios to the mean flood. Values of the mean flood coefficient as defined in Section 6.1.1 ranged from 0.05 to 0.4, compared to the range of 0.07 and 0.24 shown in Table 23. Values of the 20-year to mean flood ratio ranged from 1.9 to 5, compared to the range of 1.63 to 3.9 shown in Table 23. Thus the later data shown in Table 23 appear to support the earlier Syncrude analysis quite well.

6.1.3 Possible Extreme Floods

Analysis of maximum probable or similar flood conditions (as normally applied in the design of major hydraulic structures) was not undertaken in the present study. As a matter of general interest, however, crude estimates of possible extreme floods have been made for the Hangingstone and MacKay rivers and are shown in Table 24. Methods and results are explained below.

The first method was to apply a generalized maximum probable flood curve developed for the Canadian prairies by the Saskatchewan-Nelson Basin Board (SNBB 1970). As shown in Table 24, results are roughly four and two times greater than 20-year flood estimates for the Hangingstone and MacKay rivers, respectively.

The second method was to scale up recorded flood hydrograph peaks on unit hydrograph principles, assuming an extreme amount of net storm rainfall available for runoff. As shown in Table 24, for an

Table 24. Extreme flood estimates for two selected basins.

Basin	Drainage Area km^2	Est'd 20-Year Flood m^3/s	SNBB Peak Flow (max. probable curve)		Scaled-up Hydrographs	
			$m^3/s/km^2$	m^3/s	net runoff mm	peak flow m^3/s
Hangingstone	914	140	0.66	600	150	440[a]
MacKay	5230	740	0.25	1300	-	-

[a] Scaled up from flood of August 1976.

assumed net runoff of 150 mm in the Hangingstone basin, say from a rainfall of 200 mm, the flood peak is about 75% of the SNBB maximum probable estimate. For the MacKay River, insufficient clearcut data were available to permit application of this method without extensive analysis.

6.2 MINIMUM FLOWS

Table 25 summarizes data on minimum daily and minimum monthly flows, firstly for the eight rivers with several years of record listed in Table 23 (maximum flows), and secondly for other streams with only two years of records. Comments are as follows:

1. Mean annual minimum and minimum recorded refer to daily flows as reported by Water Survey of Canada (Inland Waters Directorate 1977).
2. Mean minimum coefficients are computed as (mean annual minimum) divided by (drainage area). These minimum coefficients vary over a much wider range than the flood coefficients listed in Table 23, being sensitive to details of basin physiography and geology;
3. Twenty-year (daily) minima, where listed, are based on statistical analysis, assuming a normal distribution; and
4. Minimum recorded monthly figures refer to the average flow in the lowest month of record.

On the basis of these data, a considerable degree of judgement would be required in estimating minimum flows for ungauged basins.

Table 25. Minimum flows.

River	Drainage Area (DA) km²	No. of Years	Mean Annual Min.(MAM) m^3/s	Minimum Coefficient $= \frac{MAM}{DA}$ $m^3/s/km^2$	Minimum Recorded Daily m^3/s	Est'd 20-year Minimum m^3/s	Minimum Recorded Monthly m^3/s	Date
Stations listed in Table 23 (Maximum flows)								
Athabasca (below Fort McMurray)	133 000	18	138	0.0010	104	95	111	Feb. 59
Clearwater	30 600	19	44	0.0014	30	30	33.4	Feb. 68
Poplar Ck.	151	5	0	0	0	0	0	Jan.-Mar. 76
Mackay	5 230	5	0.29	0.00005	0.02	0	0.10	Feb. 73
Steepbank	1 373	4	0.38	0.0027	0.25	-	0.30	Dec. 77
Muskeg	1 456	4	0.21	0.00014	0.17	-	0.21	Dec. 76
Firebag	6 035	6	7.0	0.0013	7.1	5.6	7.08	Feb. 72
Hangingstone	914	9	0.20	0.00022	0	0	0.09	Feb. 75
Other Stations								
Beaver (above Syncrude)	176	2			0		0	(Feb.)
Dunkirk	1 580	2			0.03		0.03	Jan. 76
Thickwood	170	1			0		0.006	Mar. 77
Upper Ells	1 365	2			0.20		0.21	Mar. 77
Lower Ells	2 480	2			0.40		0.64	Mar. 77
Joslyn	248	2			0.003		0.009	Dec. 77
Upper Tar	97	1			0		0	(Feb.-Mar.)
Calumet	181	2			0		0	(Feb.)
Pierre	130	2			0		0	(Feb.-Mar.)
Asphalt	149	2			0		0	(Feb.-Mar.)
Unnamed	280	2			0.03		0.03	Dec. 76
Hartley	368	2			0.008		0.007	Jan. 77
Horse	2 180	2			0.34		0.42	Jan. 76

7. SUMMARY AND RECOMMENDATIONS

The study has described and interpreted salient features of the surface water hydrology of the oil sands area, utilizing general principles of hydrological analysis and hydrometeorological information available up to December 1977. Coverage and discussion of several aspects are necessarily incomplete, because judgemental decisions had to be made concerning which aspects were most worth pursuing, given limitations of time and budget. In particular, it was not found practicable to investigate in depth the influence of physiographic and geological factors on differences in hydrologic behaviour between individual basins. The sections following summarize some of the more signficant findings and make some recommendations on future studies.

7.1 SUMMARY OF SIGNIFICANT FINDINGS

Following the sequence of topics by which the report is arranged, the most significant findings appear to be as follows:

7.1.1 Data Utility

Streamflow data generally cover too short a period of record to give a reliable picture of streamflow variability in space and time. Some extension is possible by the use of historical precipitation data, but full-year coverage is available at only one or two points. Data networks now in service will enable a much clearer picture to emerge within the next five years or so.

7.1.2 Streamflow Balance

Less than 10% of the average flow in the Athabasca River at its mouth originates as runoff from the study area. It is not possible to determine year-to-year variations in study area runoff by taking differences in Athabasca River flows as gauged at Fort McMurray and Embarras, because of inherent limitations on gauging accuracy and the difficulty of establishing a small difference between two large numbers subject to errors of measurement. On a monthly basis, contributions from the study area to the outflow of the Athabasca River may range from less than 5% to more than 15%.

7.1.3 Water Balance

Roughly 80% of the precipitation falling on the study area under present conditions is returned to the atmosphere by evaporation and transpiration, from the ground and from vegetation. There are indications that annual evapotranspiration in parts of the area is normally limited by moisture supply rather than atmospheric capacity, increasing in wet years and reducing in dry years. For certain parts of the study area, particularly the east slopes of the Birch Hills, indicated extremely low runoff percentages are probably due in part to ungauged subsurface flow out of the basins. Elsewhere, it is unlikely that groundwater leakage plays an important role in the overall water balance.

7.1.4 Runoff Variability

Average runoff, expressed as depth of water per year over basin areas, varies considerably over the study area, from a high of about 160 mm south of Fort McMurray to a low of about 30 mm on the east slopes of the Birch Hills. To some extent these differences reflect differences in precipitation, but they must also reflect differences in physiographic and climatic factors that influence evapotranspiration. In the case of the lowest runoff areas as noted above, groundwater leakage is probably a significant factor.

Year to year variability in runoff is high for some parts of the study area; in wet years it may be many times greater than in dry years. Similar comments apply to the year to year variability of flows in a given calendar month, except for the low winter months when flows are fairly consistent from one year to another.

7.1.5 Streamflow Response to Snowmelt and Rainfall

Reliable analysis of snowmelt runoff was possible only for 1976. For that year, runoff from snow represented, on average, about 33% of the water content of the late winter snowpack. The remainder of the snow water content is probably accounted for mainly by soil moisture recharge, but part is probably evaporated directly from the snow surface and from the ground. Peak snowmelt runoff rates in 1976 ranged from 0.007 to 0.06 m^3/s per km^2 of basin area.

Runoff from seasonal rainfall represents, on average, about 20% of precipitation, but varies greatly in different basins, being highest south of Fort McMurray and lowest on the east slopes of the Birch Hills. Percentages of runoff from individual rainstorms of one or two days' duration appear to be quite similar to seasonal percentages.

7.1.6 Maximum and Minimum Flows

Mean annual flood coefficients, defined as mean annual flood in m^3/s divided by the 4/5 power of drainage area in km^2, range from 0.07 to 0.24 for basins with a few years of record. Ratios of estimated 20-year flood to mean annual flood range from about 1.6 to 3.9. Hypothetical extreme floods in the maximum probable category may be two to four times greater than 20-year floods.

Minimum flows are erratic and do not correlate well with drainage area. Some of the smaller river basins show zero flow in the late winter.

7.2 IMPLICATIONS FOR FUTURE INVESTIGATIONS AND IMPACT STUDIES

Stated objectives for the study (see Section 9.1) included identification of problems in data collection and (possibly) recommendations for additional research. A number of points related to these objectives are set out below.

7.2.1 Streamflow Data Network

Recommendations regarding the streamflow gauging network are contained in a previous AOSERP report (Yaremko and Murray, in prep.). The present study indicates that it is desirable to continue gauging a selected set of rivers that represent reasonably the range of basin sizes and characteristics present in the study area. Continuation has two purposes: firstly, to define better the spatial and temporal variability of runoff and, secondly, to facilitate detection of future changes due to development. However, there is little point in continuing all of the stations that were gauged in 1976 to 1977.

The meteorological network presently in place appears to be adequate to supply future hydrologic data requirements in relation to precipitation and temperature. Attention should continue to be given to snow on the ground. One aspect of the hydrologic cycle that does not appear to have had much attention is soil moisture.

7.2.2 Interaction Between Surface Water and Atmosphere

The study appears to have revealed some curious features of the relationships between runoff and evapotranspiration. Obviously there is scope for much further research of a scientific nature. A question of practical significance might be whether runoff is sensitive to changes in land use, especially to clearing of forest and muskeg. There are indications that it may be quite sensitive. It would be useful scientifically to determine exactly why evapotranspiration is so high in the study area, in comparison with other areas of similar latitude.

7.2.3 Interaction Between Surface Water and Groundwater

Water balance analyses suggest that in some parts of the study area there must be considerable subsurface flow, especially on the east slopes of the Birch Hills. This would seem to have significant implications for in situ oil sands development. It may be wise to plan field studies on subsurface flow systems and rates.

7.2.4 Computer Simulation (Modelling) Studies

Reference has been made in previous studies to the desirability of setting up computer simulation models for streamflow. It is not clear to the present writer that this would serve any definite purpose at the present time, except for specific project-related studies in particular drainage basins. To develop or adapt a physically-based runoff model of the continuous simulation type for general use in the study area might be an expensive exercise, difficult to justify in terms of the overall objectives of the AOSERP program.

7.2.5 Factors Controlling Spatial Variability of Runoff

As noted in Section 4.1.2, it has not been found practicable to make an adequate analysis of differences in mean runoff depths from one basin to another, although on the basis of Table 10 and Figure 8 these differences are clearly quite large. There were two reasons for not pursuing this question further in the present study: firstly, that two years of data (1976 and 1977) scarcely give an adequate basis for reliable analysis and, secondly, that a great deal of time-consuming map work would have been required to quantify various physiographic characteristics with which mean runoff depths might be correlated.

In relation to questions of impact and mitigation, the relationship of runoff to changeable basin characteristics has considerable implications. It is therefore suggested that a study of factors affecting volume and distribution of runoff should be commissioned at a later date, say when four or five years of data are available from many of the gauging stations within the study area.

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9. APPENDICES

9.1 TERMS OF REFERENCE

Objectives

1. Provide researchers in the water, land, and air systems with an understanding of the main features and processes of surface water hydrology in the study area and how these affect the physical aquatic habitat.
2. Consolidate and summarize what is known and what is not known.
3. When encountered, identify problems in data collection and analysis and information gaps and possibly recomment additional research in surface water hydrology.

Research Procedure

1. Gain familiarity with the needs of other investigators with regard to knowledge of the hydrologic cycle of the AOSERP area. In addition to contacts with the air and water research managers in AOSERP, AOSERP will solicit comments on an interim report from scientific advisors.
2. Assemble presently available data relevant to the hydrologic cycle.
3. Summarize and explain the state of knowledge regarding natural streamflow conditions in the AOSERP area, to include statistics and predictions of the following items:
   - Mean flows and mean runoff per unit area.
   - Distribution of flow through the year.
   - Occurrence and frequency of floods and low flows and their relation to physiographic factors.
   - Geographic factors influencing differences in streamflow characteristics between basins.

   Efforts will be made to define regional variations in key hydrologic parameters. The Athabasca River and Delta will be considered as well as the AOSERP area drainage.

4. Summarize the state of knowledge regarding rainfall, snowfall, and snowmelt in the AOSERP area and the general response of streamflow to meteorological input. Conduct hydrograph analyses for selected streamflow stations and examine approximate relationships between rainfall, snowmelt, and streamflow.
5. Determine an approximate long-term balance for the AOSERP area as a whole or in parts, as may be appropriate, taking account of precipitation, runoff and evapotranspiration. Consider annual and seasonal water balances for normal, wet, and dry years.
6. Determine whether useful inferences can be made regarding exchanges between surface runoff, shallow subsurface flow, and ground water in various physiographic environments, and whether more study of these processes is advisable.
7. Prepare a bibliography related to the hydrology of the Athabasca River and the AOSERP area. References will either be cited in text or annotated.
8. Include all the results in a report suitable for publication, and provide three draft copies for review.

9.2 DEFINITIONS

The following definitions, arranged alphabetically, cover some specific hydrological terms as they are used in the report.

Autocorrelation coefficient: a number indicating the degree to which values of a time series depend on preceeding values, separated by a specific time interval or 'lag'.

Detention: temporary storage of water in surface depressions, on vegetation surfaces, etc.

Discharge: rate of streamflow in volume per unit time. (Expressed also as 'flow'.)

Evapotranspiration: total return of water to the atmosphere by evaporation from vegetation, soil, or water surfaces, and by transpiration through plants. (See also potential evaporation.)

Flood, annual: the highest flow attained each year; may be based on daily or on instantaneous values.

Flood frequency curve: a graph indicating the percentage of years in which the annual flood exceeds a given value.

Flood, maximum probable: a hypothetical extreme flood estimate utilized in the design of major dams or similar facilities.

Gauging station: a point on a stream where discharge is measured and reported regularly.

Groundwater recharge: return of water to deep groundwater storage to replace leakage or withdrawal. (Represents a loss to available runoff.)

Hydrograph: a graph of stream discharge against time.

Hydrograph, unit: a hydrograph indicating the response of a stream to unit depth of runoff over the drainage basin.

Infiltration: entry of precipitation to the soil. Infiltrated water may be disposed of as runoff, evapotranspiration, groundwater recharge, etc.

Isohyetal: a line drawn on a map joining points of equal precipitaton.

Monthly or daily flow: average flow over a specified month or day.

Potential evapotranspiration: the evaporation that would occur, under given environmental conditions, from a land area with a continuous supply of moisture at the surface. (Actual evapotranspiration is usually less.)

Recession: the falling part of a streamflow hydrograph.

Runoff: surface water reaching the stream system by overland flow or by shallow subsurface flow; often quoted in units of average depth over a basin per unit of time.

Runoff coefficient: the ratio of volume of runoff to volume of precipitation or of snow on the ground, for a specified event or period.

Simulation: representation of hydrological processes by a computer program.

Water balance: quantitative relations between main components of the hydrological cycle in a given drainage basin or region.

Water year: in Canada, a year extending from 1 October to 30 September.

10. AOSERP RESEARCH REPORTS

1.		AOSERP First Annual Report, 1975
2.	AF 4.1.1	Walleye and Goldeye Fisheries Investigations in the Peace-Athabasca Delta--1975
3.	HE 1.1.1	Structure of a Traditional Baseline Data System
4.	VE 2.2	A Preliminary Vegetation Survey of the Alberta Oil Sands Environmental Research Program Study Area
5.	HY 3.1	The Evaluation of Wastewaters from an Oil Sand Extraction Plant
6.		Housing for the North--The Stackwall System
7.	AF 3.1.1	A Synopsis of the Physical and Biological Limnology and Fisheries Programs within the Alberta Oil Sands Area
8.	AF 1.2.1	The Impact of Saline Waters upon Freshwater Biota (A Literature Review and Bibliography)
9.	ME 3.3	Preliminary Investigations into the Magnitude of Fog Occurrence and Associated Problems in the Oil Sands Area
10.	HE 2.1	Development of a Research Design Related to Archaeological Studies in the Athabasca Oil Sands Area
11.	AF 2.2.1	Life Cycles of Some Common Aquatic Insects of the Athabasca River, Alberta
12.	ME 1.7	Very High Resolution Meteorological Satellite Study of Oil Sands Weather: "a Feasibility Study"
13.	ME 2.3.1	Plume Dispersion Measurements from an Oil Sands Extraction Plant, March 1976
15.	ME 3.4	A Climatology of Low Level Air Trajectories in the Alberta Oil Sands Area
16.	ME 1.6	The Feasibility of a Weather Radar near Fort McMurray, Alberta
17.	AF 2.1.1	A Survey of Baseline Levels of Contaminants in Aquatic Biota of the AOSERP Study Area
18.	HY 1.1	Interim Compilation of Stream Gauging Data to December 1976 for the Alberta Oil Sands Environmental Research Program
19.	ME 4.1	Calculations of Annual Averaged Sulphur Dioxide Concentrations at Ground Level in the AOSERP Study Area
20.	HY 3.1.1	Characterization of Organic Constituents in Waters and Wastewaters of the Athabasca Oil Sands Mining Area

21. AOSERP Second Annual Report, 1976-77
22. HE 2.3 Maximization of Technical Training and Involvement of Area Manpower
23. AF 1.1.2 Acute Lethality of Mine Depressurization Water on Trout Perch and Rainbow Trout
24. ME 4.2.1 Air System Winter Field Study in the AOSERP Study Area, February 1977.
25. ME 3.5.1 Review of Pollutant Transformation Processes Relevant to the Alberta Oil Sands Area

26. AF 4.5.1 Interim Report on an Intensive Study of the Fish Fauna of the Muskeg River Watershed of Northeastern Alberta
27. ME 1.5.1 Meteorology and Air Quality Winter Field Study in the AOSERP Study Area, March 1976
28. VE 2.1 Interim Report on a Soils Inventory in the Athabasca Oil Sands Area
29. ME 2.2 An Inventory System for Atmospheric Emissions in the AOSERP Study Area
30. ME 2.1 Ambient Air Quality in the AOSERP Study Area, 1977

31. VE 2.3 Ecological Habitat Mapping of the AOSERP Study Area: Phase I
32. AOSERP Third Annual Report, 1977-78
33. TF 1.2 Relationships Between Habitats, Forages, and Carrying Capacity of Moose Range in northern Alberta. Part I: Moose Preferences for Habitat Strata and Forages.
34. HY 2.4 Heavy Metals in Bottom Sediments of the Mainstem Athabasca River System in the AOSERP Study Area
35. AF 4.9.1 The Effects of Sedimentation on the Aquatic Biota

36. AF 4.8.1 Fall Fisheries Investigations in the Athabasca and Clearwater Rivers Upstream of Fort McMurray: Volume I
37. HE 2.2.2 Community Studies: Fort McMurray, Anzac, Fort MacKay
38. VE 7.1.1 Techniques for the Control of Small Mammals: A Review
39. ME 1.0 The Climatology of the Alberta Oil Sands Environmental Research Program Study Area

41. AF 3.5.1 Acute and Chronic Toxicity of Vanadium to Fish
42. TF 1.1.4 Analysis of Fish Production Records for Registered Traplines in the AOSERP Study Area, 1970-75
43. TF 6.1 A Socioeconomic Evaluation of the Recreational Fish and Wildlife Resources in Alberta, with Particular Reference to the AOSERP Study Area. Volume I: Summary and Conclusions
44. VE 3.1 Interim Report on Symptomology and Threshold Levels of Air Pollutant Injury to Vegetation, 1975 to 1978
45. VE 3.3 Interim Report on Physiology and Mechanisms of Air-Borne Pollutant Injury to Vegetation, 1975 to 1978

46.	VE 3.4	Interim Report on Ecological Benchmarking and Biomonitoring for Detection of Air-Borne Pollutant
47.	TF 1.1.1	A Visibility Bias Model for Aerial Surveys of Moose on the AOSERP Study Area
48.	HG 1.1	Interim Report on a Hydrogeological Investigation of the Muskeg River Basin, Alberta
49.	WS 1.3.3	The Ecology of Macrobenthic Invertebrate Communities in Hartley Creek, Northeastern Alberta
50.	ME 3.6	Literature Review on Pollution Deposition Processes
51.	HY 1.3	Interim Compilation of 1976 Suspended Sediment Data in the AOSERP Study Area
52.	ME 2.3.2	Plume Dispersion Measurements from an Oil Sands Extraction Plant, June 1977
53.	HY 3.1.2	Baseline States of Organic Constituents in the Athabasca River System Upstream of Fort McMurray
54.	WS 2.3	A Preliminary Study of Chemical and Microbial Characteristics of the Athabasca River in the Athabasca Oil Sands Area of Northeastern Alberta.
55.	HY 2.6	Microbial Populations in the Athabasca River
56.	AF 3.2.1	The Acute Toxicity of Saline Groundwater and of Vanadium to Fish and Aquatic Invertebrates
57.	LS 2.3.1	Ecological Habitat Mapping of the AOSERP Study Area (Supplement): Phase I

These reports are not available upon request. For further information about availability and location of depositories, please contact:

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