STREAMFLOW FORMATION IN THE MISTAYA RIVER BASIN, ROCKY MOUNTAINS, CANADA 1/

By

H. S. Loijens 2/

Introduction

In remote mountain regions detailed and long-term hydrometeorological data are not generally available although some of these areas are important sources for water supply and hydroelectric power generation. Most of the headwaters of Canada's major rivers are fed by glacier melt and therefore a thorough knowledge of the influence of glacier melt on the streamflow regime is required.

Subject of this report is the Mistaya River Basin in the headwaters of the North Saskatchewan River, Banff National Park, 100 km northwest of Banff, Alberta. It covers an area of 244 km^2, of which 12% is glacierized. The largest single glacier in the basin, Peyto Glacier, is included in the international chain of selected representative glaciers (1,2). Extrapolation of mass balance data, collected on Peyto Glacier in the period 1965-1969, indicates that the average ice ablation* contributed 15% to the annual Mistaya River streamflow (3). Derikx and Loijens (4) have described a mathematical model to simulate glacier runoff. The model is based on two years of data from Peyto Glacier (1968,1969) and is used to calculate glacier melt for all permanent snow and ice areas in the Mistaya Basin. A detailed hydrometric program was carried out in the Mistaya Basin in 1971 to collect the necessary hydrologic data for streamflow routing down the river to the main stream gauging station (Fig. 1, Station No. 7) and to test the results of the simulation model developed by Derikx and Loijens (4). During the summer, all the major inflows from glacier basins to the Mistaya River were gauged (72% of the total glacier area) and, where possible, lake levels and outflow from lakes were measured along the course of the river. Streamflow of the Mistaya River from 14 July to 3 September 1971 has been analyzed and the contribution from glaciers to streamflow calculated.

Three adjacent glacier subbasins show significant differences in runoff. The runoff from these basins is analyzed with respect to genetic origin and compared with Peyto Glacier mass balance data.

Physical and Hydrological Characteristics

The elevation of the Mistaya River Basin ranges from 1625 m at the main stream gauge to 3290 m at Howse Peak (Fig. 1); mean elevation is 2240 m. The western boundary of the basin coincides with the Continental Divide. Runoff from the basin flows into the North Saskatchewan River which travels eastward across the Prairies to Hudson Bay.

Coniferous forest covers the valley bottom and the mountain slopes to the tree line at 2100 m. The underlying rocks are paleozoic sediments consisting of sandstones, shales, and limestones which have developed karst features in some areas.

Glaciers cover an area of 33.48 km^2, according to glacier inventory of maps (5) (Table 1). The glacier outline on the inventory maps is based on aerial photography taken during the period 1949-1955. Henoch (6), however, reported that between 1948 and 1966, the glacierized area decreased by 10% in the North Saskatchewan headwaters due to glacier recession and shrinkage, and the disappearance of small patches of perennial snow and ice. The data on glacier area presented in Table 1 are consequently reduced by 10% in subsequent calculations. The area of Peyto Glacier is taken from the 1:10,000 topographical map. The principal glaciers are on the west side of the valley and all are oriented to NNE, except Delta Glacier, which is oriented towards SSE. On the east side of the valley there are only a few small glaciers (Fig. 1).

* Glacier mass balance terms are defined in Ref. 2. A few terms specific to this report are defined in the appendix.

1/ Presented at Western Snow Conference, April 16-20, 1974, Anchorage, Alaska

2/ Water Resources Branch, Environment Canada, Ottawa, Ontario, K1A 0E7

TABLE 1. DISTRIBUTION AND AREA OF GLACIERS IN THE MISTAYA RIVER BASIN

Area interval (km^2)	Frequency	Total area (km^2)
<0.25	31	3.31
0.25-0.50	15	5.23
0.50-1.00	3	1.87
1 - 2	2	2.93
>2	2	20.14
TOTAL	53	33.48

The Mistaya basin has been considered as 6 subbasins (Fig. 1: Nos. 1, 2, 3, 4, 8 and 10, respectively). For each subbasin, the streamflow at the mouth was gauged during part of 1971. Peyto, Delta, and Barbette are the major glaciers which were gauged during the summer of 1971. Combined, they cover 72% of the total glacier area in the Mistaya Basin.

The Mistaya River rises from Peyto Lake and flows NW through Mistaya Lake and Waterfowl Lakes. Below the lowest lake, the river meanders through deposits of silt and glacier till before it drops 250 m over 10 km to join the North Saskatchewan River (Fig. 1).

The hydrologic regime is strongly influenced by the annual temperature cycle which shows temperatures well below freezing from November to April. The average runoff depth during 1951-1971 was 0.860 m, of which 92% occurred in May-October and 70% in June-August (Table 2). Monthly discharges for the years 1968-1971 are shown in Fig. 2.

TABLE 2. STREAMFLOW CHARACTERISTICS OF MISTAYA RIVER (1951-1971)

Month	Length of record years	Mean Monthly Discharge mm	Coefficient of variation
January	5	8	0.18
February	5	6	0.23
March	5	7	0.38
April	6	12	0.48
May	11	58	0.37
June	21	181	0.21
July	21	237	0.14
August	21	188	0.17
September	21	93	0.27
October	17	42	0.39
November	6	18	0.22
December	6	10	0.20
Total		860	

Period of Analysis

The period 14 July - 3 September 1971 was selected for the analysis of glacier runoff contribution for the following reasons:

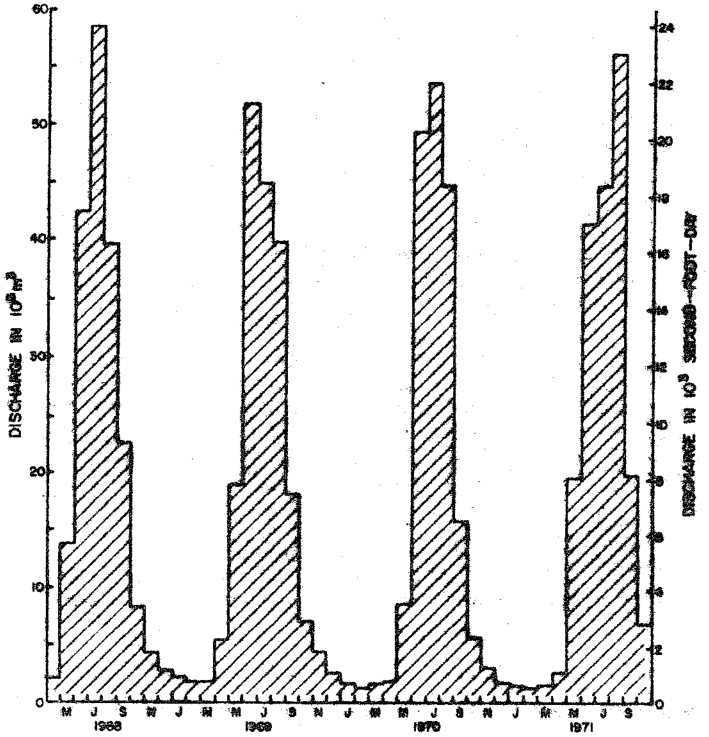

Figure 2. Monthly discharge of Mistaya River

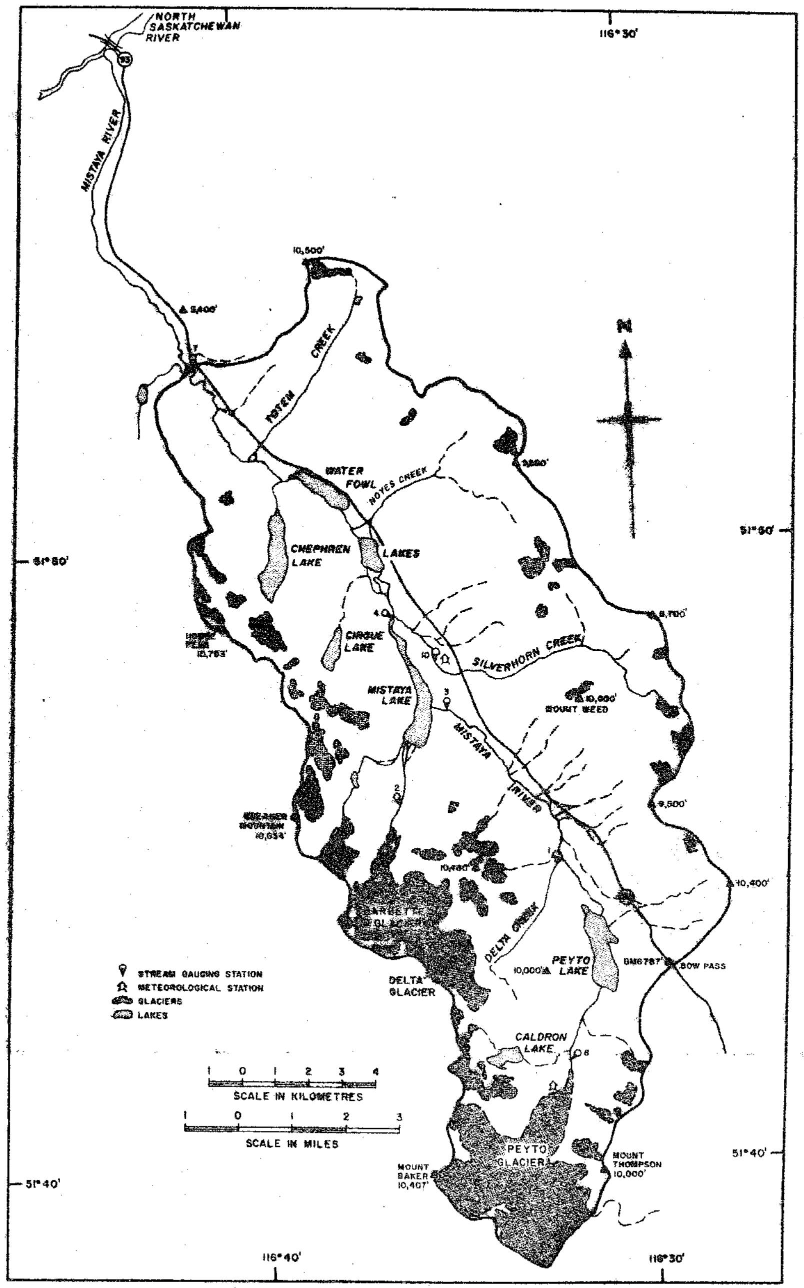

Figure 1. Mistaya River Basin, Alberta

1. Continuous data are available from three stream gauging stations (Fig. 1, Nos. 7, 8, and 10) which are part of the hydrometric network maintained by the Water Survey of Canada and 6 temporary stations, installed in late June, 1971 and operated throughout the summer.

2. Mid-July coincides with the first appearance of glacier ice. On 3 September the main melt season ended.

3. Streamflow at the start and at the end of period was nearly equal except for three stations.

The basin snow cover below the tree line was ripe at the time of the first survey in the spring of 1971 (22-26 April), but no appreciable runoff had taken place; runoff started in early May. Snow-course data, photographic records, and visual observations indicate that the snow line had receded to 2300 m by 10 June and to about 2600 m at the end of June - early July.

The snout of Peyto Glacier became snow-free by 10 July. This is later than in previous years for it is normally snow-free in mid June. Climatological data taken from the valley station Silverhorn Dump, show that temperatures remained low in June. These low temperatures and the almost daily fresh snowfall at the higher elevations until 12 July retarded the snowmelt.

By 14 July the weather improved and the snow on the rocks melted in about one week and runoff from glaciers increased rapidly (Fig. 3). From mid-July until early September all discharge was derived from glacier runoff, high elevation snowmelt, groundwater, and springs. It was assumed that no runoff from precipitation has occurred except from precipitation on lake and stream surfaces and on glaciers. The station at Silverhorn Dump recorded only 9 days with precipitation in the period 14 July - 3 September. The total precipitation was 0.030 m. This is far less than the computed actual evaporation for July and August, 0.081 and 0.046 m, respectively (Morton, personal communication).

Measured discharges of subbasins covering the period 14 July - 3 September 1971, are listed in Table 3. If the flow at the start and at the end of a period was not the same the difference in storage in the subbasin was calculated using hydrograph recession analysis and then it was added to the measured discharge. Streamflow hydrographs are presented in Figures 3 and 4.

TABLE 3. SUBBASINS IN THE MISTAYA RIVER BASIN - SURFACE AREA, GLACIER-COVERED AREA, AND DISCHARGE DURING 14 JULY - 3 SEPTEMBER, 1971

Subbasins	Surface drainage area km^2	Area covered by glacier km^2	Glacierized basin area %	Measured discharge $10^6 m^3$	Change in storage $10^6 m^3$	Total generated flow $10^6 m^3$	Yield (discharge/ glacier area) $10^6 m^3/km^2$ or m
8 Peyto Creek	22.13	13.84	63	36.47	-	36.47	2.64
1 Delta Creek	13.57	2.56	19	9.34	-	9.34	3.65
3 Mistaya River at Rock-Cut	93.52	18.94	20	53.48	+0.66	54.14	
2 Barbette Creek	13.74	5.53	40	8.37	-	8.37	1.51
4 Mistaya Lake Outlet	126.97	26.78	21	72.34	+1.00	73.34	
10 Silverhorn Creek	20.15	0.77	4	5.50	-0.26	5.24	
7 Mistaya River (main)	244.00	30.90	13	93.71	-	93.71	

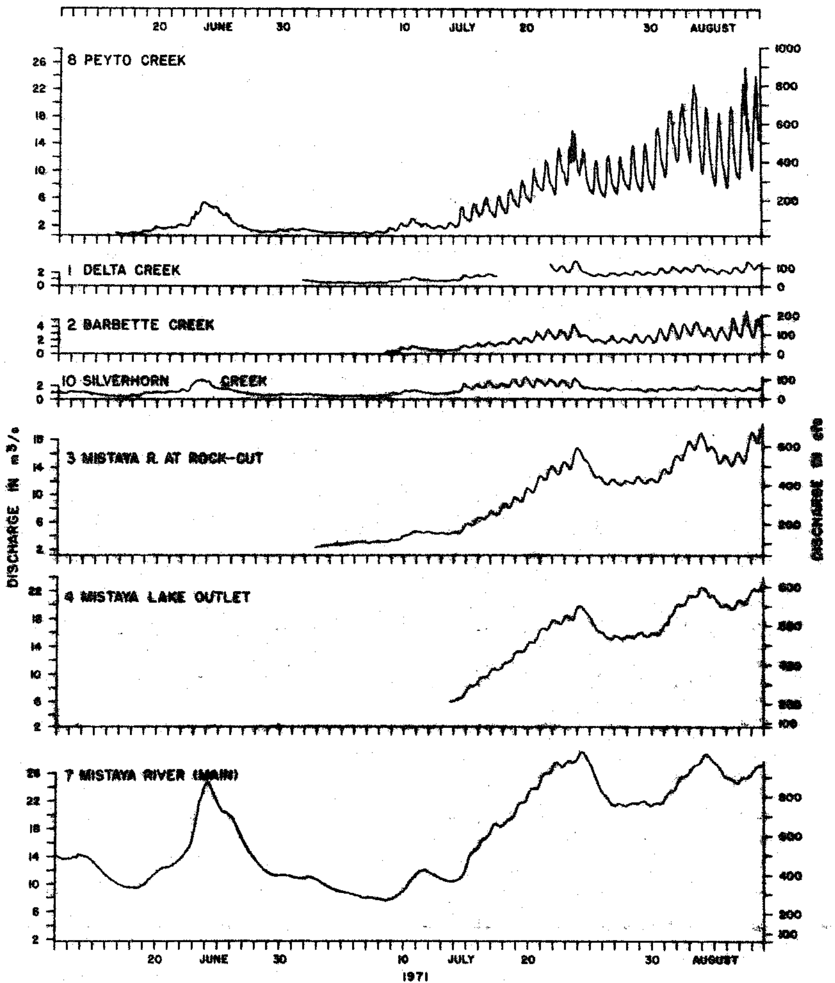

Figure 4. Daily variation in streamflow for selected stations in the Mistaya River Basin.

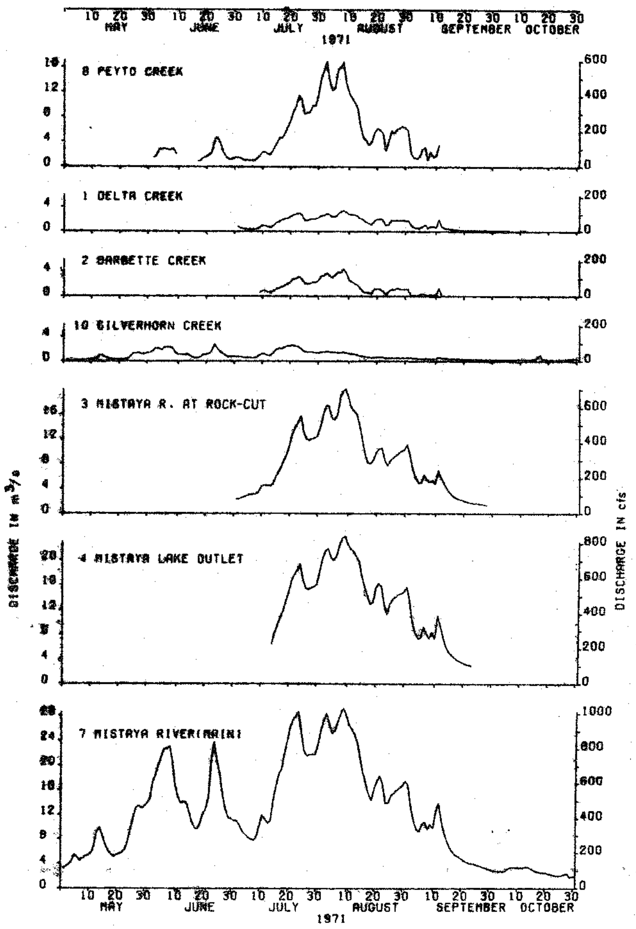

Figure 3. Mean daily discharge at selected gauging stations in Mistaya River Basin, 1971.

Runoff Analysis

Streamflow data covering the period 14 July - 3 September 1971 for the three highly glacierized subbasins of Delta, Barbette, and Peyto, identified as Nos. 1, 2, and 8 respectively in Fig. 1, are given in Table 3. Streamflow is expressed in volumetric units and as an equivalent water depth over the glacier surface (yield). By 14 July 1971, there was still snow left in the subbasins outside the area covered by glaciers; snowmelt from this source is included in the runoff yield values in Table 3.

In this section, streamflow from subbasins 1, 2, and 8 have been separated into runoff derived from glaciers and runoff derived from the melt of snow outside the area covered by ice. Then, the proportion of the Mistaya River flow derived from glacier runoff and ice/firn melt has been estimated.

Water and ice balance - Peyto Basin (No. 8)

The mass balance of Peyto Glacier over the period 14 July - 3 September 1971, shows a loss of 1.89 m (Table 4); streamflow data indicate 2.64 m (Table 3, Station 8). This diferance can not be accounted for by the snow left in the basin outside the glacier area by 14 July. Therefore, the hydrologic balance of Peyto Basin has been calculated for the 1971 melt season, 5 May - 15 September.

The hydrologic balance can be expressed as:

$$R = P + SN + B_s + E + \Delta S \qquad (1)$$

where R = measured runoff at Peyto Creek, P = basin precipitation, SN = snow accumulation on nonglacierized areas of basin on 5 May, B_s = summer balance of Peyto Glacier, E = condensation (+) - evaporation (-) balance, and ΔS = difference in liquid water storage in this basin between the start and the end of the period. The values for R, P, SN, and B_s are given in Table 4.

TABLE 4. PEYTO BASIN - HYDROLOGIC BALANCE DATA 5 MAY - 15 SEPT., 1971

Period	Precipitation (*)		Snowmelt, outside glacier area	Glacier mass loss		Discharge Peyto Creek (Station 8)
	Peyto Camp	Peyto Basin (P)	(SN)	(B_s)		(R)
	m	10^6m^3	10^6m^3	m	10^6m^3	10^6m^3
5 May - 13 July	0.157	3.96	4.56	0.30	4.12	6.95
14 July - 3 September	0.038	0.97	1.66	1.89	26.14	36.47
4-15 September	0.017	0.43	0	0.04	0.62	1.44
TOTAL	0.212	5.36	6.22	2.23	30.88	44.86

(*) Precipitation ratio Peyto Basin - Peyto Camp is 1.14 (4).

Measurements of snow accumulation outside the glacier area were not available; SN data are based upon photographic records. E, in equation (1) is assumed to be zero, because evaporation and condensation on snow are nearly equal as shown by Föhn (7) and net evaporation over the nonglacierized part of the basin when it becomes free of snow is small compared with B_s. ΔS is assumed to be zero for at the start of the melt season water storage is zero and at the end of the season water remaining in the basin is small compared with the summer runoff. The runoff calculated from equation (1) is 6% lower than the measured value (Table 4). Errors in mass balance measurements are difficult to evaluate (8) and it is assumed that the measured runoff at Peyto Creek is overestimated. The flow at the stream gauging station is turbulent and rough. The 1971 rating curve was constructed from 6 measurements with a maximum relative error of 25%. In subsequent calculations, the runoff data from station 8, Peyto Creek, are reduced by 6%.

Glacier-runoff delay

Data in Table 4 show that during the period 5 May - 13 July 1971, streamflow at Station 8 is appreciably lower than snowmelt in the drainage basin. The following period 14 July - 3 September 1971, had streamflow conversely much higher than snow and glacier ice melt. A similar feature was observed by Stenborg (9) for the Mikkagläciaren in Sweden, (basin area 13.4 km^2, glacier area 7.9 km^2) and by Tangborn et. al., (10) on the South Cascade Glacier, Washington (basin area 6.11 km^2, glacier area 2.55 km^2). Stenborg suggests various reasons for this runoff delay which may be summarized into surface storage (formation of slush areas) and internal storage (firn area, blocking of drainage channels, crevasses, etc.). Glacier size, surface slope, formation of bedrock, etc., may all influence the delay of runoff. Data for Peyto Basin presented here and data from Stenborg (9) and Tangborn et. al., (10) suggest an increase of runoff delay with increasing glacier size. Due to extensive runoff delays, glacier runoff for Peyto Glacier cannot be computed directly from mass balance measurements for a 7-week period during the summer.

Streamflow derived from glacier runoff

The runoff has been measured of three highly glacierized subbasins (Nos. 1, 2 and 8) comprising 72% of the total glacier area within the Mistaya Basin. The runoff from the remaining nongauged glaciers had to be estimated from mass balance data, despite the difficulties discussed above. Results are presented in Table 5.

TABLE 5. MISTAYA RIVER BASIN, 14 JULY - 3 SEPTEMBER, 1971.
(a) CALCULATION OF RUNOFF NOT SUPPLIED BY GLACIERS;
(b) GLACIER RUNOFF
(c) COMPARISON OF GLACIER-RUNOFF YIELD OF HIGHLY-GLACIERIZED SUBBASINS.

	area (km^2)	Discharge (10^6m^3)
a) Mistaya Basin	244	93.71 (M) (*)
Subbasins 1, 2 and 8	49.44	51.99 (M)
Glaciers in Mistaya Basin outside subbasins 1, 2 and 8	8.97	16.95 (E) (**)
Mistaya Basin minus subbasins 1, 2 and 8, minus glaciers	185.59	24.77

Runoff yield: $\frac{24.77}{185.59} = 0.13 \times 10^6 \text{m}^3/\text{km}^2$.

(*) M = measured discharge; (**) E = estimated discharge.

b) Glacier runoff = Total runoff from subbasins 1, 2, 8 - runoff from areas of subbasins not covered by ice + calculated runoff from nongauged glaciers.

$$= 51.99 - (27.51 \times 0.13) + 16.95$$

$$= 65.36 \times 10^6 \text{m}^3.$$

c)	Subbasins 1 + 2 (Delta & Barbette)	Subbasin 8 (Peyto)
Measured streamflow	17.71×10^6m^3	34.28×10^6m^3
Estimated runoff from snow outside glacier area	2.50×10^6m^3	1.68×10^6m^3
Glacier runoff	15.21×10^6m^3	33.20×10^6m^3
Glacier runoff per unit glacier area	$\frac{15.21}{8.09} = 1.88 \times 10^6 \text{m}^3/\text{km}^2$	$\frac{33.20}{13.84} = 2.40 \times 10^6 \text{m}^3/\text{km}^2$

For the period 14 July - 3 September 1971, streamflow from snowmelt outside the areas covered by glaciers is given in Table 5a. It amounts to 0.13 x $10^6 m^3/km^2$ and is based on the assumption that the Mistaya Basin is not gaining or loosing water to adjacent basins. This value has been used subsequently to calculate the contribution from the ice-free areas within subbasins 1, 2, and 8. The total computed glacier runoff of Mistaya Basin (Table 5b) is 65.36 x $10^6 m^3$, representing 70% of the Mistaya River flow in the period 14 July - 3 September 1971.

Streamflow data from Delta and Barbette Creek (Nos. 1 and 2, respectively) in Table 3 show that the measured discharge at Delta Creek is larger than at Barbette Creek, although the glacier area in subbasin Delta is about half the size of the glacier area in subbasin Barbette. The continuous streamflow hydrograph (Fig. 4) at Station No. 1 contains an extensive slow runoff component, while Station 2 shows a flashy daily pattern, especially in late August, when all drainage channels are well developed. This suggests that meltwater from the firn area within subbasin Barbette may be measured at Station 1, Delta Creek.

Diversion of meltwater from the accumulation area of Barbette Glacier to Delta Basin, through limestone bedrock, is probable. In addition, Delta Glacier has a SSE exposure, while Barbette Glacier is exposed to the NNE. Hence, differences in the amount of solar radiation received by both glaciers will be reflected in the runoff. The glacier runoff yield for these subbasins combined (i.e., measured discharge minus snowmelt from the ice-free area) is 1.88 m for the period 14 July - 3 September 1971, compared with 2.40 m for Peyto Glacier (Table 5c). The measured glacier-mass loss on Peyto Glacier for the corresponding period is 1.89 m (Table 4). The extent to which glacier-runoff yield of 1.88 m for subbasins 1 and 2 is affected by delayed runoff is unknown. If the runoff delay is proportional to glacier size the yield of 1.88 m represents well the glacier ablation.

The proportion of ice/firn melt to glacier runoff is computed from glacier ice balance data. The ice balance on Peyto Glacier for 1971 was 0.94 m. Assuming that all glaciers in the Mistaya Basin have a similar ice balance, the glacier ice contribution to streamflow becomes:

$$0.94 \text{ m} \times 30.9 \text{ km}^2 = 29.04 \times 10^6 \text{m}^3$$

This is 31% of the Mistaya River flow in the period 14 July - 3 September 1971, and 14% of the total 1971 streamflow. A summary of glacier contribution to streamflow is presented in Table 6.

TABLE 6. SUMMARY OF MISTAYA RIVER STREAMFLOW AND GLACIER CONTRIBUTION FOR 1971

	($10^6 m^3$)	
Total streamflow 1971	202.31	0.829 m runoff depth
Flow 14 July - 3 September	93.71	46% annual flow
Glacier runoff, 14 July - 3 Sept.	65.36	70% flow (Mistaya River) 14 July - 3 September
Ice Ablation	29.04	31% flow (Mistaya River) 14 July - 3 September 14% annual flow (Mistaya River)

Conclusions

Hydrologic analysis of a glacierized basin in the headwaters of the North Saskatchewan River, Alberta, the Mistaya Basin, has shown that in 1971, 12% of the basin area contributed 32% to the annual river flow. Melt of glacier ice contributed 14% to the annual flow of the Mistaya River. A very important factor is the timing of glacier runoff.

During the seven week period, 14 July - 3 September 1971, 46% of the annual flow occurred; 70% of this flow was supplied by glacier runoff. The remaining amount was supplied by snowmelt from the area not covered by glaciers. The ablation of glacier ice accounted for 31% of the flow over this short period.

These data are derived from streamflow measurements of the three most extensive glaciers in the Mistaya Basin covering 72% of the total glacierized area and mass balance data from Peyto Glacier. These values are the best available assessment until it is possible to separate the total streamflow hydrograph into components of different genetic origin by chemical, tracer, or other methods.

Streamflow data of three adjacent glacier basins showed large differences for a selected period during the summer, 14 July - 3 September 1971. These differences may result from variations in glacier ablation or glacier runoff delay. Extensive glacier runoff delay on Peyto Glacier in the early part of the melt season has been indicated. Glacier runoff delay effects the timing of meltwater release. This should be recognized in glacier hydrology studies and glacier basin runoff forecasting procedures.

Discharge data of two adjacent glacier basins within the Mistaya Basin indicated that possibly meltwater was diverted from one subbasin to another. This is a commonly observed feature in karst areas.

ACKNOWLEDGEMENTS

I am much indebted to Messrs. G. W. van de Wall Bake and A. Wankiewicz for the collection of hydrometric data. The cooperation of the Water Survey of Canada, Calgary District, is sincerely appreciated. The Banff National Park Administration offered logistic support by making accommodation available, which is gratefully acknowledged here. Dr. A. D. Stanley supplied Peyto Glacier mass balance data and offered valuable advice in glaciological aspects. His comments and suggestions on this manuscript are gratefully appreciated.

REFERENCES

1. STANLEY, A. D. (1970). Combined balance studies at selected glacier basins in Canada. In: "Glaciers", Proc. of the Workshop Seminar, Sept. 24-25, 1970, Vancouver, B. C. Publ. by The Secretariat, Canadian Nat. Comm. for the Intern. Hydrol. Decade, Ottawa, Ontario, pp. 5-9.

2. U.N.E.S.C.O./I.A.S.H. (1970). Combined heat, ice and water balances at selected glacier basins. Technical papers in hydrology, No. 5. A contribution to the International Hydrological Decade.

3. LOIJENS, H. S. (1971). Assessment of glacier melt contribution and streamflow hydrograph synthesis in the North Saskatchewan headwaters, Alberta. Internal Report, Inland Waters Branch, Department of the Environment, Ottawa, Ontario.

4. DERIKX, A. L. and LOIJENS, H. S. (1971). Model of runoff from glaciers. In: "Runoff from Snow and Ice" Hydrology Symposium No. 8, Quebec City, Quebec, May 26-27. Inland Waters Branch, Dept. of Energy, Mines & Resources, Ottawa, Ontario,Canada, pp. 152-199.

5. OMMANNEY, C. S. L. (1970). The Canadian Glacier Inventory. In: "Glaciers", Proc. of the Workshop Seminar, Sept. 24-25, 1970, Vancouver, B.C. Publ. by the Secretariat, Canadian Nat. Comm. for the Intern. Hydrol. Decade, Ottawa, Ontario, pp. 23-30.

6. HENOCH, W. E. S. (1971). Estimate of glaciers secular (1948-1966) volumetric change and its contribution to discharge in the upper North Saskatchewan River Basin. J. Hydrol., Vol. 12, pp. 145-169.

7. FÖHN, P. M. B. (1973). Short-term snowmelt and ablation derived from heat and mass balance measurements. J. of Glaciology, Vol. 12, No. 65, pp. 275-289.

8. MEIER, M. F., TANGBORN, W. V., MAYO, L. R., and POST, A. (1971). Combined ice and water balances of Gulkana and Wolverine Glaciers, Alaska, and South Cascade Glacier, Washington, 1965 and 1966 hydrologic years. U.S. Dept. of the Interior, Geological Survey, Professional Paper 715-A, Washington, D. C., 23 pp.

9. STENBORG, Th. (1970). Delay of runoff from a glacier basin. Geografiska Annaler, Vol. 52, Ser. A 1970-1, pp. 1-30.

10. TANGBORN, W. V., KRIMMEL, R. M. and MEIER, M. F., (1971). A comparison of glacier mass balance measurements by glaciologic, hydrologic and mapping methods, South Cascade Glacier, Washington (Paper presented at Symposium on "Snow and Ice in Mountainous Areas", IUGG, XV General Assembly, Moscow, August 9-13, 1971).

APPENDIX

Glossary of Terms

Glacier runoff	:	runoff or discharge of water from an area covered by glacier.
Glacier ice melt Glacier ice ablation	:	melt of firn and ice on a glacier (seasonal snowmelt excluded). Confined to that part of a glacier where the net balance - elevation relationship is negative.
Ice ablation	:	ice and firn melt.