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THE SIGNIFICANCE OF PERENNIAL SNOW AND ICE TO THE WATER RESOURCES OF THE SOUTH ISLAND, NEW ZEALAND

P. W. Anderton*

ABSTRACT

The volume of water stored as perennial snow and ice in the glaciers of the Southern Alps is estimated to be approximately 50 km^3, using area/mean-depth relationships. Under present climatic conditions, these glaciers are releasing water from long-term storage in excess of the input from snowfall. The quantities of water derived from this depletion of storage are significant in terms of contribution to streamflow in the Waitaki River and certain West Coast rivers but are relatively insignificant in most of the glacierized basins. However, the glaciers are influential in regulation of streamflow, tending to increase summer flows particularly during dry summers and to decrease winter flows relative to glacier-free catchments. These effects are greatest in the rivers draining the dry eastern regions of the South Island.

INTRODUCTION

The Ministry of Works, under its hydrological programme, is carrying out a survey of the water resources of New Zealand. The purpose of this paper is to make a provisional assessment of the significance of perennial snow and ice to the water resources of the South Island. Three aspects are considered: first, the quantity of water stored as perennial snow and ice in glaciers of the Southern Alps; second, its availability; and third, the role of glaciers in the regulation of streamflow.

Information available at present is only sufficient to estimate the order of magnitude of the water resources of the glaciers, and analysis has been restricted to glaciers and glacierets greater than 0.1 km^2 in surface area. Numerous small patches of perennial snow and ice exist, but these are unimportant on a regional scale.

DISTRIBUTION AND VOLUME OF GLACIERS

Ideally, an assessment of glacier resources should be based on a detailed glacier inventory similar to those being prepared overseas under the auspices of the IHD programme (UNESCO, 1970). Because such an inventory has not yet been prepared for New

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* Water and Soil Division, Ministry of Works, Christchurch.

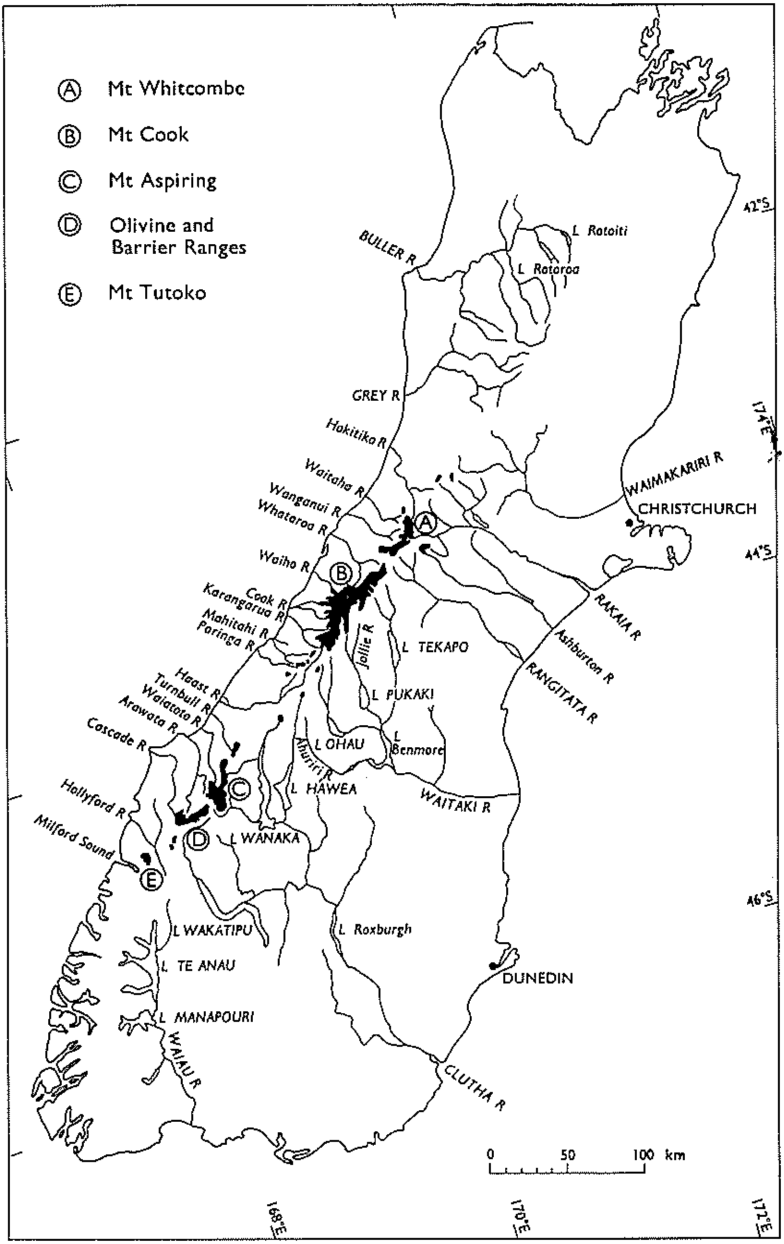

FIG. 1 — The South Island, showing glacial regions and major lakes and rivers.

Zealand and not all the glacial regions have yet been mapped in detail, it has been necessary to use generalized information.

A total of 527 glaciers has been identified on small-scale (1:250 000 or 1:100 000) maps covering the Southern Alps from Milford Sound to Arthur's Pass (Fig. 1). Surface areas of these glaciers were determined to an accuracy of ±5 percent, and the area distribution curve (Fig. 2) shows that most of the glaciers are small (median area 0.7 km^2). These measurements indicate that the total area occupied by glaciers is 810 ± 40 km^2.

In order to estimate the volume of snow and ice stored in each glacier, mean depths have been determined from assumed area/mean-depth relationships for five types of glacier (Table 1). The only glacier in New Zealand on which depth measurements have been made is the largest, the Tasman Glacier. Seismic surveys by the Geophysics Division, Department of Scientific and Industrial Research, indicate maximum ice thicknesses at two locations of 630 m and 430 m, respectively (M. P. Hochstein, pers. comm.), and a gravity survey near the terminus indicates ice thicknesses of about 200 m (M. Broadbent, pers. comm.). The geophysical data, together with surface topographic data, have been used to prepare a map of the Tasman Glacier showing approximate contours of ice thickness (Fig. 3). Mean depth of the main trunk glacier as determined from this map is 270 m. The Ivory Glacier, a small cirque glacier in the headwaters of the Waitaha River, Westland, is currently under investigation as an IHD representative basin, and sufficient morphological data are available to estimate thickness of the glacier. Contours of estimated ice thickness are shown in Fig. 4, and the mean depth derived from these estimates is 44 m.

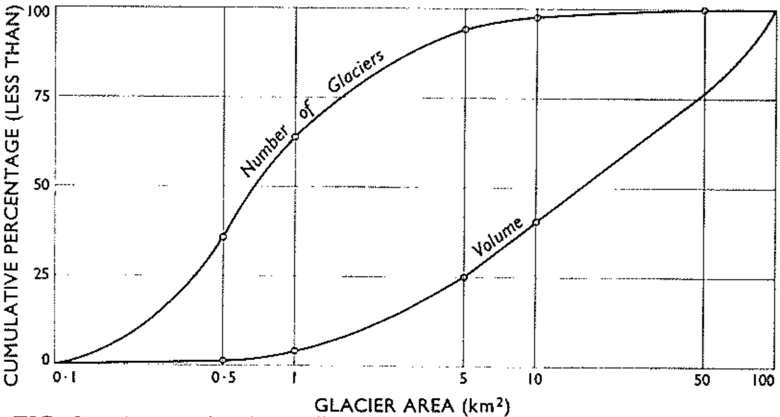

FIG. 2 — Area and volume distribution of glaciers in the Southern Alps, based on a sample of 527 glaciers.

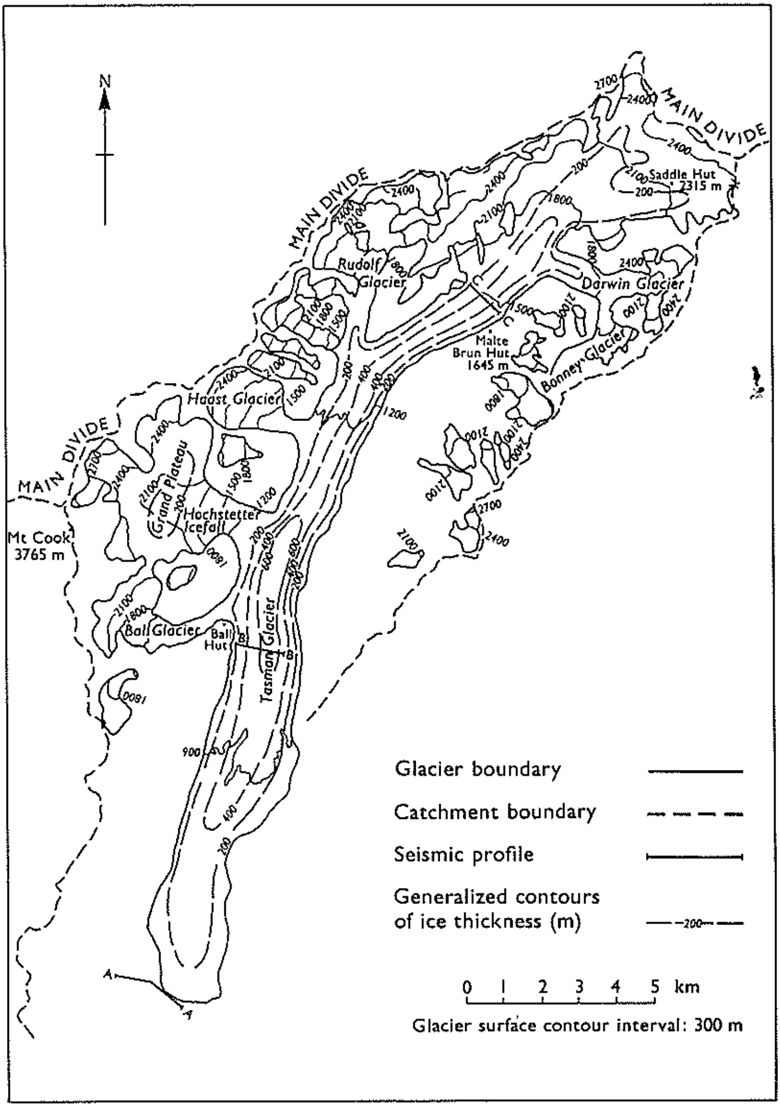

FIG. 3 — The Tasman Glacier system, showing generalized contours of ice thickness.

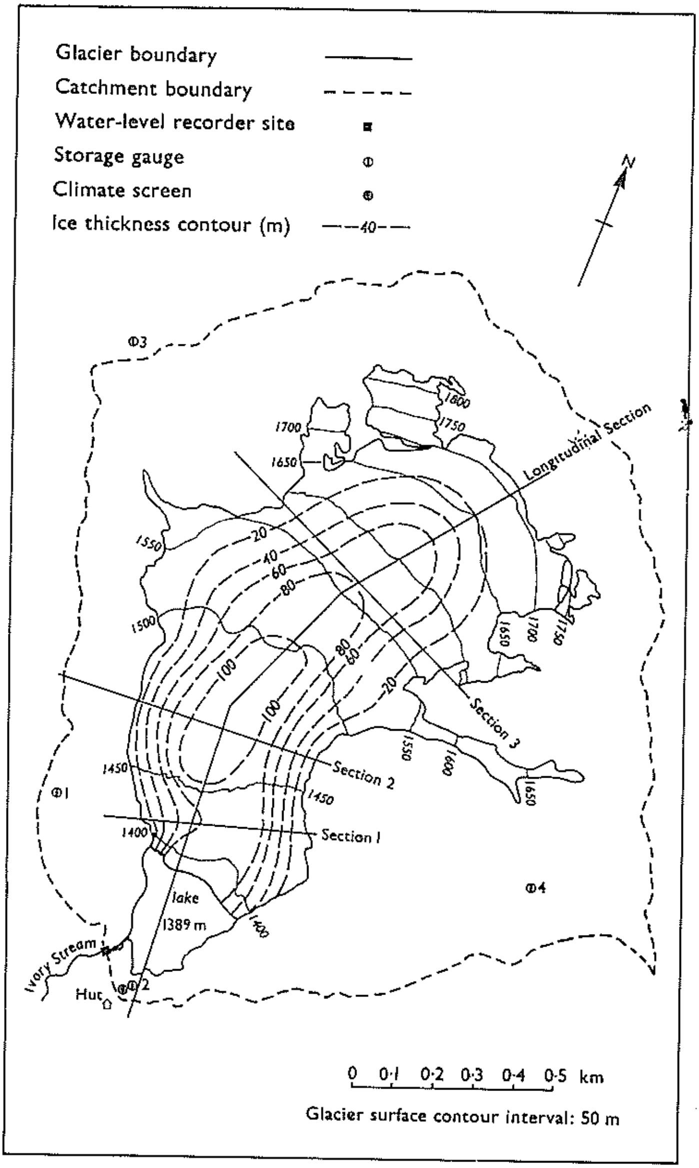

FIG. 4 — The Ivory Glacier, showing contours of estimated ice thickness.

TABLE 1 — Area/mean-depth estimates for glaciers.

Type	*Area* *(km^2)*	*Mean depth* *(m)*
Valley glacier, compound	1–5	40
	5–10	60
	10–20	90
	20–50	150
	50–100	>250
Valley glacier, simple	1–5	40
	5–10	75
	10–20	120
Mountain glacier, shelf	1–5	30
	5–10	60
	10–20	120
Mountain glacier, cirque	0–1	30
	1–2	40
	2–5	50
	5–10	90
	10–20	120
Glacieret and snowfield	0–0.5	15
	0.5–1	20
	1–2	25

In view of the scarcity of local information, data from overseas have been used in deriving the area-depth relationships shown in Table 1. The mean depths which have been assumed are judged to be minimum values.

The minimum estimate of the total volume of the glaciers obtained from these figures is 63 ± 4 km^3. Conversion of the glacier volume to water equivalent requires an estimate of mean density for the ice and snow. Glacier ice has a density of about 0.9 Mg/m^3, while firn (old snow in the process of alteration to glacier ice) densities in the Southern Alps can be as low as 0.6 Mg/m^3. At present, the snowfields (névé) of the Southern Alps are severely depleted and it is likely that the mean density of glaciers will be close to 0.9 Mg/m^3. A figure of 0.85 Mg/m^3 has been assumed, giving an estimate of 53 km^3 for the total quantity of water stored as perennial snow and ice.

The estimated areas and volumes of glaciers in each major river basin are summarized in Table 2. About 57 percent of the total volume is contained in basins draining to the east coast, and of these the Waitaki Basin alone accounts for 45 percent of the total. Most of the volume is contained in a small number of relatively large glaciers (Fig. 2). Thirteen glaciers greater than 10 km^2 in area contain about 60 percent of the total volume.

TABLE 2 — Glacier resources of the Southern Alps.

East coast basins			*West coast basins*		
Basin	*Glacier area (km^2)*	*Glacier volume (km^3)*	*Basin*	*Glacier area (km^2)*	*Glacier volume (km^3)*
Waitaki —			Cook —		
Lake Pukaki	186.9	24.58	Fox	41.7	5.27
Lake Tekapo	43.1	2.58	Others	12.9	0.93
Lake Ohau	20.7	0.71			
			Cook total:	54.6	6.20
Waitaki total:	250.7	27.87			
			Waiho	57.8	5.61
Clutha —			Arawata	56.2	3.82
Lake Wakatipu	38.1	2.22	Whataroa	47.7	3.28
Lake Wanaka	32.5	1.32	Karangarua	34.6	1.68
Lake Hawea	4.2	0.12	Wanganui	39.2	2.11
Others	2.9	0.12	Waiatoto	27.1	1.51
			Haast —		
Clutha total:	77.7	3.78	Landsborough	30.4	1.06
			Hollyford	11.6	0.41
Rakaia	43.6	2.26	Milford Sound	7.7	0.33
Rangitata	39.4	1.59	Paringa	6.1	0.24
Ashburton	4.2	0.20	Hokitika	5.9	0.18
Waimakariri	4.3	0.11	Waitaha	4.5	0.13
			Cascade	2.9	0.11
			Turnbull	1.4	0.06
			Mahitahi	1.9	0.04
East coast total:	419.9	35.81	*West coast total:*	389.6	26.77

AVAILABILITY OF GLACIAL MELTWATER

A continuation of present climate would bring about a continuing decrease in the surface area of glaciers available for melt, by surface lowering, terminal retreat, and insulation of underlying ice by accumulation of ablation moraine on the surface. Most of the smaller glaciers would disappear within 100 years, while the larger and the higher-altitude glaciers would probably eventually establish an equilibrium state.

Accurate estimates of present water yield from the glaciers of the Southern Alps cannot be made at present. Of the snow that falls on the glaciers during winter and spring, most is lost by melting (and, to a limited extent, by evaporation) by the end of the ablation season in April or May, leaving a residual increment of storage in the névé regions. In addition, firn and ice stored during a long sequence of earlier years is also lost by ablation, and at present this annual loss of ice exceeds the annual addition to storage in the snowfields. The glaciers are therefore releasing water from long-term storage, in excess of the amount expected from precipitation input.

The health of a glacier is determined by the net mass balance – the change in mass of the glacier from the end of one melt season to the end of the next. Virtually all glaciers in the Southern Alps are receding and thinning at present – as they have been for the past 100 years – and consequently these glaciers must show negative net balances for most years.

Actual measurement of the mass balance of a glacier requires considerable field work and, so far, measurements in the South Island have been limited to the Tasman and Ivory Glaciers. It has been estimated that the net balance of the Tasman Glacier during 1958–59 was equivalent to a loss of 0.8 m depth of water over the entire surface area (Goldthwait and McKellar, 1962). Estimates of the thinning of the glacier over the period from 1890 to 1962 (Skinner, 1964) suggest that the annual net balance for this period was close to 1 m water equivalent. Recent estimates of ice discharge through the upper part of the glacier also suggest an average annual transfer of mass of close to 1 m water equivalent.

During 1969–70 and 1970–71, negative net balances were recorded on the Ivory Glacier. The estimated water losses, averaged over the area of the glacier, were 2.1 and 1.3 m, respectively (NWASCO, in press). As the Ivory Glacier is a rapidly wasting glacier at unusually low altitude, its net balance values probably represent extreme values for the years concerned.

It is important to remember that a negative net balance represents only the output of water from a glacier in excess of that expected from snowfall input. The total water yield comprises the net balance together with melt of seasonal snowpack on the glacier and melt of firn and ice compensating for the snowpack retained in storage. For example, the total output of water from the Ivory Glacier was 4.2 m during 1969–70 and 5.2 m during 1970–71, averaged over the glacier area. While these values are of more interest for hydrological purposes, they are more difficult to measure and estimate than net balance.

If the estimated average net balance for the Tasman Glacier of about 1 m loss of water over the surface area is assumed to apply to all glaciers in the drainage basin of Lake Pukaki, the mean annual contribution of water from long-term storage in these glaciers is about 1.9×10^8 m^3. If it is further assumed that this meltwater is released during the period from January to March, the contribution is equivalent to a mean flow of 24 m^3/s, and represents about 10 percent of the inflows to the lake for this period. In dry summers, this contribution would be greater. Total meltwater contribution from glaciers would be at least twice the depletion of long-term storage, and extend over a greater period of time. These estimates ignore the melt of seasonal snowpack lying outside the boundaries of the glaciers. This snowpack covers a much greater area of the basin and at present no satisfactory estimate of its melt contribution has been made.

REGULATION OF STREAMFLOW

The effects of glaciers on streamflow are considered here with respect to rivers draining to the east coast of the South Island. Data are lacking for the principal glacial basins of the west coast, where the effects are in any case likely to be less significant because of the abundant rainfall at lower altitudes. The quantitative contribution of the present depletion of long-term storage to streamflow is very small, except for the Waitaki Basin and certain western basins such as the Cook and Waiho, but regulation of streamflow is significant in many catchments. Flow data illustrating the effects of glacial

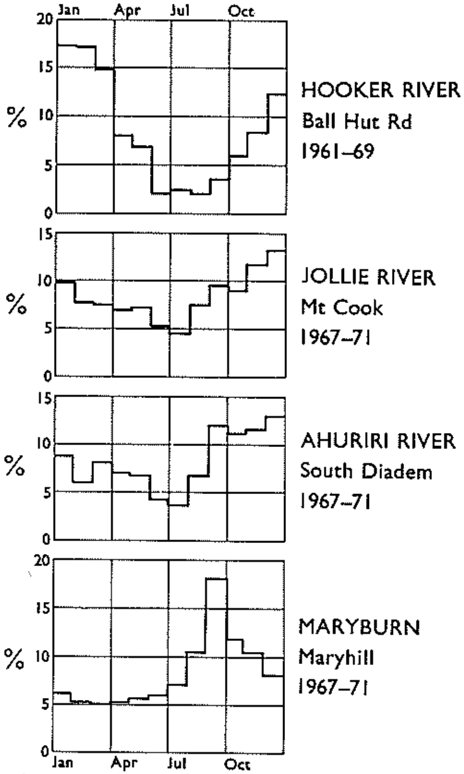

FIG 5 — Seasonal variations in the flow of the Hooker, Jollie, Ahuriri and Maryburn Rivers. Monthly flows are expressed as percentages of annual flow.

regulation have been obtained from the Ministry of Works and the North Canterbury Catchment Board, and represent flows which are either unaffected or affected only to a limited degree by man-made controls upstream.

The Hooker River in the Upper Waitaki Basin drains a highly glacierized catchment containing two large glaciers, the Hooker and the Mueller. Its seasonal flow pattern is characteristic of glacier basins, showing very low winter flows and high spring and summer flows (Fig. 5). Summer flows exceed spring flows, partly because snowmelt is delayed in the higher-altitude basins of the glaciers and partly because ice melt is concentrated during the summer months. During spring storms which cause melt of seasonal snow in the foothills, heavy snowfalls which occur in the upper parts of the glacial basins are important in delaying snowmelt.

The seasonal flow patterns of the Ahuriri and Jollie Rivers, which drain glacier-free catchments in the Upper Waitaki Basin, show relatively higher winter flows and maximum flows coinciding

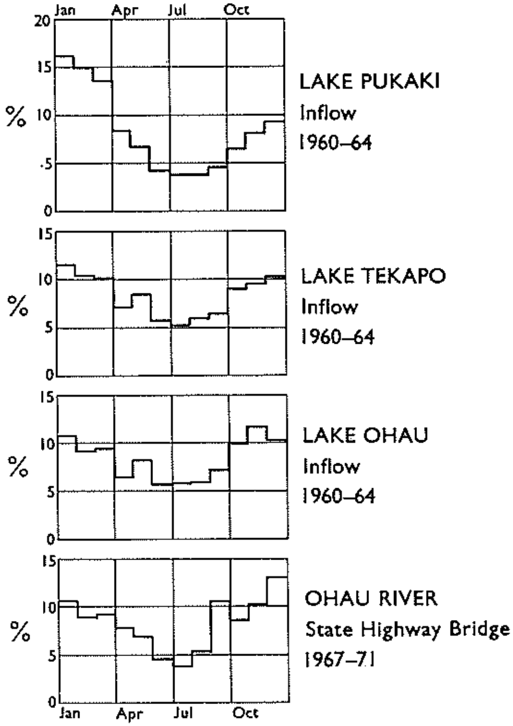

FIG. 6 — Seasonal variations in the inflow to Lakes Pukaki, Tekapo and Ohau and the flow of the Ohau River. Monthly flows are expressed as percentages of annual flow.

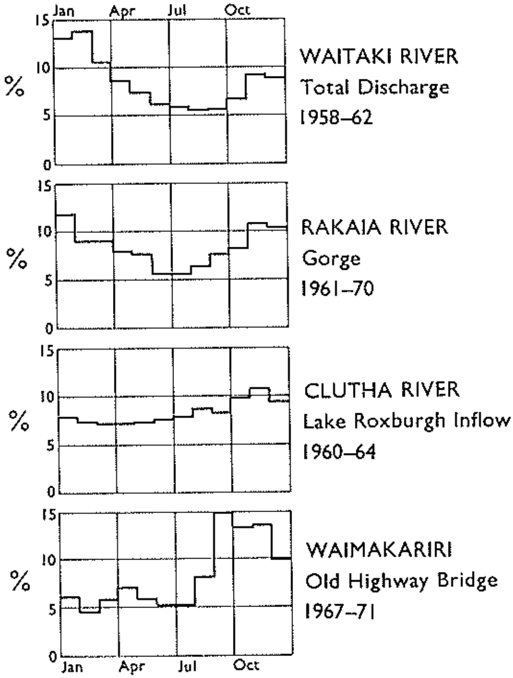

FIG. 7 — Seasonal variations in the flow of the Waitaki, Rakaia, Clutha and Waimakariri Rivers. Monthly flows are expressed as percentages of annual flow.

with spring melting of seasonal snow (Fig. 5). In the Maryburn Basin, which is a smaller basin at lower altitude, the spring snowmelt peak is even more marked and the seasonal flow variation is almost 180° out of phase with the Hooker Basin.

On a larger scale, the drainage basins of Lakes Pukaki, Tekapo and Ohau show seasonal flow variations correlated with the degree of glacierization of the basins (Fig. 6). Inflows to Lake Pukaki follow the pattern of the Hooker River, reflecting the high concentration of glaciers within its catchment, while inflows to Lake Ohau and outflows via the Ohau River show a similar pattern to the Ahuriri and Jollie Rivers, reflecting the relatively few glaciers in the catchment. Lake Tekapo has a catchment less glacierized than that of Lake Pukaki and shows an intermediate type of seasonal flow pattern.

Even the major rivers show seasonal variations in flow which can be correlated with the degree of glacierization of their basins. Flow patterns are shown in Fig. 7 for the Waitaki, Rakaia, Clutha and Waimakariri Rivers, arranged in descending order of glacierization of their basins. The Waitaki shows a 'glacial' pattern and the Rakaia a less developed 'glacial' pattern, while the Clutha and particularly the Waimakariri show 'snowmelt' patterns.

Most of the differences in seasonal flows of these major rivers can be attributed to differences in altitude of their headwaters regions, with which the occurrence of glaciers is correlated. However, the presence of glaciers modifies their local climate to cause increased snowfall and retention of snowpack relative to glacier-free areas and serves to accentuate the effects of altitude.

Glaciers are often regarded as beneficial regulators of river flow, releasing increased amounts of water from storage to compensate for dry summers. This is certainly true for the rivers draining to the east coast of the South Island from the glacial regions of the Southern Alps. Smoothing of seasonal flow variations is also attributed to glaciers. This is most apparent in more humid regions where a winter maximum in precipitation brings increased rainfall to lower altitudes to compensate for snowfall retention in the glacial regions. In the dry eastern regions of the South Island this effect is not so apparent, as precipitation in the headwaters regions dominates the river flows.

DISCUSSION

Under present climatic conditions the glacier basins in the Southern Alps yield water in excess of precipitation input. The quantitative effect on streamflow is significant in the Waitaki Basin and probably significant in certain West Coast basins but is small in most of the major basins. A more significant influence is the regulation of streamflow, tending to increase summer flows, particularly low flows during dry summers, and to decrease winter flows relative to glacier-free basins.

The effects on streamflow of a change towards climatic conditions favourable for glacier growth are difficult to predict. Glacier growth is favoured by a number of factors which are not necessarily correlated. Increased winter snowfall and reduced summer melt are important factors, but cold spells in spring and light snowfalls in late summer or autumn may be significant in determining whether the net balance is positive or negative in a given year. For instance, light snowfalls on the Ivory Glacier during the winter of 1971 were followed by sporadic spring snowfalls which retarded melt, while the heavy snowfalls during the winter of 1972 were counteracted by increased spring and summer melt. Glacier growth might be associated primarily with increased precipitation which would maintain streamflow, or alternatively with colder, drier conditions tending to reduce streamflow.

Since 1950, a halting of glacier recession and readvance of many glaciers have been noted in many parts of the northern hemisphere. Evidence from studies of Greenland ice cores (Johnsen *et al.*, 1970) and studies of solar activity (Bray, 1971) suggests that this glacier behaviour is related to a short-term cooling phase which is likely to persist until the end of the century. Glaciers in New Zealand have not shown any indication of this trend so far and may not be affected because of their occurrence at relatively low latitude.

The volume of ice stored in New Zealand glaciers is similar to the volumes of ice present in glaciers of the European Alps, Norway and the United States, excluding Alaska. In these regions glacier behaviour is monitored extensively in comparison to the very limited observations of glaciers in New Zealand. This reflects more intensive development of these regions and the greater pressures on water resources.

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