JOURNAL OF HYDROLOGY
NEW ZEALAND
Published twice annually by the New Zealand Hydrological Society

Volume 25 1986 Number 1

SEASONAL ACCUMULATION AND LOSS OF SNOW FROM A BLOCK MOUNTAIN CATCHMENT IN CENTRAL OTAGO

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ABSTRACT

Seasonal accumulation and loss of snow were measured between 1963 and 1979 in the Fraser Catchment (120 km^2) Central Otago, New Zealand. The catchment has low (less than 1000mm a^{-1}) precipitation, maximum windspeeds of up to 29ms^{-1} and winters with up to five months of temperatures below 0°C.

Snow cover is highly variable, both within each season and from year to year. Snow depths are shallow (less than 1.3m in all years) and densities moderate (300–350 kg m^{-3}) at the time of maximum accumulation. Aspect is important in controlling snow depth and water equivalent; exposed south east to west slopes recorded a maximum water equivalent of less than 200mm and sheltered north east slopes over 450mm. The maximum recorded volume of water stored as snow was 23.3 x 10^{6}m^3. The driest winter had a 40% lower catchment water equivalent, and produced 55% less runoff, than the winter with the heaviest snow cover. Snowdrifts contribute approximately 4 x 10^{6}m^3 storage and up to 9% of the spring runoff. Densities within drifts increase from 300 to 600 kg m^{-3} through winter and spring.

INTRODUCTION

In the basins and ranges of Central Otago, demand for water for irrigation is high, and water resources must be carefully managed. Downfaulted valleys receive 400–600mm annual precipitation, while intervening upfaulted mountain blocks receive about 1000mm, increasing to 4000–6000mm toward the western divide. The importance of seasonal snow on the mountains was recognised early (Gillies, 1964), but data collection was hampered by problems with logistics. The variation in seasonal snow can now be examined for the Fraser River, where flow and rainfall have been recorded within the 120 km^2 basin since 1969, and snow has been measured at 20 sites since 1974, including a snow pillow installed in 1978.

The Fraser River drains north from 1500m on the gently rolling crest of

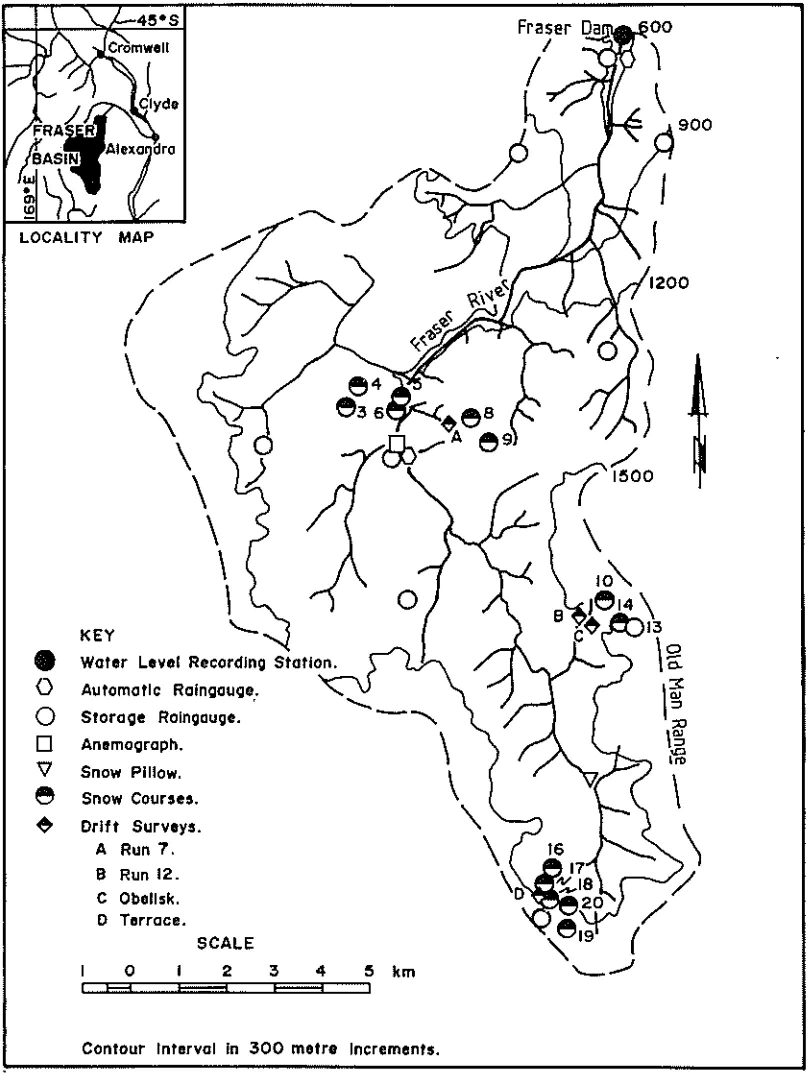

FIG. 1 — Fraser River basin, Central Otago, New Zealand — location and instrumentation.

the Old Man Range (Fig. 1), meandering through a series of upland peat bogs before descending through a steep gorge to emerge at Fraser Dam at 600m. Two thirds of the basin is covered regularly by winter snow, and river flow is strongly seasonal.

BASIN CLIMATE

Several investigations of block mountain climate, particularly that of the

Old Man Range, have been carried out over the past 25 years by Mark et al. (1959), Mark (1965; 1974), Billings and Mark (1961), Mark and Bliss (1970) and Bliss and Mark (1974). Bare fellfield ridge crests and dwarfed tundra-like vegetation attest to the climatic severity of the highest and most exposed sites.

Climatic records for the Fraser Basin are short, and in part unreliable. Some data are available for precipitation, wind and temperature.

Precipitation

An early attempt at assessing precipitation above the winter snowline was made by the Otago Catchment Board. A trial plot at 1585m, using three 130mm stand pipe and two c-type gauges was operated for several years. Rime ice formation during southerly storms produced false readings and the project was abandoned (Gillies, 1964). The present storage raingauge network in the basin has gauges of composite fibreglass and polyvinylchloride, fitted with Alter shields and set to a common height of 1.5m. They are uniformly spread by area and altitude.

Mean annual precipitation, calculated for the period 1972–79 for the individual gauges, approximates the 30-year normal; the nearest long-term station, Alexandra, is within 3% of its 30-year normal over the same period. Raingauges in the outlet gorge of the Fraser River had the lowest means (435–480mm) over an elevation range of 580m. At higher elevations, values rise to 525–1015mm at 1250–1460m but these fall somewhat short of previous estimates. Mark (1965), using four years of data from the east face of the Old Man Range, recorded 656mm at 1330m and found an increase in precipitation southwards, of 32mm a^{-1} km^{-1} over a horizontal distance of 20 km, reaching a maximum of 1300mm. From this he deduced an annual mean of 1600mm at the source of the Fraser River, on the west face of the range.

Accurately estimating high elevation precipitation remains a problem. Gauge placement is significant in determining catch: Mark (1965) recorded an annual precipitation of 2480mm at one gauge on a 10° slope with easterly exposure in the winter snow accumulation zone.

Wind

The distribution of snow on the ground is very irregular, much of which can be attributed to erosion and redeposition by wind. A southwest influence is apparent in drift alignment; drifts produced by rock tors on the range crest parallel this direction (northeast to southwest) while those on northeast faces associated with cirques and valleys cut across it. High windspeeds occur on the range crest, with the maximum instantaneous value of $29ms^{-1}$ recorded by Mark (1965); however much lower speeds ($7ms^{-1}$ at 10m) are sufficient to drift snow (Weir, 1979).

Mark and Bliss (1970) measured an average windspeed of $5.7ms^{-1}$ at the crest of the Old Man Range over a two year period. An anemometer near the snowline in the centre of the Fraser Basin, 440m below the crest, recorded a mean value of $3.4ms^{-1}$ from September 1977 to March 1979. A short period of concurrent record from the two sites showed that, during storms, windspeeds on the crest were two to four times those at the lower site.

Erosion and melt of snow commonly occur with strong northwesterly winds. Turbulent transfers (latent and sensible heat) associated with northwesterly conditions that preceeded a major flood in October 1978 were estimated to have provided 58% of the total energy requirement (121 Wm^{-2} of 209 Wm^{-2}) for melt (Fitzharris et al 1980). By contrast, southerly winds are generally depositional, and rarely reach the high velocities of northwesterlies. However, drift alignment on the range suggests southerlies dominate drift formation, actively transporting and depositing snow when densities are low and the ice crystals friable.

Temperature

Mark (1974) reported mean air temperatures at 1.2m above ground surface at three sites above 1200m on the Old Man Range. Mean monthly temperatures were below 0° C for five months of the year at the highest site (1590m), declining to one month a year at the snowline.

METHOD

An analysis was made of the Otago Catchment Board 1963–69 data on snow depths and densities from 29 poles on the Old Man Range. These data are limited, as only ten of the poles were located above snowline. Surveys were conducted during September, which is normally close to the time of maximum accumulation, and before the spring thaw. Snowline records from the northeast face of the Old Man Range are also available for this period (Goodyear, pers. comm.) and for 1973–77. The daily snowline elevation was estimated during the snow season, initially from Alexandra and after 1973 from Earnscleugh. These observations were used to calculate the number of days per month the snowline was at or above elevations between 300 and 1500m, using a method applied by Green (1973; 1975) in the Scottish Highlands.

During 1973 the Fraser catchment was mapped for slope (4 units) and aspect (8 units), from which the proportion of total catchment area occupied by each of 32 slope/aspect combinations was then calculated. Twenty courses, comprising 3 poles each, were installed on those units which covered the greatest area. Snow poles of 150mm wood or 70mm steel marked by 0.5m deep alternating coloured bands located points at which depth and density measurements were made. The few visits made during each winter caused little site modification. Densities were measured with a Federal sampler using the method of Garstka (1964) and the data used, along with average depths, to determine the site water equivalent.

After two years of operation the network was reduced to 13 courses, as many poles had been buried, displaced, bent or broken by compaction and movement within the pack. Surveys of individual snowdrifts were substituted instead for the seven courses lost.

Snow courses were surveyed twenty-six times between 1974 and 1979. Snow data from each course were weighted in proportion to the total area of each slope/aspect unit above snowline. Where a course could not be surveyed, data were generated by regression from other data sets, or a mean value from other courses was used. The total water volume of stored snow for slopes of less than 15° above snowline was then converted to an equivalent precipitation depth for the whole catchment.

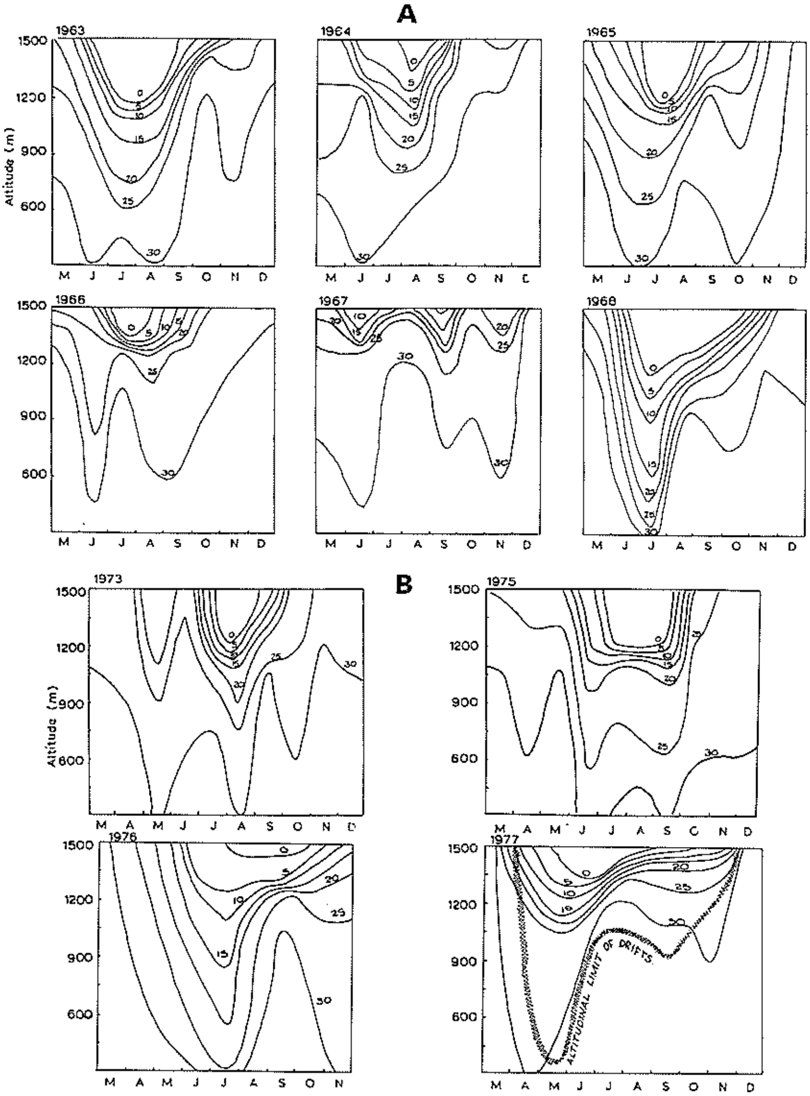

FIG. 2 — Isolines of annual snow cover during (A) 1963–68 and (B) 1973 and 1975–77. The altitude limit of snowdrifts was recorded only during 1977. Isolines represent the number of days per month that the snowline was at or above the specified elevation.

A 2.6m diameter snow pillow coupled to a water-level recorder was installed at a level site in the upper catchment (Fig. 1) to record changes in water equivalent of snow for the winter of 1978. The chart record was calibrated

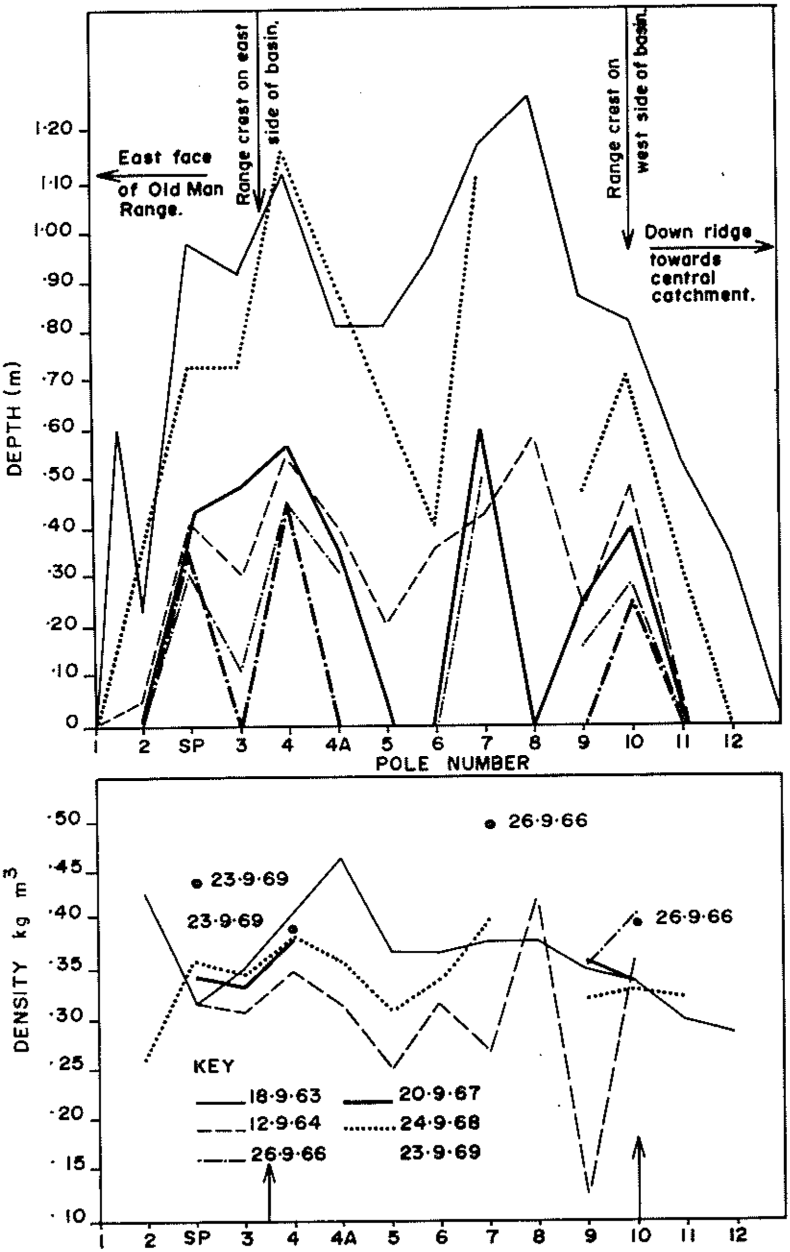

FIG. 3 — Depth and density data from an Otago Catchment Board snow course for poles 1–12, during September 1963 and 1964, and 1966 to 1969. For course map see Gillies (1964).

from depth and density measurements of snow adjacent to the pillow. Data from this site were then related to other course data.

The volumes of three large snowdrifts were routinely surveyed during 1976–79, using a tape and Abney level and an assessment made of their contribution to spring flow.

RESULTS AND DISCUSSION

Catchment Snow Surveys 1960–70

Gillies (1964) observed: "in the Fraser Catchment, snow accumulation is not a continuous cumulative process as in continental snow fields; but it thaws, recedes and reforms at intervals throughout the winter, so that the water content of the snowpack is variable and difficult to measure". This erratic behaviour of the snowpack made early attempts at monitoring difficult. Isolines of snow cover (Fig. 2A) show the annual and seasonal variation. Snowline data of this type were used by Green (1975) to determine shifts in the climate of the Scottish Highlands, but the period of record of the Old Man Range is too short for a similar analysis. The graphs display a general symmetry centred on late July and early August, the snow season extending from April to October-November. A continuous snow cover may form after southerly storms at any time of year, but outside the snow season it rarely persists for more than a few days. Four years are particularly noteworthy:

(i) 1963 was a severe winter in inland Otago, with low temperatures, high precipitation and substantial snow in all months;
(ii) 1964, in contrast, had three successive months with frequent north-westerlies which eliminated the small amount of snow that had accumulated;
(iii) 1967 was dry throughout the winter with frequent northerly winds. There was no month with a continuous snow cover over the face of the Range, however, some heavy late snowfalls in September and November temporarily lowered the snowline; and
(iv) in 1968, a wet June was followed by a wet, cold July with the lowest mean monthly air temperatures since July 1938. Eight days of nearly continuous snowfall produced a substantial snowpack, and lowered air temperatures so that snow remained frozen on the valley floors of Central Otago for 3–4 weeks.

Snow course data from the catchment (Fig. 3) reflect similar trends: snow depths for severe winters are double those of mild winters, whereas densities are less variable, fluctuating within a 250–400kg m^{-3} range, with the average being 320–350kg m^{-3}. Snow depths in all winters are less than 1.3m in the upper catchment and shallower on more exposed ridges. Greatest depths occurred at poles 6 — 9 in the vicinity of a chain of relict cirques at the western catchment margin. Poles exposed on the windward face of the Old Man Range recorded shallower (36% less) depths with calculated water equivalents lower (19% less) than around adjacent poles on leeward faces, for the severe winter of 1963. During milder winters, snow cover is irregular and the influence of micro-topography is more pronounced.

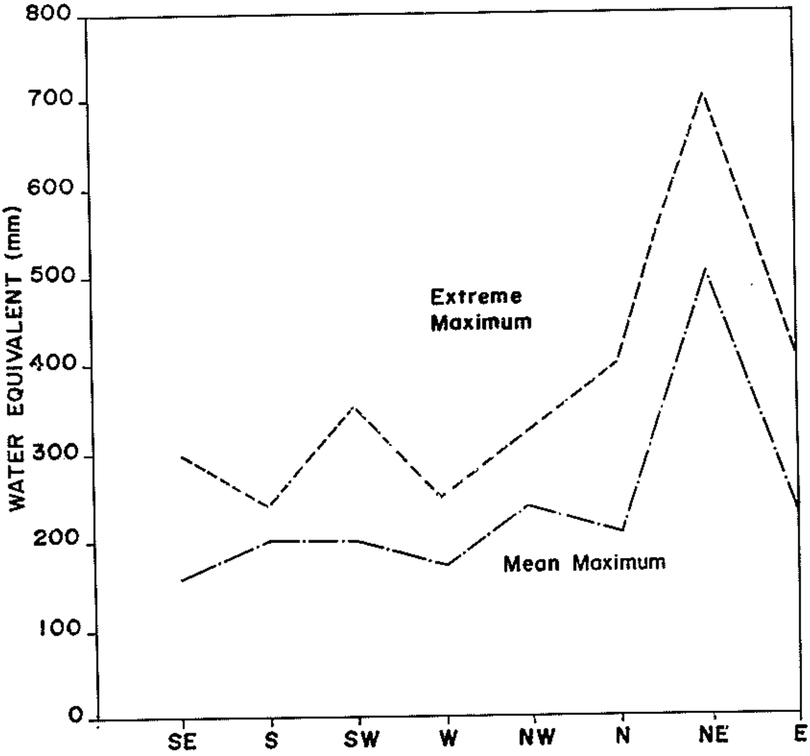

FIG. 4 — The effect of aspect on snowpack water equivalent for slopes of 5–15°. The extreme maximum is the highest recorded value for each slope-aspect unit, and the mean maximum is the mean of all annual values.

Catchment Snow Surveys 1970–79

The catchment has moderate (5–15°) slopes over much (55%) of its area, with almost half of them facing east-northeast. Snow courses on these slopes recorded a uniform snow cover except where major topographic features of higher relief lay to windward.

Steep (15–25°) and very steep (35°+) faces covered less than one third of the area. On some northeast-facing valley sides near the range crest, snow depths exceeded pole height by up to 6m.

Although a clear altitudinal snow wedge is not present in the Fraser Basin, an increase in water equivalent was evident on three courses, located on level sites above 1330m and spaced at altitudinal intervals of 170m. On the range crest, at 1670m, annual maximum snow depths of 380–880mm (153–290mm water equivalent) were measured during 1974–77. The lesser snow years of 1974–75 recorded 52% of the maximum depth (61% the water equivalent) of 1976–77. Within the elevation band of 1500 to 1670mm, water equivalents increased from 66mm/100mm in 1975 to 206mm/100m in 1976. Below 1500m, the corresponding values were 48mm/100m in 1975 and 33mm/100m in 1976.

TABLE 1 — Total volume of water stored on slopes of $< 15°$ in the upper Fraser Basin, including the equivalent depth of precipitation.

Survey Date	Water Equivalent of Stored Snow $\times 10^6 (m^3)$	Catchment Precipitation Equivalent (mm)
9. 8.74	16.4	163
30. 8.74	13.4	158
17. 9.74	7.1	102
25. 9.74	3.0	68
24.10.74	0.6	35
1. 7.75	4.6	60
7. 8.75	7.5	97
2. 9.75	14.0	181
17. 9.75	7.4	158
21.10.75	0.5	29
8. 7.76	6.8	81
28. 7.76	8.8	112
9. 8.76	6.5	80
30. 8.76	16.4	200
20–21. 9.76	22.1	299
5– 6.10.76	23.3	315
3– 4. 8.77	14.2	193
23–24. 8.77	17.1	232
27. 9.77	17.8	282
19.10.77	14.8	280
27–28. 7.78	8.2	113
21–22. 8.78	9.6	133
5. 9.78	14.1	179
21. 9.78	11.0	174
4.10.78	5.5	119
20–21. 8.79	13.5	156

On steeper slopes, the volume of retained snow is more variable and more influenced by site exposure. Mean annual maximum water equivalents are greatest on northeast faces (over 450mm) and least on southern to west slopes (less than 200mm) (Fig. 4).

Over 4 years, late September snow storage (Table 1) was equivalent to 40% of the annual runoff. Fitzharris and Grimmond (1982) estimated 33% of the Fraser River's annual flow was derived from net snow storage and Fitzharris (1979) considered 10–25% appropriate for large South Island catchments. Of the total winter and spring flow, less than 20% left the catchment before thaw commenced, 31% was stored as snow, and the balance was supplied directly from precipitation in spring. Alexandra climate station at the base of the range recorded 28% of its annual precipitation when snow was accumulating (May-September) and 27% during the thaw (October-December).

Snow accumulates steadily in winter so that, by July on average, $8 \times 10^6 m^3$ of water is held in storage, equivalent to 110mm of rainfall. By late August, this increases to $10–17 \times 10^6 m^3$ of water, equivalent to 140–230mm of rainfall. By September, snow storage is extremely variable, ranging from 3 to $22 \times 10^6 m^3$ (or 70–300mm of rainfall). The highest recorded snow storage ($23.3 \times 10^6 m^3$) occurred in October 1976. Snow course surveys were concluded in October because the discontinuous cover made sampling difficult.

Substantial variation is apparent in annual maximum water equivalents for 1974 to 1979 (Fig. 5). The winter with least snow recorded a 40% lower water equivalent of the pack, and had 55% less runoff compared with the year with the heaviest winter snow cover. During years with little snow, maximum water equivalent is reached by late August, whereas in winters experiencing heavy snowfalls, it occurs around mid-September. O'Loughlin (pers. comm.) recorded even greater variation at Alans Basin, on the Craigieburn Range, where the maximum snow course water equivalent for 1967 was only 22% of that recorded in 1968.

The snow pillow and recorder functioned satisfactorily throughout the winter of 1978. Water equivalents for this period show two peaks of accumulation (Fig. 6) of up to 260mm followed by rapid melting in both August and October. Fitzharris et al. (1980) and Fitzharris and Grimmond (1982) examined the second melt period, which involved a net water loss from the snowpack of 97mm in three days at the site, and snowmelt of 80mm over the whole basin. Energy for melt was attributed mainly to advective heat transfer and condensation. Water equivalents from the snow pillow correspond well to calculated catchment values. Snow course 14, on a moderate west-facing slope at 1600m, corresponds best with both the catchment mean value and that of the pillow.

Winter snow cover was persistent during 1976 and 1977. The range crest was totally covered 25 days per month in 1976 and again in 1977, whereas in both 1973 and 1975 it declined to five days (Fig. 2B). The winter of 1976 was the most severe of the study period and produced the greatest volume of runoff for the years 1969–78. Although winter temperatures were near average, spring temperatures were unusually cold, with the mean monthly air temperature at Roxburgh (elevation 110m), at the base of the east face of the Old Man Range, at 1.3°C below normal.

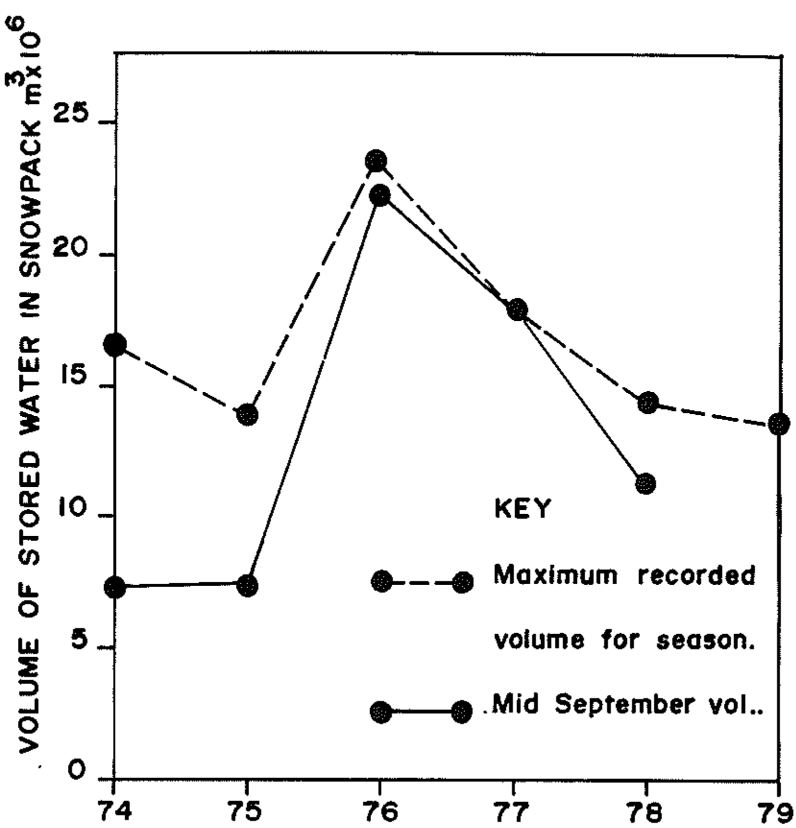

FIG. 5 — Volume of snow storage on slopes less than 15° during 1974–79, showing mid-September and maximum recorded values.

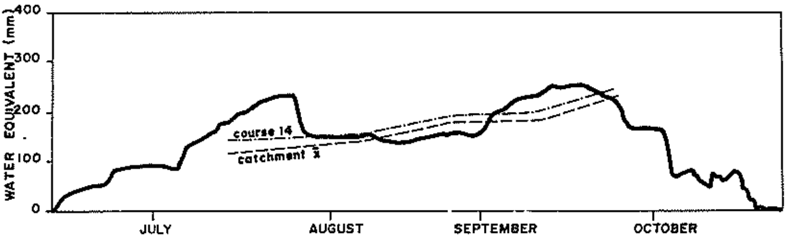

FIG. 6 — Snow pillow and snow course data for 1978. The solid line represents snow accumulation and loss on the snow pillow. The broken lines give mean values for the three poles on course 14, and for all snow courses in the catchment.

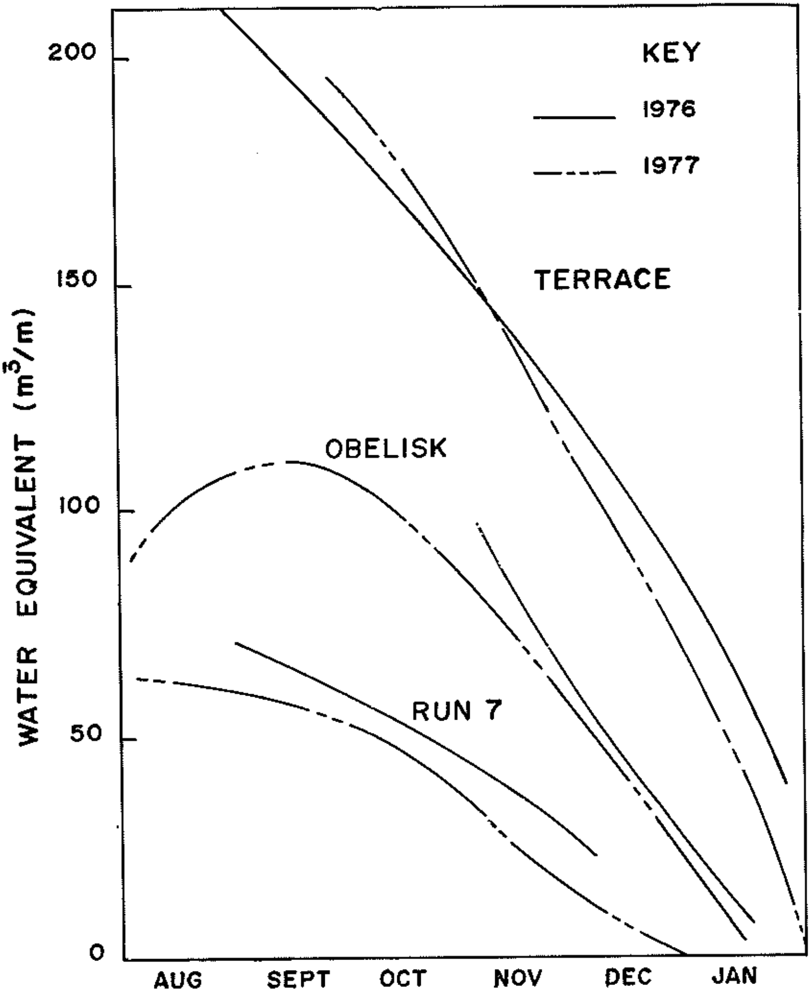

FIG. 7 — Behaviour of three snowdrifts within the Fraser catchment: m^3 of stored water for each lineal metre of drift. Terrace was on a cirque headwall at 1580m, Obelisk on an asymmetric valley side at 1490m, and Run 7 in a shallow valley system at 1310m (see Fig. 1).

Drift Surveys

Major snowdrifts begin to form after April, when the density of the snowcover is less than 300 kg m^{-3}, and the cover is easily eroded and redeposited by wind. By July, densities reach 300–400 kg m^{-3} and drifts develop a profile consistent with their final form. Further snowfalls, wind action, and freeze-thaw during August produce great variations in density (180–480 kg m^{-3}), but the modal density at the midline of major drifts is less than 300 kg m^{-3}. At

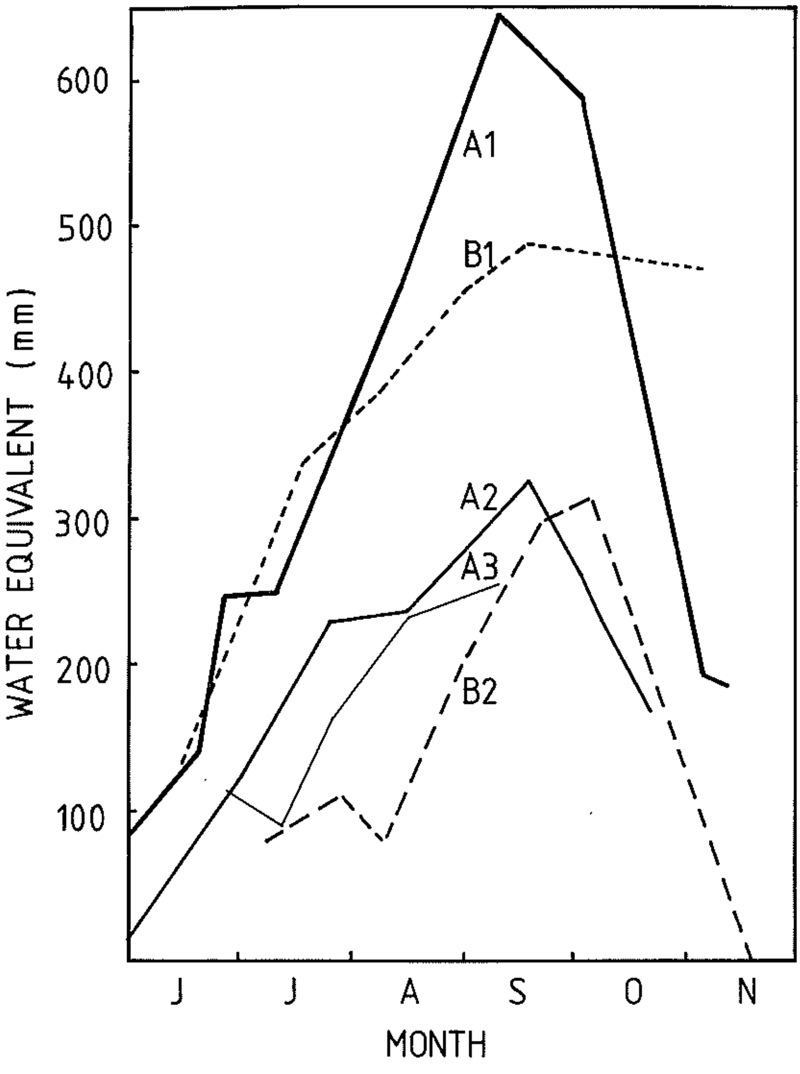

FIG. 8 — Snow course data from several South Island mountain ranges. Location, mean elevation, year and observers are:

A1 — Alans Basin, Craigieburn Range, 1700m, 1963 (Morris and O'Loughlin, 1965)
A2 — Fraser Basin, Old Man Range, 1500m, 1963
A3 — Camp Stream, Craigieburn Range, 1430m, 1963 (Morris and O'Loughlin, 1965)
B1 — Rastusburn, Remarkables Range, 1800m, 1976 (Owens, 1979)
B2 — Fraser Basin, Old Man Range, 1500m, 1976

the time of maximum accumulation, densities increase to 400–600 kg m^{-3}, with greater densities (480–610 kg m^{-3}) on elevated surfaces, and more massive drifts along the catchment rim. By the October thaw, densities reach 500–600 kg m^{-3}, and continue rising through summer to 620–730 kg m^{-3} at the most sheltered sites. The maximum density (810 kg m^{-3}) was recorded during April 1978 on a 2m deep ice mass which had survived from the previous winter.

Snow drifts monitored from August display progressive changes in water equivalent with time (Fig. 7). The larger drifts ablate at 35m^3/month for each lineal metre of drift after the disappearance of surface snow, and persist until the end of January. Those located within cirques may remain through the summer. Some lower elevation valley-side drifts (run 7) ablate initially at only half the rate of the larger drifts, but their small volume and lower elevation prompt their disappearance four to six weeks earlier.

Drifts account for 4×10^6m^3 of the seasonal water storage and up to 9% of the runoff generated during spring thaw. Although small in volume, the flow that drifts produce is still sufficient to partly recharge the Fraser reservoir (storage capacity 5×10^6m^3), and late enough to increment the summer drawoff from the dam of 1.3m^{3}s^{-1}.

Comparison Wth Other Mountain Ranges

Mid-altitude ranges in the South Island show a similar seasonal pattern of snow accumulation and loss, as evidenced by course data from the Ben Ohau (Archer, 1970), Craigieburn (Morris and O'Loughlin, 1965; Prowse and Owens, 1982) and Remarkables (Owens, 1979) Ranges. Accumulation commences as early as May; however, on lower elevation courses, such as the Fraser, significant accumulation does not normally begin before July or early August. The maximum water equivalent is reached in September or early October followed by a rapid decline associated with thaw. Snow courses below 1500m lose all of their surface snow cover by late November, but large drifts may persist well into summer.

Years with the deepest snow cover in the Fraser basin were 1963 and 1976. Water equivalents from surveys around poles SP and 3 (Fig. 3) at 1550m show a similar pattern of accumulation to Camp Stream (1430m) on the Craigieburn Range (Fig. 8) for 1963. Alans basin, alongside Camp Stream but 270m higher, produced double the peak water equivalent of Camp Stream and the Fraser snow courses. A similar elevation-related difference is evident at Rastusburn (elevation 1800m), 30 km northwest of the Fraser, where significant snow accumulation began one month earlier with peak accumulation 165mm higher than the Fraser Basin precipitation equivalent. The unusually long delay in the thaw after the winter of 1976 was also apparent from snow depth measurements taken at Broken River on the Craigieburn Range (Prowse and Owens 1982).

Discontinuous snow data are available from both the Fraser and Alans Basins since 1962. A trend is evident in the distribution of heavier-than-normal snow years, as reflected in both snow depth and water equivalent (Fig. 9). The years 1963/64, 1968, 1972 and 1976 all record a heavy persistent snow cover. With the exception of 1968 these winters experienced predominantly southerly weather conditions, corresponding with large positive pressure differences in the southerly index (Trenberth, 1977).

CONCLUSIONS

Two thirds of the annual flow of the Fraser River occurs during a brief two and a half month period of snow thaw. Half of this flow is from water stored in the seasonal snow cover. Thus spring and summer flows partially reflect water stored within the snowpack during the previous winter.

Precipitation over the Fraser Basin is low, less than 1000mm a^{-1}. The snowpack is shallow (less than 0.5m), of moderate (less than 300 kg m^{-3}) density, and spatially variable. Snowpack water equivalents can differ by more than 200% on moderate slopes at the same altitude but varying in aspect. The shallow extensive snow cover provides the greater part of water yield, the maximum recorded being $23.3 \times 10^6 m^3$ (a water equivalent of 315mm).

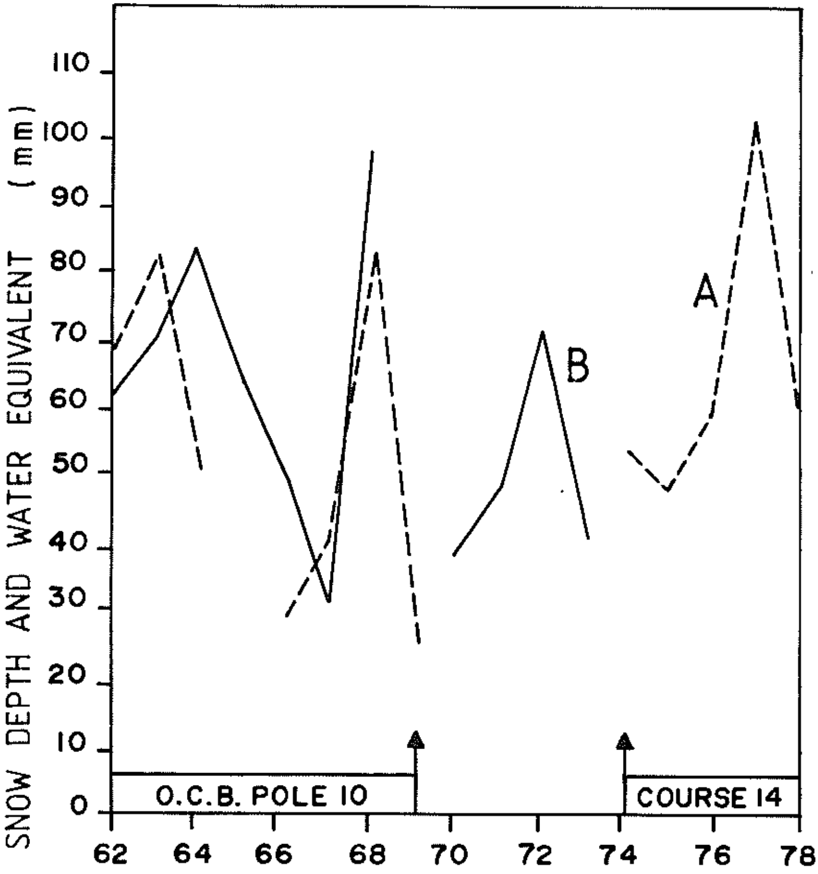

FIG. 9 — Annual fluctuations in

A. Snow depth for the Fraser Basin at pole 10 (N, 5–15° slope at 1550m) and course 14 (W, 5–15° slope at 1600m)

B. Snowpack water equivalent for Alans Basin (NE, 28° slope at 1750m) (O'Loughlin, pers. comm.)

The snowpack thaws rapidly, one to two months after peak accumulation.

Deep (8–9m) drifts that form on moderate, northeast slopes, contain large (70–200m^3/per lineal metre of drift) volumes of water. They may remain throughout the summer months, but their storage is small (less than $4 \times 10^6 m^3$) compared to the surface cover. They may, however, be significant in regulating baseflow and extending the recession period.

Snow course data from other South Island basins show a seasonal pattern of accumulation and loss similar to the Fraser Basin.

ACKNOWLEDGEMENTS

Thanks go to the Dunedin and Alexandra hydrological staff — particularly Messrs M. B. Thomas, I. S. Hamilton and W. R. Thompson.

Also acknowledged both for data and technical assistance are Professor A. F. Mark, Dr C. L. O'Loughlin, Dr B. B. Fitzharris, Dr P. W. Anderton, Mr K. R. Dawber, Mr T. Walker and Mr G. W. Goodyear.

Mr D. G. Bragg assisted in the preparation of diagrams while Dr M. J. McSaveney, Dr B. B. Fitzharris and Ms B. H. Vaile reviewed the script.

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