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EFFECTS OF SNOW FENCES ON THE SNOWPACK OF A BLOCK MOUNTAIN IN OTAGO

W. Harrison

Hauraki C.B. P.O. Box 246 Te Aroha

ABSTRACT

Eleven snow fences, differing in height and location, were installed in the headwaters of the Fraser River, Central Otago, New Zealand, to establish whether seasonal snow storage could be increased and extended, as an aid to water management. Assessments were also made of the influence of the fences on vegetation associations and of snow tussock on snow cover. Flow records from the Fraser River and snow data from the catchment were used to establish the contribution of melt to the volume and timing of spring flow.

Fences on the crest of the range trapped more snow than adjacent bare ground and drift life was extended a maximum of five weeks. Fences on valley sides produced no increase; any gain in cross-sectional area was offset by scouring elsewhere in the drift. Fences produce a major floristic shift in the upland plant association, suppressing the dominant species (*Dracophyllum muscoides*) and increasing bare ground and litter. The tussock sward doubled the water equivalent relative to the bare ground surface and extended the period of snow cover by 2 to 3 weeks. The spring thaw occurs over 61 to 77 days and yields up to $50 \times 10^6 m^3$ of water. Results from this study indicate the use of snow fences would not significantly alter or sustain flow in the Fraser River, but future improvements in fence design and placement may change this.

INTRODUCTION

Block mountains dominate the skyline of Central Otago, their broad crests rising up to 1695m on the Old Man Range. Aligned northwest to southeast, they intercept and modify the prevailing westerly airflow, so that they receive two to three times more precipitation than adjacent valley floors. Above 1300m, as much as half of the precipitation may fall as snow. Occasional light summer snowfalls contribute little to regional water storage, whereas the nearly continuous snow cover that persists between late autumn and early spring strongly influences the timing and volume of spring runoff.

Most high elevation precipitation is available for runoff, but spring flows occur at a time when there is little need for the water. By contrast, late-summer water demand may far exceed the natural late-summer flow of many of the region's rivers and streams. To offset the uneven distribution of seasonal flow, and to partially satisfy the regional water deficit, extensive irrigation schemes have been developed to store water in reservoirs on major tributaries along the margin between mountains and plains.

Fraser Dam, at the northern end of the Old Man Range, provides storage for the Blackmans — Earnscleugh irrigation scheme. Of the Fraser River's mean annual discharge ($60 \times 10^6 m^3$), 8% is detained within this reservoir. Since 1954, a number of alternatives for improving storage by raising the dam crest have been considered, and discarded on technical grounds. As a result, most of the water still runs to waste early in the irrigation season. This situation is not unique to the Fraser; most Central Otago irrigation schemes are small and do not use all the available flow.

An alternative to ponding water is to store it in the headwaters as seasonal snow, through the erection of snow fences. This option, suggested by the Otago Regional Development Council (1977) and Fitzharris (1979), aims at trapping and retaining snow at higher elevations to supplement river flows during recession periods. This study assesses the viability of this option for the region.

Eleven snow fences were erected in the headwaters of the Fraser River catchment to determine whether:

(i) a significant volume of snow could be trapped;
(ii) the volume of snowdrifts could be influenced by the location and dimensions of the fences;
(iii) native plant communities would be affected by the fences and their associated drifts;
(iv) the fences would be more efficient than tussock grassland at trapping snow;
(v) artificial drift formation could be used to enhance river flows.

Fences were located on broad ridge crests and valley sides, where wind velocities are high and snow transport most active. These are zones of substantial natural drift formation: rocktors initiate drifts up to 450m long and 5m deep, with water equivalents of $1.5 \times 10^4 m^3$ per drift, while valley side drifts reach 110m wide and 9m deep with water equivalents of $1.3 \times 10^6 m^3$ per drift.

SNOW FENCES AND DRIFT FORMATION

Stationary snowdrifts formed by fences on flat surfaces have a characteristic shape, which Cornish (1914) termed the fundamental curve. Tabler (1968) described the shape as resembling an ichthyoid curve, and calculated a drift length for this form from Bekker's (1951) equation:

$$L = 360\ (7.22 + 3.28h)\ /\ 3.28\ (22.1 \div d) \qquad (1)$$

where L is drift length (m), h is fence height (m), and d is fence density (%).

Martinelli (1972) related fence height (h) to cross sectional area of the drift by:

$$A = a\ (1 - e^{-bh})^c$$

where A is cross-sectional area, e is the base of natural logarithms, and a, b, and c are weather, fence and site-related parameters which control the upper asymptote and the rate of approach to it.

TABLE I — Characteristics of the snow fence network

Site Location	Length (m)	Height (m)	Slope (°)	Aspect	Density (%)
A Range Crest	13	2	8	SW	50 batten
	13	2	8	SW	30 mesh and batten
B Range Crest	5	2.25	7	SW	50
	5	2.25	0	flat	50
	5	2.25	7	NE	50
	5	1.5	0	flat	50
	5	3.0	0	flat	50
C Valley Side — Terrace	5	2.25	40	NE	50 batten
	5	2.25	40	NE	30 mesh
— Obelisk	5	2.25	25	NE	50
— Run 7	5	2.25	23	NE	50

Grishen (1972) considered the length of fetch upwind of fences to be important in their ability to trap snow. He noted that, on plateaus in the Ural Mountains, 60 — 70% of the blowing snow required to saturate the airflow was derived from their upwind edges. As a result, ridge crests narrower than 200m could be stripped completely bare, while those wider than 600m retained an intact snow cover. The crest of the Old Man Range varies in width between 300 and 700m and could therefore be expected to trap some, but not all, of the snow transported across it.

Surface angles affect the trap efficiency of snow fences. Isayenko and Vasilyev (1976) produced a series of aerodynamic simulations for fences on slopes of 0-45°. They calculated approximate snow retention from field measurements of wind velocity when snow drifting and deposition were occurring. Fences on windward slopes of 10°, 20°, 30° and 45° reduced trapped snow by 30, 50, 67 and 83%, respectively, compared to fences on flat surfaces. Only 13% of the area of the Fraser catchment has near level (0–5°) slopes. The greatest surface area (55%) has 5–15° slopes, and at windward sites a reduction in trapped snow of up to one third could be expected.

Martinelli (1973) fenced four breaks in terrain with snow fences. Results were not consistent: two sites retained more snow, the third produced an increase early in the season, which declined later, and the fourth site recorded a reduction in drift volume. The latter two sites, reducing trapped snow, were located on slopes of 26° and 40°, respectively. Many valley systems in the Fraser catchment have narrow zones below ridge crests where slope angles exceed 35°. As a result, the effect of fences on snow retention and accumulation with them is uncertain.

METHOD

Fence and Network Design

Eleven fences were located at three sites in the survey area (Table 1).

(i) Site A. Comprised two fences, built in 1959 by the Otago Catchment Board, to protect a vegetation trial. Located 200m west of the crest of the Old Man Range, the fences were set 7° off vertical and contained no air gaps. One fence was constructed of vertical wood slats at a 50% density, the other of wood battens inserted in wire mesh at 30% density.

Early investigations of Site A indicated marked drift scour at the mesh and batten fence, so later observations were confined to the wood slat fence. Drift lengths were measured and compared with a theoretical value obtained from equation (1). In 1976, a pit was dug at the deepest point in this drift to determine the characteristics of the snowpack.

(ii) Site B. Contained five fences built in 1977 to determine the effect of height and location on snow retention. Three identical 2.25m high fences extended in line from a 7° windward to a 7° leeward slope with the middle one upon the flat range crest. Two additional 1.5m and 3.0m fences completed the array along the crest. The air gap on these fences was 0.2h, slightly higher than 0.1h used in other studies (Martinelli, 1972) due to the uneven ground surface. Slat density of all fences was set at 50%, the normal range for snow fences being 40–60% (Martinelli, 1972). Slat width was 100mm, the maximum acceptable being 250mm. The 6° fence angle improved stability in high winds.

(iii) Site C. Was installed early in 1978. The four fences, of similar design to those at Site B, were installed on three valley sides to determine whether large drifts could be augmented with additional high-density snow. Slopes were steeper (32°) with maximum drift depths of 6 to 10m.

The two highest fences (1585m) were on the headwall of a relict cirque at Terrace. One was wood batten, the other was of dark polymer mesh of lower density. The flexible fabric was used to limit rime ice formation, a common problem with fences on the range. The slat fence was destroyed by wind, but was reinstated for the winter of 1979. The other two fences of standard design were located on asymmetric valley sides: Obelisk at 1524m and Run 7 at 1280m.

Snow surveys at the fences were conducted during late winter and early spring using a tape, probe and Abney level. Surveys stopped with the disappearance of the surrounding snow cover.

Snow accumulation was measured along a transect through the midline of each fence, and cross-sectional area (m^2/lmf) and stored snow volume (m^3/lmf) calculated for each lineal metre of fence. These values were then compared with accumulation along two parallel control transects 5m from the end of each fence.

During the autumn of 1979, fences at Terrace and Obelisk were relocated 15m upslope of the drifts, after it was found that they had produced areas of intense scouring.

Since their installation in 1959, the Site A fences had noticeably affected the structure and composition of the alpine plant community in their immediate vicinity. To measure the extent of this change, twelve 26m long transects were established in four groups. Two groups were centred through the midline of the fences, with two parallel control groups 12m out from the fence ends. Along these transects the plant species and occurrence of bare ground and litter were recorded as point values at 25cm intervals.

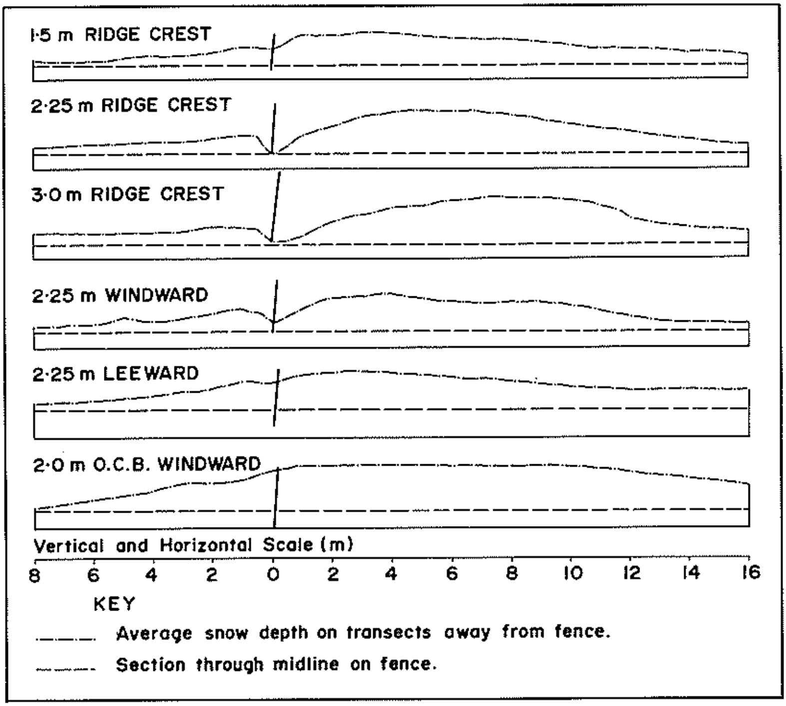

FIG. 1 — Profiles of range-crest snow drifts at Sites A and B.

Snow Trapping by Vegetation

Snow tussock is an effective agent in intercepting precipitation, both fog (Rowley, 1970; Mark and Rowley, 1976) and snow (Fitzharris, 1976; 1979).

Few surfaces containing snow tussock (*Chionochloa macra*) remain in the upper catchment. Where tussocks occur, an increase in snow depth and cover, relative to adjacent bare ground surfaces, is apparent. In September 1977, eleven drifts behind solitary plants were measured for maximum depth and length: seven behind snow tussock and four behind speargrass (*Aciphylla sp*).

Because results indicated that isolated plants acted as effective snow traps, a site was established to assess the effect of tussock sward on intercepting and retaining windblown snow. The only suitable site on the range crest was a trial site established in 1974–75 by the Otago Catchment Board to determine tussock survival. Tussocks were planted in northeast — southeast lines to minimise windscour (Mark pers. comm.), at a density of one plant/ m^2 — a lower density than in natural associations elsewhere on the range. The sampling area was labelled with a central pole and marker disk surrounded by a compass rose of four stakes. Within this area mean height and diameter of tussock crowns were calculated for a 10% random sample.

At each visit, depth and density were measured at 0.5m intervals along the four radii, and the snowpack water equivalent was then calculated from:

$$WEa = WEb + Dt\,(Xa - Xb)$$

where WEa is the water equivalent of the sample area (m^3),

WEb is the water equivalent of the snowpack above a mean tussock tiller height of .221m (m^3),

Dt is mean density (%),

Xa is total snow volume up to the mean tiller height (m^3), and

Xb is the total volume of tussock crowns in the sample area from a mean crown diameter of .247m (m^3).

River Flow

Flow data for the Fraser River from 1969 were examined to establish seasonality.

Mass curves were plotted for July-December from each year of flow data. Two points on each curve where changes in slope occurred indicated dates of the beginning and end of spring thaw. Curves for each event were then extracted, fixed to a common time base, and transposed. Recession constants were graphically derived for periods recording a uniform decline in flow. From these it is possible to assess the impact of variable snow storage in the catchment headwaters on river flows, and the potential effect of snow fences on runoff.

RESULTS

Snow Fences

Site A Profiles of drifts downwind of the fences (Fig. 1), show the greatest snow depth (2.1m) occurring within 12m of the fences. Measured drift lengths conform to that calculated from Bekker's (1951) equation (21m). Table 2 presents cross-sectional area, drift densities, and water equivalents measured at the time of peak accumulation, for both the fenced area and the control area adjacent to it.

To establish the nature of the fence drifts a snow pit was dug to the ground surface at the time of greatest snow depth during October 1976 when the snowpack was considered isothermal. Ten ice bands were encountered, varying in thickness from 5 to 15mm. At the base of the profile, 7 layers, each less than 320mm thick, were distinguishable, representing snow deposition in early winter. Compressive deformation with melt-freeze, and equi-temperature metamorphism (Sommerfeld and La Chapelle, 1970) had locally increased densities to 510 — 530 kg m^{-3}. Above this, densities decreased to 440 kg m^{-3} and ice bands became less apparent. Wet surface snow with coarse-packed powder identified the zone of most recent deposition where melt-freeze metamorphism was taking place.

Site B Fence drifts were of variable form (Fig. 1). All were foreshortened 4-8m, compared to those at Site A, as a result of air gaps in the fence. The distance to the deepest point in drift (D) corresponds to the air gap depth (d) by

$$D = 12.4\,d$$

The 2.25m leeward fence, on the edge of a depositional zone

TABLE 2 — Calculated water equivalents for drifts at range crest snow fences at peak accumulation on 6 October 1977.
† O.C.B. — Otago Catchment Board

			Cross Sectional Area (m^2/lmf)		Density (kg m^{-3})		Water Equivalents (m^3/lmf)		Percentage Increase in Water Equivalent Due to Fence
			Control Lines On Ground Surface	Produced by Fence	Control Lines On Ground Surface	In Fence Drift	Control Lines On Ground Surface	Produced by Fence	
Site A	O.C.B.† Fence	2.00m	16.6	24.0	450 (est)	500	7.5	12.0	62
Site B	Range Crest Fences	1.50m	9.6	15.2	420	480	4.0	7.3	65
		2.25m	12.0	17.8	340	420	4.1	7.5	65
		3.00m	13.2	18.9	450	410	5.9	7.8	57
	2.25m Fences	Windward	14.4	15.4	260	400	3.7	6.2	63
		Leeward	28.8	17.3	430	450	12.4	7.8	39

TABLE 3 — Water equivalents of drifts at range crest snow fences at Site B on 8 November 1977.

		Cross-Sectional Area (m^2)	Density (kg m^{-3})	Water Equivalents (m^3/mf)
Range Crest	1.50m	7.6	500	3.8
	2.25m	7.0	510	3.6
	3.00m	6.5	480	3.7
Windward	2.25m	6.9	560	3.9
Leeward	2.25m	23.8	460	11.0

extending along the range crest, caused the height of the snow surface to exceed that of the air gap. As a result, the fence was buried within the drift at peak accumulation.

The three fences along the ridge crest increased the cross-sectional area of drifts and water storage in drifts, the magnitude of the difference increasing with fence height (Table 2). Densities of drifts behind the fences were only marginally higher than those of the control line. Relative contribution to the water equivalent of the snow cover behind the fences decreased with fence height.

The substantial variation in exposure of the three 2.25m fences over the range crest (Table 2) is reflected in the cross-sectional areas of snow cover on the control line. The area of the leeward site drift is double that of the two more exposed sites. Water equivalents for these areas followed a similar trend, with equivalents of the most exposed sites around a third of that on the more sheltered leeward site. The fences increased drift cross-sectional area and water storage, while reducing the effect of site exposure. Drift densities behind the fences were higher than on the adjacent control line, with the leeward site showing only a marginal increase. This is also reflected in the 39% contribution to the water equivalent of the snowpack produced by the leeward fence, compared to 63 and 65% for the two more exposed sites.

From October until early November all drifts, with the exception of the leeward fence drift, lost half of their mass (Table 3). By contrast, the leeward fence drift increased its water storage by 3.2m^3//mf over the same period because of its location in a zone of enhanced accumulation and reduced ablation. By mid-November, all but the leeward fence drift had disappeared; and this, reduced to one third its original size, remained for a further two weeks.

Site C At the Terrace site the fences altered drift geometry compared to drifts on the control transects (Fig. 2). A decrease in depth of up to 6m occurred behind the fences, while upwind depths increased

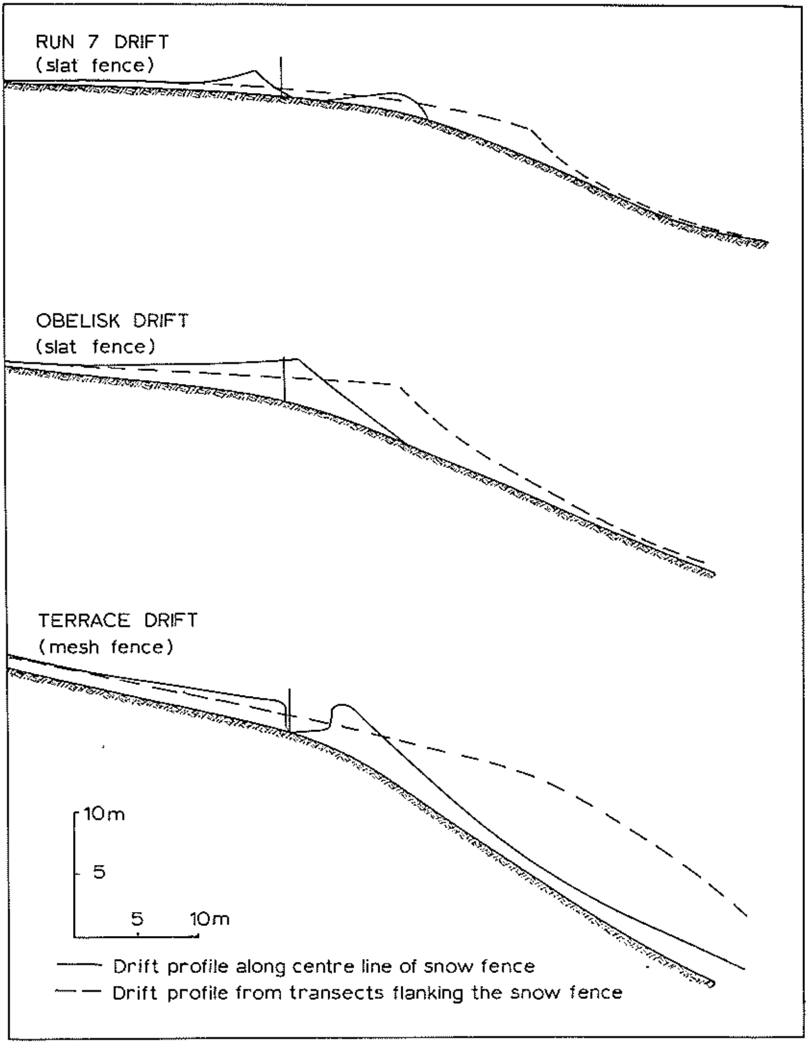

FIG. 2 — Profiles of valley-side snow drifts at Site C — snow fences located on the break in slope.

by up to 1m. At fence edges scouring bared the ground surface, while drifts were shifted further upslope: a distance of 1.5h for the mesh fence, and 3.0h for the slat fence. At the time of maximum accumulation, all fences showed a reduction in volume, this being most apparent for the mesh fence.

The effect of the fences and the resultant scouring along drift margins (Fig. 3) can be seen from Table 4. The Terrace mesh fence reduced

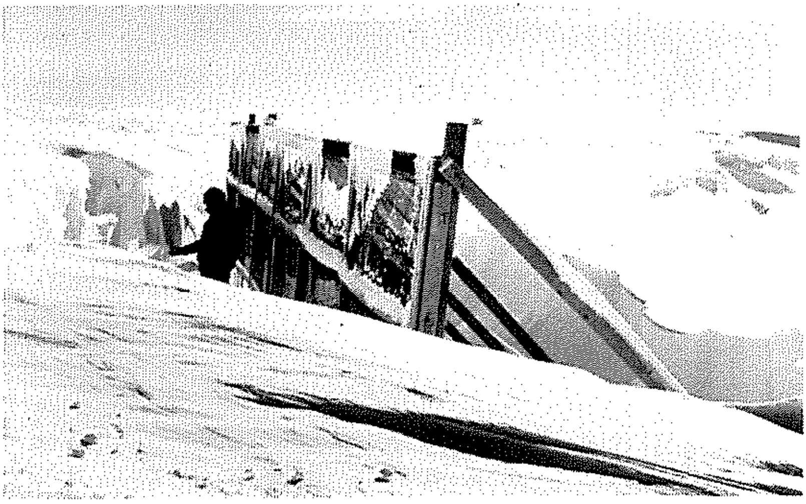

FIG. 3 — Terrace mesh fence showing the 2.5m deep scour hollow upwind of the fence.

drift cross-sectional area by 73% near the time of maximum accumulation, which increased to 92% by early summer. This difference in snow retention relative to the control lines is further accentuated by a 90 kg m^{-3} reduction in density, resulting in a 79% decline in water equivalent at the time of maximum accumulation.

Fences at Obelisk and Run 7 performed in a similar manner to the Terrace fence. By late October, a 13% reduction in drift cross-sectional area was apparent at Obelisk along with a 120 kg m^{-3} reduction in density, resulting in a 40% reduction in water equivalent compared to the control lines. By early November, the fence drift retained only half the water equivalent of the undisturbed drift area. The Run 7 drift was small (water equivalent of less than $80m^3/l$mf for 1976–78) and ablated rapidly. By late winter, the fence drift cross-sectional area had decreased by 39% compared to the control transects; this being consistent with a 35 and 41% reduction on the other Site C fences.

Relocation of the fences in 1979 substantially reduced scouring, although by late spring the gain in cross-sectional area immediately behind the fences (Table 4) only balanced a loss further to leeward (Fig. 4). Obelisk remained the most adversely affected fenced drift, losing a third of its mass, relative to the control lines, by late spring.

Effect of Fences on the Ground Cover

A survey of vegetation at Site A revealed major changes in the composition of the alpine plant community (Fig. 5). In unfenced areas, *Dracophyllum muscoides* occupied 49%, litter 17%, and bare ground 12% of the total area. In the fenced area, *D. muscoides* declined to 4%, while litter and bare ground increased to 21% and 15%, respectively. The increased shelter provided by

TABLE 4 — Surveyed cross-sectional areas and mean densities for valley side drift transects at Site C 1978–79

Fence	Date	Control Lines		Fence Line		Change in
		Cross Sectional Area (m^2)	Density ($kg\ m^{-3}$)	Cross Sectional Area (m^2)	Density ($kg\ m^{-3}$)	Cross Sectional Area (%)
Run 7	28. 8.79	56.25		34.31		–39
Obelisk	18. 9.78	54.69	450	32.50	450	–40
	3.10.78	27.81	460	28.75	480	+ 3
	25.10.78	57.50	390	50.00	270	–13
	7.11.78	36.88	—	18.75	600	–49
Terrace (Mesh)	21. 9.78	201.56	440	131.25	370	–35
	4.10.78	305.63	440	81.25	350	–73
	7.11.78	250.31	600	106.25	560	–58
	28.11.78	214.69	530	66.25	550	–69
	19.12.78	153.75	—	12.50	550	–92
	23. 1.79	7.19	—	NIL	600	
Obelisk	28. 8.79	90.00	—	46.87	—	–48
	12.11.79	38.13	—	25.00	—	–34
Terrace (Slat)	12.11.79	154.00	—	150.00	—	– 3
Terrace (Mesh)	12.11.79	245.00	—	203.00	—	–17

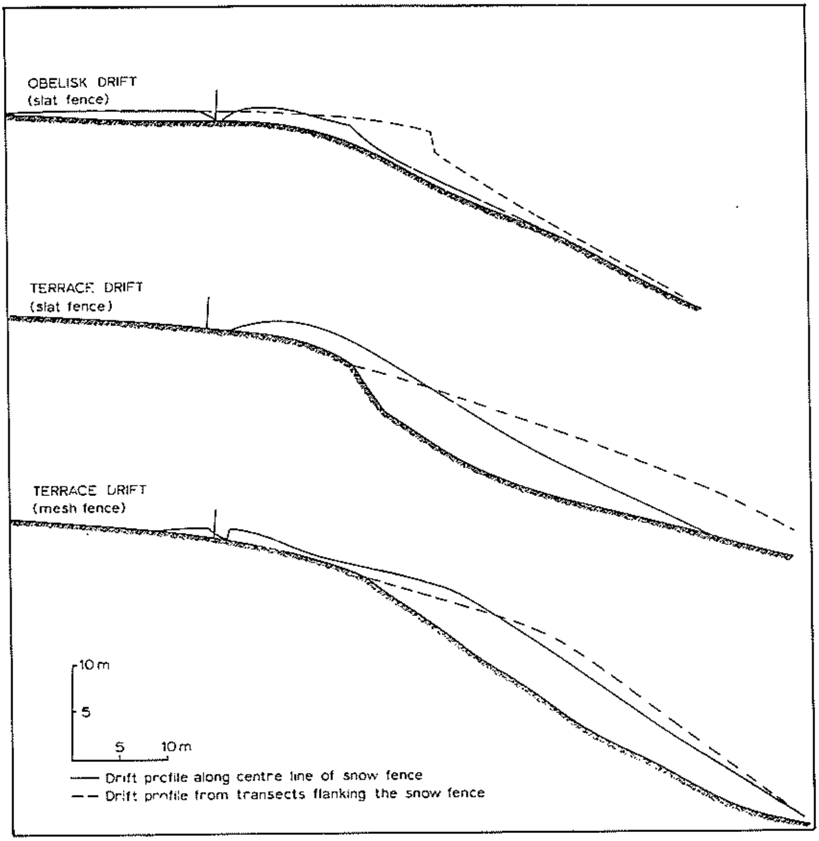

FIG. 4 — Profiles of valley-side snowdrifts at Site C — snow fences located upslope of the drift.

the fences produced an expansion in numbers of other plant species, for example *Cotula goyenii* increased from 1.5% to 15% and *Polystichum sp* from 1% to 17%. Although flora was more diverse behind the fences, some species, like *Thamnolia vermularis* and *Certraria islandica,* had disappeared.

Snow Trapping by Vegetation

Snow drifts trapped by individual plants had average lengths and depths of 2.6m and 0.3m for snow tussock and 1.5m and 0.4m for speargrass.

The trial plot was visited in late autumn, and surveyed during the spring thaw. Drift densities were generally uniform with mean values of 260 and 370 kg m^{-3} for the tussock-covered and bare surfaces, respectively. Densities increased to 670 kg m^{-3} for both tussock and bare ground at the time of emergence of tussock tillers from the snow cover.

Maximum water equivalents at the trial plot were reached in mid-October (Fig. 6) when the sampling site retained twice the water content per unit

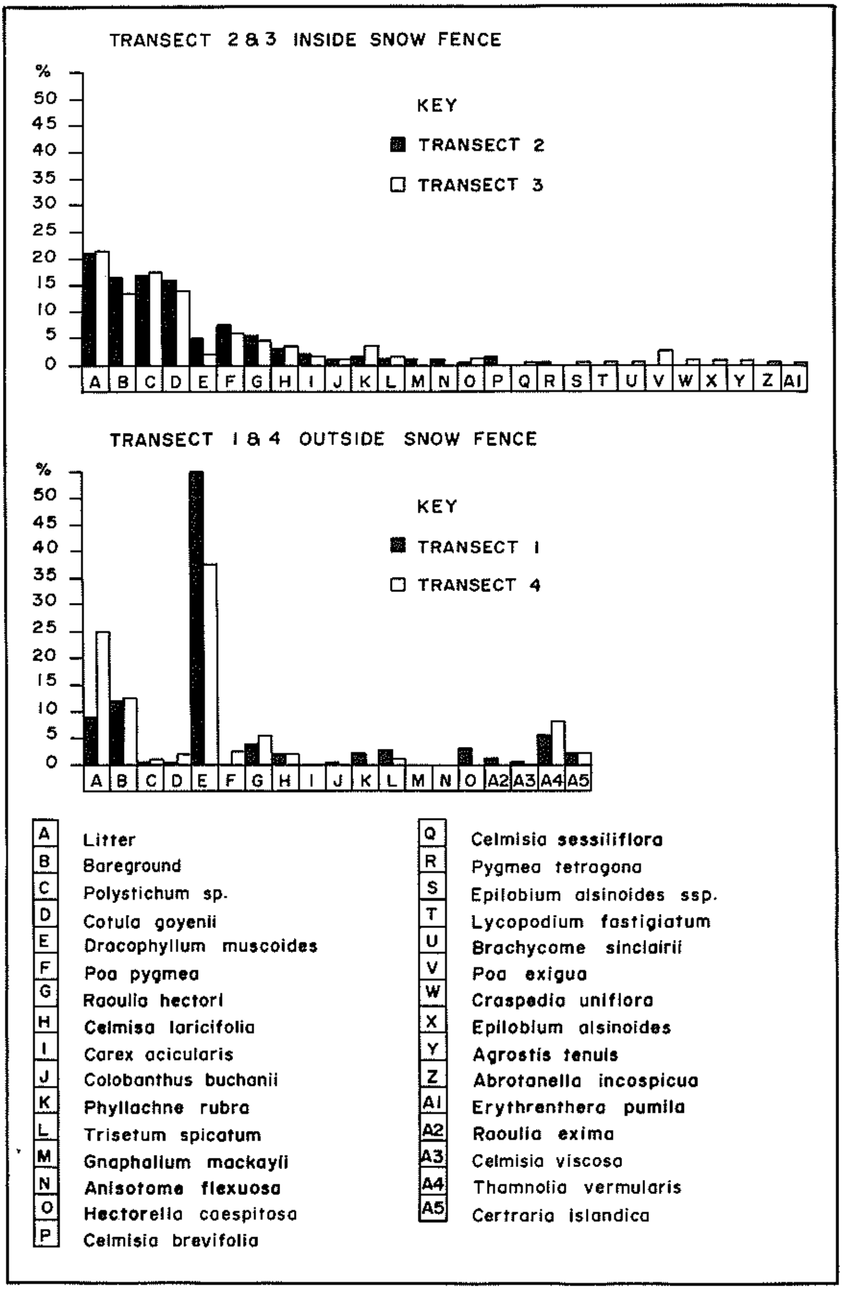

FIG. 5 — Vegetation transects through and alongside the Site A snow fence.

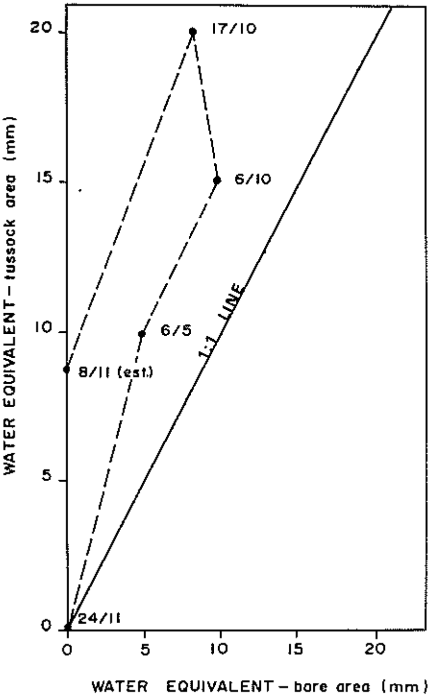

FIG. 6 — Calculated water equivalent of the tussock trial plot compared to an adjacent bare area containing an alpine cushion-plant community.

area of the adjacent bare ground surface. These values, however, may reflect only relative snow retention, as tussock density in the trial plot was only half that of the natural association. Also, within this plot, 20% of the plants were dead and a further 20% in poor health (Mark, pers. comm.).

By November, no snow remained on the bare ground surface, whereas on the trial plot a uniform depth of 0.2m had been retained to a distance 7m in from the upwind edge. In 1977 and 1978 snow cover within the tussock canopy remained 2–3 weeks longer than on the adjacent bare ground surface. The location of the sampling site, within a 7m wide zone where some scouring was apparent, indicates that snow retention may be somewhat under-estimated.

Influence of Snow Cover on River Flows

Fraser River flow is distinctly seasonal (Fig. 7), with high flow associated with spring thaw and low flow in late summer and mid winter. The Fraser yields a greater proportion of its annual flow (56%) during the spring months than other Central Otago catchments, where spring yields are less than 40% of the annual total, as more than 65% of the Fraser catchment lies above winter snowline.

Highest flows occur with rapid melt of the snow pack during major spring

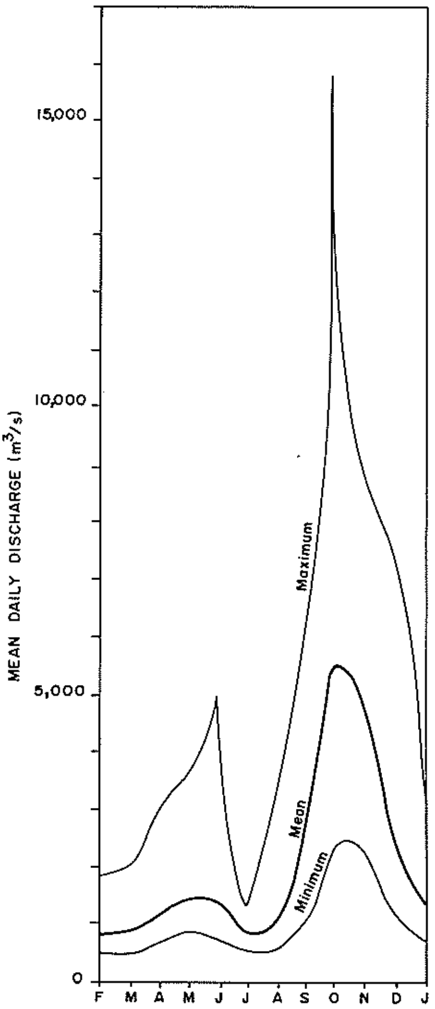

FIG. 7 — Monthly flows of the Fraser River 1969–1979.

storms. The highest estimated instantaneous discharge of 88m^{3}s^{-1} occurred on 14 October 1978, burying the weir under 3m of gravel, and precluding precise measurement of river flows from that time onwards.

Timing of high spring flows is a function of a basin's altitude and proportion of catchment area above snowline. In Central Otago, catchments below 1100m in altitude to the east of the study area record their highest flows a month earlier than the Fraser River, and higher altitude (up to 2300m) catchments to the west, one month later.

Cumulative mass curves of river flows for the spring thaw (Fig. 8) show differences in the timing, rate and volume of flow over the 11-year period.

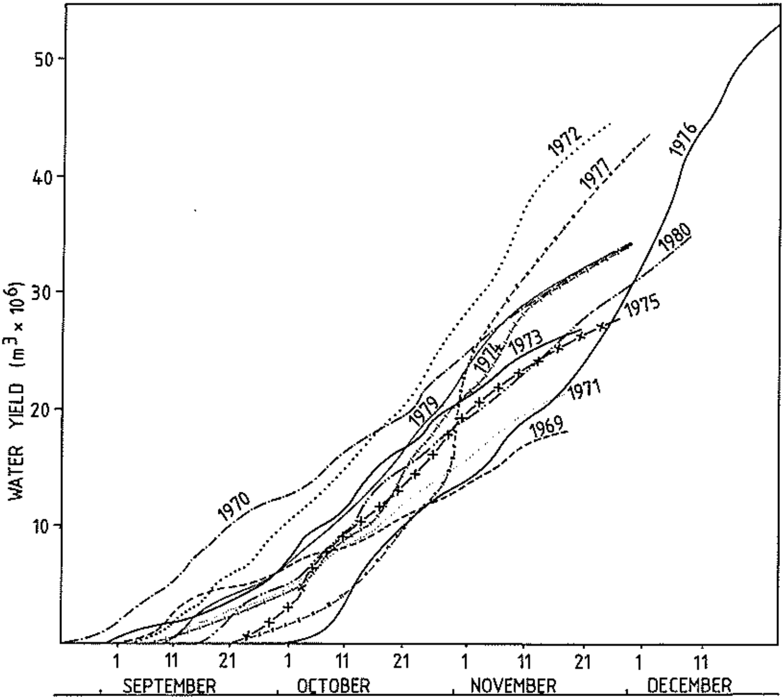

FIG. 8 — Cumulative mass curves for river flows during the spring thaws 1969–1980 (1978 excluded because of site damage).

Discharges generally average 4–7m^3s^{-1} during late August and early October. In years with little snow, a reduction occurs; for example a decrease of 2.4m^3s^{-1} occurred in 1969. Years with heavy winter snowfalls showed an increase in the rate of discharge to 7.3–10.2m^3s^{-1} towards the end of the thaw. All seasonal snow cover leaves the catchment by mid-December.

The volume of spring runoff is highly variable, ranging from 17.2 to 50.0 × 10^6m^3 in the eleven year record between 1969–1980 (Table 5). For 1974–79, on average 47% of this runoff was stored in the seasonal snow cover at the time of maximum accumulation. Most of the balance is contributed from increased spring precipitation; Birchdale Station 30 km southwest of the Fraser records 53% of its precipitation for July-November in the two months following the commencement of the thaw. The melting of large snow drifts is estimated to generate less than 9% of the spring runoff (Harrison, 1986, in press).

Stored water from the snowpack is yielded over 61 to 77 days (Fig. 9). Beginning on 13 September (± 21 days) the thaw continues for 10 weeks, ending on 21 November (± 28 days). During this time, flow recession is determined by the prevailing weather. A slow rise in temperature produces a recession constant of 0.90, however a shift to cold southerly conditions reduces it to 0.86. Winters with little snow cover are followed, in the absence

TABLE 5 — Total volume of runoff generated during the spring thaw, and its relation to the volume of stored water in the snowpack at the time of maximum accumulation.

Year	Maximum Recorded Volume ($m^3 \times 10^6$) of Stored Water as Snow (Drifts Excluded)	Total Volume of Runoff ($m^3 \times 10^6$) From the Spring Thaw	Percentage of Spring Runoff Stored as Snow
1969	—	17.2	—
1970	—	26.9	—
1971	—	19.9	—
1972	—	43.2	—
1973	—	26.3	—
1974	16.4	31.9	51
1975	14.0	25.6	54
1976	23.3	50.0	47
1977	17.8	40.9	43
1979	13.5	32.5	42
1980	—	33.5	—

of storms, by a rapid decline in flow to $1.7m^3s^{-1}$. More severe winters produce a curve flattening at $4m^3s^{-1}$ and an increase in recession constant to 0.95 beyond this time. The reduction in flow is still rapid, with flow halving in 14 days, and reflects accelerated depletion of stored water in saturated bogs and larger drifts. Frequent summer storms may maintain the recession constant at 0.95; however in dry summers, when flows decline below $0.6m^3s^{-1}$, true baseflow occurs. Then flow is derived primarily from groundwater and bank storage in the riparian zone and the constant then increases to 0.98, with flow halving in 34 days.

The effect of a delay in melt on the pattern of river flow is demonstrated by the 1976 data (Table 6). Runoff from the spring thaw in this year would have been sufficient to maintain the lake behind Fraser Dam near its maximum level through most of the summer. Drawoff from the reservoir is set at 1.3m s^{-1} during normal years, and so the reservoir would have remained full until the end of January.

In years with a shallow intermittent snow cover, inflow to the Fraser Dam is insufficient to satisfy the irrigation requirement of $0.85m^3s^{-1}$ (Table 6); without rainfall the supply of stored water would last 45 days. During most years water level declines after late December; water drawn from reservoir storage is not replenished by river inflows until 105 to 118 days beyond the beginning of the thaw.

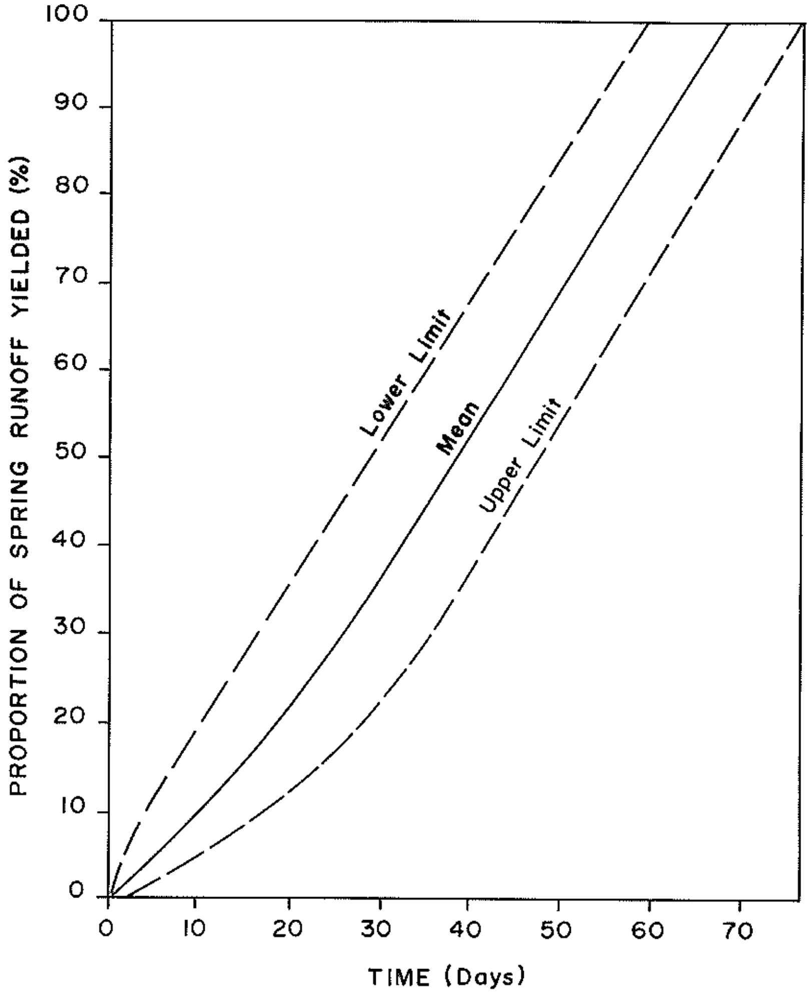

FIG. 9 — Timing of spring thaw — all recorded values are included within the specified limits.

DISCUSSION AND CONCLUSIONS

The Fraser Dam stores between 10 and 29% of the total runoff from the spring thaw, the remainder running to waste within a 69-day period. Snow fencing in the higher altitude sector of the catchment has been advocated as one means of storing more water. There are, as yet, insufficient data to establish whether fences would increase the total volume of snow stored through trapping snow that would either blow elsewhere or sublimate while wind borne. The main function of fences is causing snow to pile in larger drifts and by so doing extend the period of melt.

TABLE 6 — Comparative dates and time periods for recessions during spring and early summer

Year	Spring Thaw			Discharge of 1.3m^3/s Reached		Discharge of .85m^3/s Reached	
	Start	Finish	Number of Days	Date	Number of Days From Start of Thaw	Date	Number of Days From Start of Thaw
1969	4. 9.69	11.11.69	68	25.11.69	82	11.12.69	98
1970	28. 8.70	4.11.70	68	4.12.70	98	24.12.70	118
1971	11. 9.71	11.11.71	61	7.12.71	87	23.12.71	103
1972	6. 9.72	20.11.72	75	2. 1.73	118	18. 1.73	134
1973	30. 8.73	14.11.73	76	27.11.73	89	8.12.73	100
1974	13. 9.74	19.11.74	67	6.12.74	84	27.12.74	105
1975	19. 9.75	20.11.75	62	22.12.75	94	19. 1.76	122
1976	6.10.76	17.12.76	72	30. 1.77	116	28. 2.77	145
1977	23. 9.77	25.11.77	63	21. 1.78	120	7. 2.78	137
1978	7. 9.78	—	—	—	—	—	—
1979	12. 9.79	23.11.79	72	25. 2.80	166	—	—
1980	24. 9.80	4.12.80	71	2. 1.81	100	—	—
x̄			69		105		118

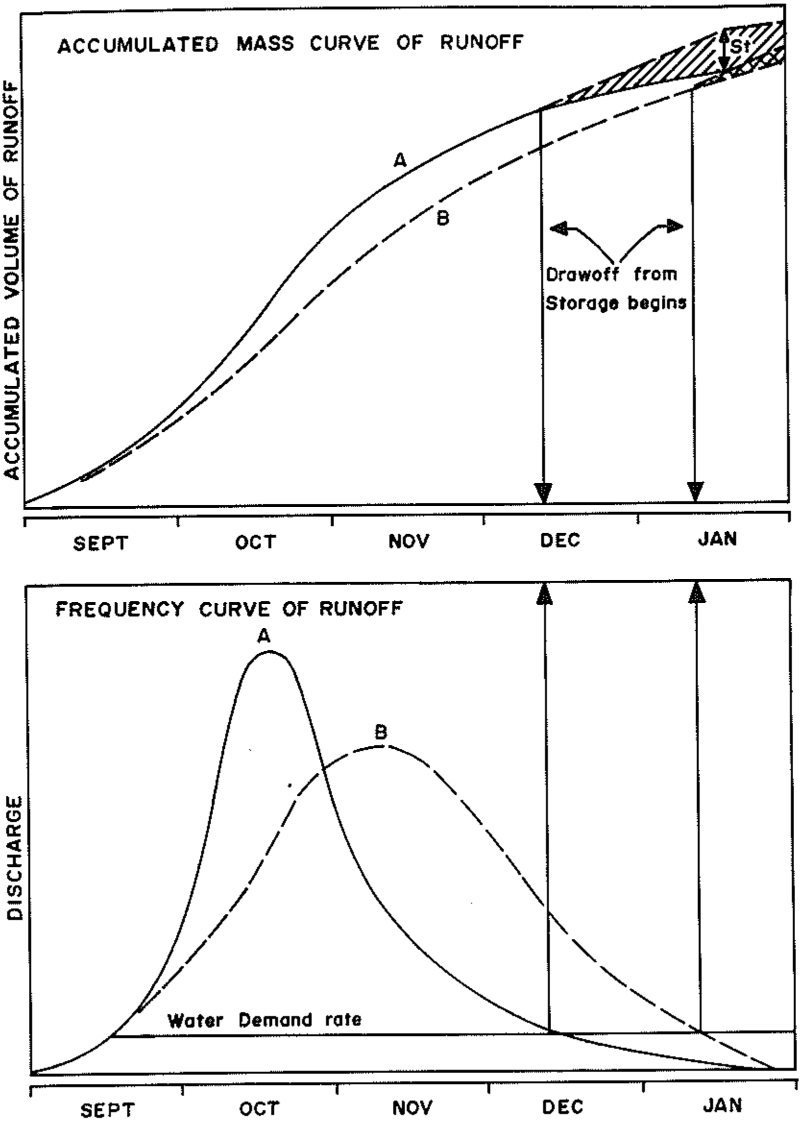

FIG. 10 — Idealised modification to seasonal flows of the Fraser River to improve summer runoff:

A. existing situation

B. situation if water management were effective

St is the time at which the maximum rate of drawdown from the reservoir is reached.

Successful management of river flow requires extending the period of melt, thus storing a substantial volume of water through until mid summer, and so maintaining the Fraser Dam reservoir close to its maximum level for much of the irrigation season. If the water equivalent of the snowpack were to remain much the same as at present, but through concentration into higher elevation drifts melt were delayed, river flows might be expected to change (Fig. 10). This would reduce the magnitude of the early spring peak flows and shift a greater volume of runoff until later in the season. It would also delay the time at which the maximum rate of drawdown from the reservoir is reached from January to February the following year.

The fence trials gave highly variable results with respect to improving snow retention and delaying melt. Fences at Sites A and B increased the volume of retained snow from 39 to 65%, the amount being determined by fence height and location. Increases in water equivalent relative to the surrounding area of up to 183% were achieved by fences of medium to low height on and to the windward of the range crest. The leeward snow fence, although located in a zone of natural accumulation, contributed over a third of the snow to the profile, giving almost double the water equivalent (20.2m^3/*l*mf) of the range crest fence (11.6m^3/*l*mf) of the same height. Drifts produced by the fences remained 3–5 weeks after the disappearance of the surrounding snow, but showed an accelerated ablation rate which may result from heat absorption by and reradiation from the surrounding dark ground surface and from sensible heat transfer.

Attempts to augment existing snowdrifts were unsuccessful, with $^1/_3$ to $^1/_2$ the drift volume being lost by wind scouring, with short fence length producing noticeable end effects. Martinelli (1973) achieved variable results on similar landscape features. His greatest recorded increase, 135m^3/*l*mf in a shallow valley system, was achieved using higher (3–3.7m) and longer (60–100m) fences than were used in this study. However, despite this greater volume of snow, the delay in melt was only 1 to 3 weeks.

Fences affect the structure and composition of the alpine plant community. The greater protection from wind and the greater depth with snow reduced numbers of the most dominant species (*D. muscoides*) in the vicinity of fences. Litter and bare ground increased, but so did floristic diversity. Because of the long time required for plant establishment and growth at these altitudes, the process of adjustment may be continuing.

Snow retention on tussock-covered surfaces doubles the water equivalent over that of adjacent bare ground, extending the duration of snow cover by 2 to 3 weeks. The artificial nature of the tussock trial plot in terms of spacing, orientation and thrift of the tussock lines makes it necessary to use caution when applying any of the data to natural tussock associations. An intact vegetative cover may, however, under certain conditions, substantially augment short-term snow retention in catchments.

The highly-seasonal river flows and the considerable yield during the spring thaw make it appear, superficially at least, that there is some potential for water management. Spring thaw takes place over a period of 61 to 77 days after which river levels fall at a more uniform rate. Heavy winter snow and a later thaw can maintain the reservoir close to its maximum level throughout the summer. Conversely, a mild winter and a thin, intermittent snow cover produce little flow. In the absence of summer rain and with continuous drawoff from storage, flow from the Fraser reservoir would be exhausted after 45 days.

With only a limited increase in snow retained on the range crest, loss of snow from major drifts, and a period of less than five weeks delay in melt, snow fences of the type used in this study are not suitable for augmenting water storage or extending flows to the Fraser Dam. With their limited capacity to trap additional snow, 670 km of fence would be required to provide sufficient water to fill the reservoir, which would in effect fence the entire catchment area above 1500m. At the time of construction (1977) fence cost was $15/metre, plus costs of maintainance. A variation in fence length and design might produce a deeper, more extensive and persistent snow cover. Any further studies should be directed towards determining the most effective fence design and configuration for snow trapping, the proportion of detained snow that normally would be swept beyond catchment boundaries or lost by sublimation to the atmosphere, and the time taken for melt water from drifts to emerge as flow in stream courses.

Regardless of their effectiveness, snow fences would substantially change the vegetation associations of upland environments, making these areas less suitable for both agriculture and recreation.

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