CONTRIBUTION OF SNOWMELT TO THE OCTOBER 1978 FLOOD OF THE POMAHAKA AND FRASER RIVERS, OTAGO

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ABSTRACT

Rapid melt of a Central Otago mountain snowpack produced, in three days, 97 mm of water compared with 150 mm of rainfall. The energy sources for the melt were dominated by convective fluxes. The contribution of snowmelt to the major October 1978 flood was over one-third of the flow of the Fraser River but less than 10 percent of the flow of the Pomahaka River.

INTRODUCTION

The floods of 13-16 October 1978 were the worst for a century over much of Otago and Southland. The Clutha river at Balclutha peaked at 4760 m^3/s (compared with an estimated 5660 m^3/s in 1878). This paper discusses snowmelt on a Central Otago mountain which contributed to this major flood. An assessment is made of the energy sources for melting the snow and the snowmelt contribution to flow in the Pomahaka and Fraser Rivers. An analysis of the flood for the whole Clutha catchment is given by Jowett (1979).

THE DATA

The snowmelt was recorded by a snow pillow (diameter 1.8 m) at 1370 m on the Old Man Range within the Fraser catchment (Fig. 1). Snow pillows are used extensively to continuously record snowpack water equivalent. Colbeck *et al.* (1979) note that the accuracy of these pressure recording devices depends on the accuracy of the readout chart (about 1.5% error), and on the presence of ice layers of high textural strength within the snowpack, which can cause a registration time lag for newly deposited snow. Rain held within the snowpack will increase the weight on the snow pillow; liquid water melted at the surface may percolate downwards, and be trapped within the snowpack. Therefore rate of "melt" as shown on the snow pillow chart may be less than the actual rate.

Flow of the Pomahaka River recorded at Burkes Ford (Fig. 1) is used to define the flood. Estimates of the peak flow are available only for the Fraser River above the dam, as the gauging site was washed out. The estimates are based on slope area methods, extension of rating curves, and comparison with the pack runoff of the Fraser River at the Otago Central Electric Power Board weir below the confluence with the Hawkesburn Stream.

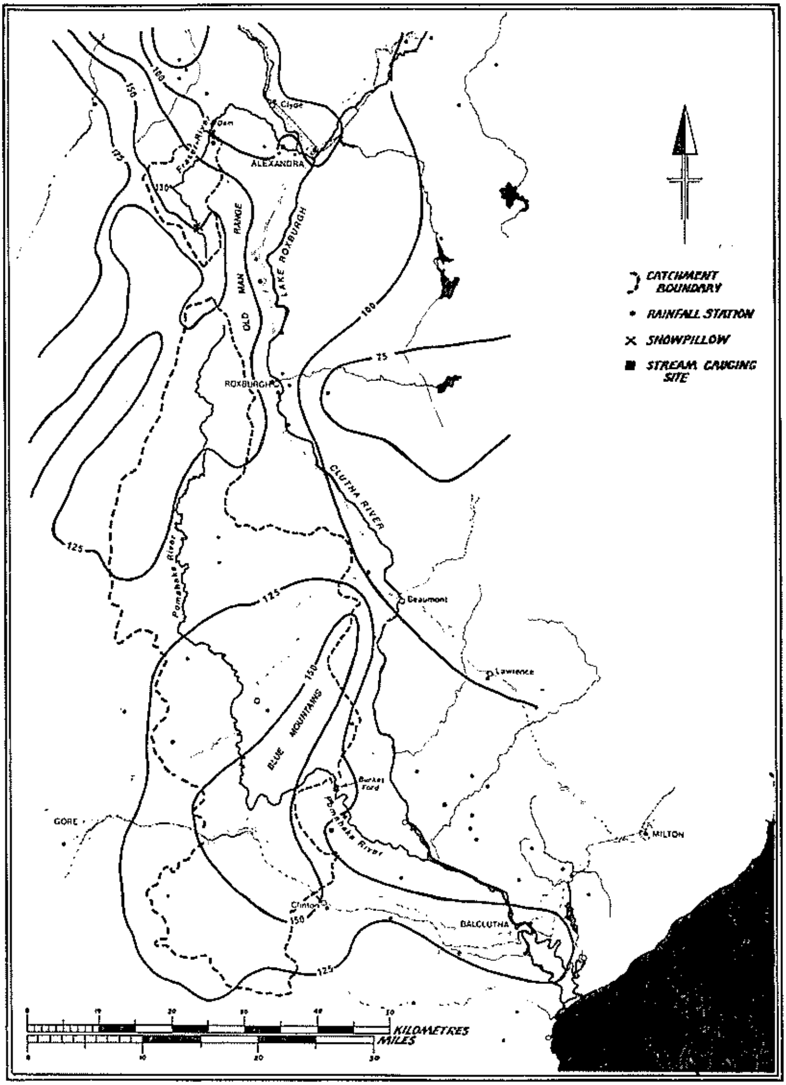

FIG. 1—Rainfall distribution in mm over the Pomahaka and Fraser catchments for period 0900 hrs 12 October 1978 to 0900 hrs 15 October 1978. Map also shows locations discussed in text. General location is indicated in Fig. 2.

A rainfall map for the adjacent Pomahaka and Fraser catchments was compiled using raingauge records for the period 0900 hours on 12 October to 0900 hours on 15 October (Fig. 1). The map is based on data for 69 stations, and is part of a larger isohyetal map of the Clutha catchment compiled by the Otago Catchment Board. The pattern of isohyets differs from that in Jowett (1979, p 123) because his periods of record were not always the same and he used fewer stations. Allowance has been made for an orographic increase in rainfall over mountain areas. Recording raingauges at Roxburgh and at Old Workings in the Fraser catchment measured rainfall intensities. A thermohygrograph at Roxburgh gave a continuous record of temperature and humidity. Daily totals of incoming shortwave radiation (sun and sky) were recorded at Alexandra with a Robitzsch-type bimetallic recorder.

The meteorological conditions that produced the heavy precipitation have been described by Hessell and Lopdell (1979). On 12 October an extremely deep depression (946 mb at Macquarie Island) passed to the south of New Zealand. The weather was initially dry and warm over Otago with gusty northwest winds, but then turned to rain. Early on 13 October a cold front moved on to Southland, and became quasi-stationary (Fig. 2). A 400 km wide band of cloud with ascending air lay along the front. A pronounced northwest flow at the surface, and at 500 mb, injected considerable amounts of warm, moist air into the system.

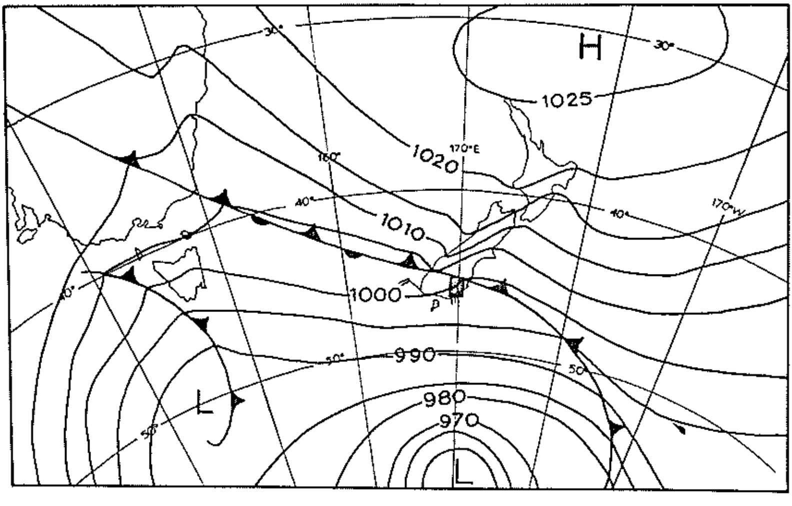

FIG. 2—Mean sea level weather map analysis 1200 hrs 13 October 1978 (after Hessell and Lopdell, 1979). The small rectangle below the stationary front is location of Fig. 1.

There was little apparent change in the synoptic situation from midday on 13 October to 0900 hours on 14 October. Pressures rose gradually over the flood area as a shallow wave depression moved away southeast along the front, which recommenced moving over New Zealand (Hessell and Lopdell, 1979). Rain ceased over most of the catchments on 14 October, although light showers of snow continued over the higher mountains.

RESULTS

The snow pillow record shows an erratic buildup of the snowpack during September, until melting began at the end of the month (Fig. 3). Melting accelerated in early October, but apparently ceased from 5-12 October. At this stage the water equivalent over the snow pillow was 160 mm. A snow survey over the Fraser catchment on 4 October estimated a mean snow depth of 0.3 mm (water equivalent, 220 mm) and snow density at 400-500 kg/m^3. The transient snow line was at about 300 m. Rapid melting of the snowpack occurred on 12-14 October, removing 97 mm water equivlent. Snow falls on 14-16 October, increased the pack by 16 mm of water equivalent of snow.

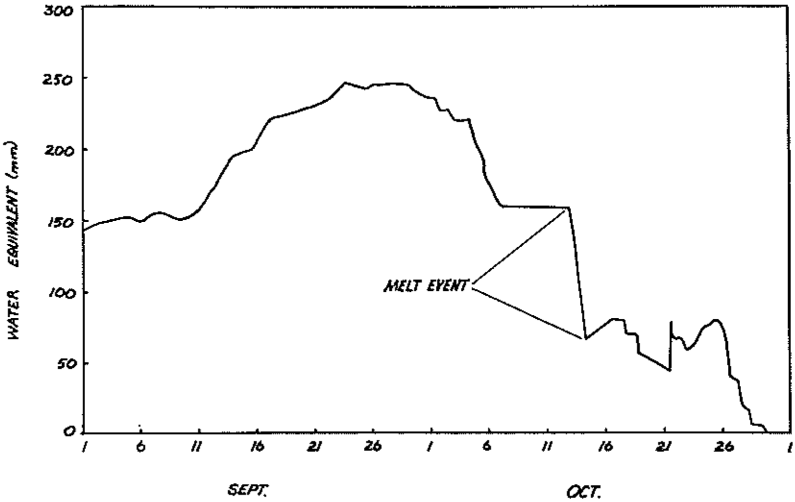

FIG. 3—The snow pillow record showing the melt event and water equivalent of the snowpack.

Rainfall totals between 80 and 150 mm were measured within the Fraser and Pomahaka catchments over the three days during the flood (Fig. 1). Rainfall at the snow pillow site over the same time is estimated to be 150 mm. The map of 24 hour rainfalls from 0900 hours, 13 October (Hessell and Lopdell, 1979) shows a pattern similar to that of Fig. 1. They report record, or near record daily rainfalls over a wide area of Otago and Southland. At Roxburgh, return periods for the 24, 48 and 72 hour rainfall intensities were very much greater than 50 years, and probably closer to 100 years.

Discharge at the Fraser River gauging site upstream of the dam is estimated to have peaked at 88-106 m^3/s. The Pomahaka River, at Burkes

Ford, rose to a flood peak at 1300 m^3/s late on 4 October, then receded rapidly to moderate flows by 16 October (Fig. 4). The return period for this flood is estimated by Jowett (1979) at 170 years.

ANALYSIS OF SNOWMELT

Melting of snow, recorded as a decrease in water equivalent at the snow pillow site, began at about 1200 hours on 12 October, and lasted for 43 hours (Fig. 4). Average melt rate was 2.3 mm water equivalent per hour, with a peak rate of 2.8 mm/h on 13 October. About 40 percent of the total melt of 97 mm occurred before significant rain, and was accompanied by warm temperatures which reached 20°C at Roxburgh. Relative humidities were low (29-54 percent) in the prevailing northwest wind regime. The remaining 60 percent of the melt occurred during rainfall, at a time when colder temperatures were measured at Roxburgh.

There are difficulties in extrapolating temperatures from Roxburgh (elevation 170 m), to the snow pillow site (elevation 1370 m). With a temperature at Roxburgh of 20°C and a saturated adiabatic lapse rate (—0.65°C/100 m) the snow pillow site would be at 12.2°C, or at 8°C if a dry adiabatic lapse rate (−1°C/100 m) is assumed. The thermograph trace at Roxburgh showed an invasion of cold air at about 1200 hours on 13 October, with temperatures plunging to 5°C, accompanied by increasing intensity of rainfall. However, air on the surrounding mountains may have remained considerably warmer, as Hessell and Lopdell (1979) illustrate in their analysis of upper air data at Invercargill. Cold air invaded as a shallow wedge, above which strong, moist, warm northwest winds continued to blow.

Energy sources for snowmelt

The energy balance of a melting snow surface is:

$$Q^* + Q_H + Q_E + Q_M + Q_G + Q_R = 0 \qquad (1)$$

where Q^* = net radiation
Q_H = sensible heat
Q_E = latent heat transfer from evaporation or condensation
Q_M = latent heat transfer by melt
Q_G = heat transfer by conduction into or out of the snowpack
Q_R = melt due to rain

It is normal to express terms as flux densities and to regard those directed towards the snow surface as positive. To relate energy to water terms:

$$Q_E = L_V E \qquad (2)$$

and

$$Q_M = L_f M \qquad (3)$$

where E is the amount of evaporation or condensation, and M is the amount of melt. L_V, the latent heat vaporisation, is 2.45 x 10^6 J/kg at 10°C and L_f, the latent heat of fusion, is 3.33 x 10^5 J/kg. Since

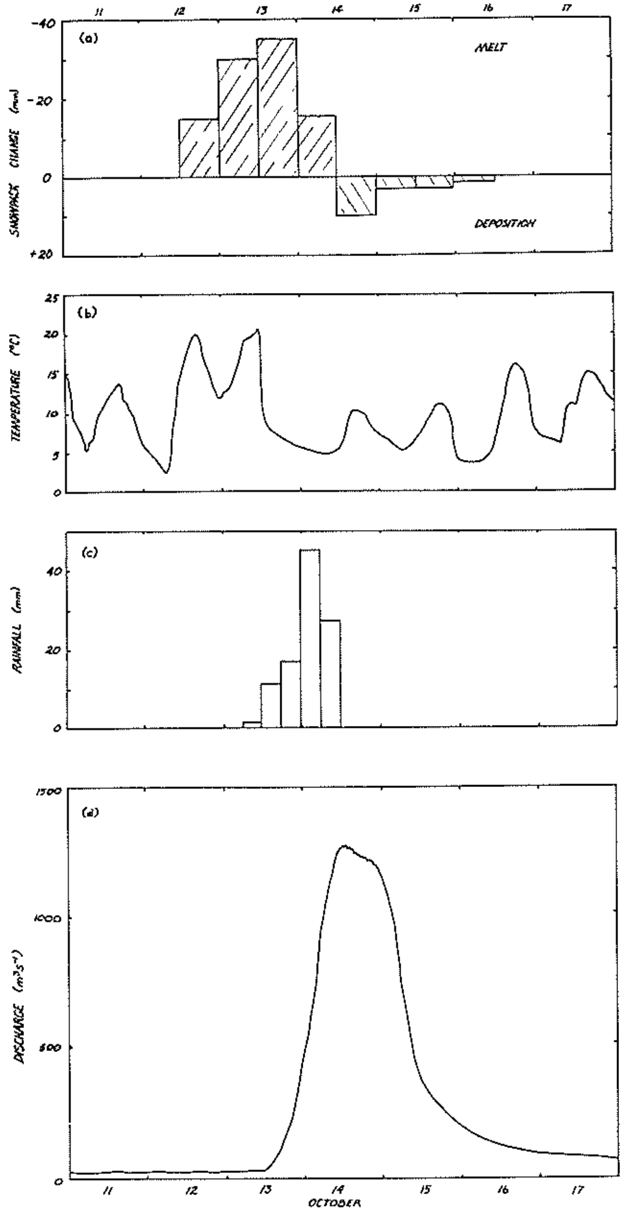

FIG. 4—Detail of the flood event for period 11-17 October 1978.
(a) Snowmelt and accumulation at the snow pillow site.
(b) Roxburgh temperature.
(c) Roxburgh rainfall.
(d) Hydrograph for Pomahaka River at Burkes Ford.

$M = 97$ mm, $Q = -3.24 \times 10^7$ J/m² over 43 hours. Thus the average flux required to produce this melt was −209 W/m². The other terms in equation (1) are now estimated for the snow pillow site to investigate the energy sources for the observed snowmelt. Errors in estimating the terms are difficult to assess, but could be up to ±20%. During melt it is assumed that $Q_G = 0$ (Paterson, 1969).

Incoming solar radiation observed at Alexandra for 12-13 October averaged 115 W/m² over the 43 hours of melt. Assuming an old snow albedo of 0.5, snow surface temperature of 0°C, air temperature of 10°C, and sky conditions that varied from clear to cirrostratus and altocumulus, to stratus, then Q^* is calculated to have averaged 47 W/m², using methods described by Paterson (1969) and by Oke (1978). Thus Q^* provided about 23 percent of the energy, or sufficient to melt 22 mm water equivalent of snow. Since melting continued at night, and during rain, some non-radiative sources of melt contained in Q_H, Q_E and Q_R must have been dominant from 12-14 October.

The melt energy supplied by rain may be calculated as (Paterson, 1969):

$$Q_R = c\,R\,(T_R - T_S) \qquad (4)$$

where c = specific heat of water
R = rate of rainfall
T_R = rain temperature
T_S = snow surface temperature

Assuming $R = 10$ mm/h, $T_S = 0$°C, $T_R = 10$°C as optimum estimates at the snow pillow site, then $Q_R = 114$ W/m², sufficient energy to account for 55% of the melt. Energy supply from rain however could have continued at this rate for short periods only; for much of the snowmelt period $R < 10$ mm/h, and probably $T_R < 10$°C at the time of heaviest rainfall. At Roxburgh rain fell for 25 hours. If the 150 mm of precipitation at the snow pillow fell over the same period, then more realistic estimates give $R = 6$ mm/h, and $Q_R = 70$ W/m² during the rain period, or 41 W/m² over the 43 hours that snowmelt was observed. This would have been sufficient to melt about 20 percent of that observed.

In summary, we have estimated values $Q_G = 0$, $Q^* = 47$, $Q_R = 41$, and $Q_M = -209$ W/m².

By balancing equation (1), 121 W/m², or 58 percent of the snowmelt, comes from the turbulent fluxes of Q_E and Q_H, with convection towards the snow surface.

Assumed weather conditions at the snow pillow are shown in Table 1. These are extrapolated from Roxburgh, and from synoptic weather maps. Since melting snow is at 0°C and has a saturation vapour pressure of 6.1 mb, there existed strong gradients of temperature and humidity toward the surface. These and strong winds aiding turbulent heat transfer would favour convective melt. Convective snowmelt, calculated using the nomographs and methods described by Kuzmin (1972, p 188-191), gives melt rates greater than those observed, illustrating that latent transfer and sensible heat were capable of providing the energy needed (Table 1), and in fact may have been greater than 121 W/m².

Kuzmin notes that melting rates of up to 9 mm/h have been measured in the European USSR, and that rates of 3 mm/h are common in warm, humid, windy conditions, when turbulent heat transfer toward the snow surface provides an important energy source. This is consistent with the 2-3 mm/h of melt observed at the snow pillow site.

TABLE 1—Assumed weather conditions and melt at the snow pillow site 12-14 October, 1978. Melt is calculated from Kuzmin (1972).

Parameter	Before Rain	During Rain
Wind Speed (m/s)	10	10
Air temperature (°C)	13	10
Relative Humidity (%)	47	100
Vapour pressure (mb)	7	12
Calculated melt rate (mm/h)	3.5	4.6
Observed melt rate (mm/h)	1-2.5	1-3

It is not possible to separate the relative roles of Q_H and Q_E. However the gradients of temperature and water vapour would favour the dominance of Q_H in the dry northwester, and Q_E during high humidity and rain. Condensation onto the snow surace (Q_E) can be a significant source of energy; condensation of 1 kg of water liberates enough heat to melt 7.5 kg of ice at 0°C (Paterson, 1969). There have been few other estimates of the energy sources for snowmelt in New Zealand. From microclimate studies at Ivory Glacier, West Coast, during summer, it was estimated that Q* supplied over 50 percent of the energy for melt, Q_H 29 percent and Q_E 17 percent, although it was thought these proportions would change during storms (Anderton and Chinn, 1978). In one major storm, precipitation accounted for 19 and 11 percent respectively of the daily input for two successive days; in another, about 45 percent of the recorded ablation was estimated to come from Q_R.

CONTRIBUTION OF SNOWMELT TO RUNOFF

Total water input above the snowline may have been 130-150 mm rain plus 100 mm melt. At the snow pillow site, melt supplied 40 percent and rainfall 60 percent. Mean rainfall for the Pomahaka catchment above Burkes Ford was calculated to be 134 mm by integrating the rainfall map (Fig. 1). Snowmelt would have come from 10 percent of the catchment, and hence provided an additional 10 mm input. The flood hydrograph of the Pomahaka at Burkes Ford was integrated, after subtraction of base flow using the method of Wilson (1974, p 178), to give a stormflow of 66 mm. This represents a runoff of 49 percent of rainfall, or 46 percent of rainfall plus melt.

The contribution of snowmelt would have been greater in higher altitude catchments such as the Fraser (80 percent of the catchment area was above the transient snowline) where the storm rainfall was estimated to be 135 mm, and snowmelt 80 mm (Table 2). The estimated peak runoff per unit area was 0.7-0.9 $m^3 s^{-1} km^{-2}$. The higher estimate is 1.3 times that of the Pomahaka. A total storm runoff of 97 mm is suggested in the Fraser, comprising 72 percent of rainfall. The melt occurring before rain fell contributed to the quick rises in the rivers. In the case of the Pomahaka, the rise from snowmelt is thought to have reached the lower catchment at the time of peak rainfall intensity. In the snow-covered Fraser, the melt effectively wetted the catchment, so priming it for rapid runoff of the subsequent heavy rain, and provided over one-third of the total water input of the storm.

TABLE 2—Comparison of the 12-14 October, 1978 storm in the Pomahaka and Fraser catchments.

	Pomahaka	Fraser
Area (km^2)	1874	120
Precipitation (mm)	134	135
Snowmelt (mm)	10	80
Total water input (mm)	144	215
Snowmelt/Total water content (%)	7	37
Peak flow (m^3/s)	1300	88-106*
Peak flow/unit area ($m^3s^{-1}\,km^{-2}$)	0.7	0.7-0.9*
Stormflow (mm)	66	86-97**

* Range of estimates.

** Values represent range of estimates based on comparisons with the Pomahaka.

CONCLUSION

The October 1978 flood was a major event in many Otago and Southland catchments. At an elevation of 1370 m on the Old Man Range it was accompanied by 97 mm of snowmelt compared with 150 mm of rain. An estimated 58 percent of the energy for melt may have come from turbulent transfer of sensible and latent heat to the snowpack surface. In the higher altitude Fraser catchment, snowmelt may have been over one-third of the water input and made a significant contribution to the size of the flood peak in this catchment. The role of similar northwest storms in producing snowmelt and priming rivers needs to be better documented.

Mild, moist northwest airflows often occur in spring storms, suggesting that similar, rapid melting of the spring snowpack may be common on Otago mountains. Estimates of the heat balance suggest there is substantial energy available from turbulent transfer of heat and water vapour to the snow surface during these warm, windy conditions. Therefore other floods, including that in 1878, may have had an important snowmelt component from high elevation catchments, such as the Fraser. Jowett (1979) suggests that in large catchments, like the Clutha, the area of seasonal snow is not sufficient to influence the volume of runoff. In lower catchments, such as the Pomahaka, the contribution of snowmelt to flooding is not important as the area above the snowline is too small.

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