Journal of Hydrology (NZ) 43 (2): 125-139, 2004

Hydrological effects of burning tall tussock grassland on the Lammermoor Range, East Otago, New Zealand

M. J. Duncan and M. B. Thomas[1]
National Institute of Water and Atmospheric Research Ltd
P O Box 8602, Christchurch, New Zealand.

Abstract

The greatest threat to high-altitude tall tussock grassland is fire. This paper examines the hydrological effects of burning tall tussock on summer (November to April) flows, using data collected from two medium-sized (124–154 ha) catchments in upland east Otago. In other seasons, snowfalls created difficulties with precipitation measurement and deep winter snows prevented servicing of the water-level recorders.

After an 8-year calibration period, about 75% of one catchment was burnt in spring 1988. Reductions in water yield from the burnt catchment were apparent during the first summer, were largest the next summer and were apparent for the subsequent summer. In the second and third summers after burning, this amounted to a reduction in summer runoff of 74 mm (32%) and 69 mm (19 %) respectively. Only some summer monthly flows from the burnt catchment were significantly lower than those during the calibration period. Summer low flows were barely changed by burning the tussock: the 7-day-average annual minimum flows for the first 3 summers after the burning were similar to those during the calibration period, except for 1990/91, which was wet and gave higher flows than any during the calibration period. For the 5 years following burning there was a reduced amount of quickflow from the burnt catchment. It also produced relatively fewer and smaller large floods than the unburnt catchment. However, none of the differences in average quickflow or average peak flow before and after burning, in any size class were significant. The reduced summer flows following burning were attributed to increased transpiration by the vigorous new tillers sprouting from the burnt stumps, and greater loss of intercepted moisture because of increased air circulation through the less dense tussock canopy.

The study implies modification of tall tussock grassland will reduce water yield and if the tussock is allowed to recover, yields will tend towards those of the original flow regime.

Introduction

The effects on water yield of snow tussock (*Chionochloa rigida* (Raoul) Zotov) grassland have been long debated (Campbell and Murray, 1990; Mark *et al.*, 1980), but there

---

[1] M. Barry Thomas (1949-1999) worked in the Dunedin Office of NIWA and its predecessors as a hydrologist. He was involved in the establishment and monitoring of the Otago suite of land-use change catchments. Later he controlled the activities of the South Island based NIWA field teams. It was during this period that Barry commenced work on this paper, but sadly he succumbed to cancer before he was able to finish.

have been few catchment studies comparing water yields from pristine snow tussock, depleted snow tussock and pasture. Snow tussock communities become depleted when repeated burning and grazing results in reduced tussock densities and lower tussock stature, with the exposed ground surface covered in short unproductive grasses and herbs, or bare ground. Campbell (1987, 1989) and Campbell and Murray (1990) investigated evaporation and the water balance of snow tussock in a large (6 m^2) weighing lysimeter in the Glendhu catchments (Fahey and Watson, 1991), which are near the catchments in this study but at a much lower altitude (460 to 760 m). Fahey and Jackson (1991) used a hydrological model (Pearce *et al.*, 1984) to predict the likely impact of converting tussock grassland to pasture in the Deep Creek and Deep Stream catchments. The model was adjusted to take account of the differing evaporative responses of introduced grasses and native tussock. Evaporation from tussock, while greater than that from improved pasture in winter, was much less in the summer months.

In 1978 a series of paired catchments were established to study and quantify gross differences in hydrologic response of catchments with differing land uses in East Otago, South Island, New Zealand. As part of that study, four catchments (two pairs) were set up on the Lammermoor Range, 60 km west of Dunedin, to compare runoff from depleted and mature snow tussock catchments. The depleted tussock catchments (Poisonous and Sentinel Creeks) had been burnt at some time prior to the experiment to promote new tiller growth, and then extensively grazed, leaving tussock 'stumps' and plants of relatively low stature (< 200 mm). They had also been oversown with clover and exotic grass species and were an example of typical tussock grasslands management. The mature snow tussock catchments (Deep and Elbow Creeks), on the other hand, were considered to be in pristine condition, with snow tussock more than 0.6 m high.

Martin (pers. comm., University of Otago) found the depleted catchments to have a lower water yield but had difficulty in determining the major cause. He surmised that increased evaporation from the introduced grasses, rather than reduced tussock stature, was responsible. However, differences in annual rainfall and altitude between the two pairs of catchments made it difficult to definitively attribute variations in water yield to differences in vegetation.

An experiment was designed to quantify the effects of removing the tussock cover by depleting one of the two pristine tussock catchments that made up one of the study pairs. In September 1988, Deep Creek was burnt to deplete the tall tussock cover. This paper examines the hydrology of Deep and Elbow Creeks to determine if burning the tall tussock vegetation of Deep Creek catchment had an effect on its hydrological behaviour during the following six summers (November to April). Our hypothesis was that burning the tall tussock cover would reduce interception loss and transpiration, leading to increased soil moisture, runoff, flood peaks and volumes, and higher and more persistent low flows.

Description of catchments

The two study catchments lie within 3 kilometres of each other, on opposite sides of the divide on the Lammermoor Range in the uplands of East Otago (Fig. 1), and both drain into the Taieri River. They have similar geology (quartzo-feldspathic schist; McKellar, 1966) and soils (high-country yellow-brown earth: Teviot and Teviot Hill; New Zealand Soil Bureau,1968).

Deep Creek, at an elevation of 950 to 1120 m, has a catchment area of 152 ha and an east to southeast aspect. Elbow Creek, at

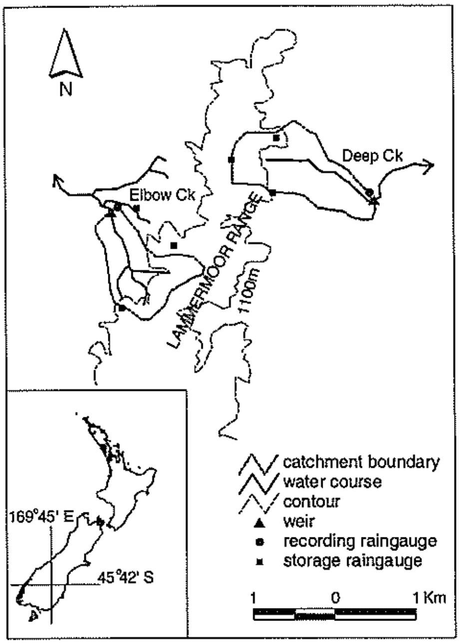


Figure 1 – Location of the study catchments and instruments.

an elevation of 900 to 1100 m, has an area of 124 ha and a northwest aspect. Narrow-leaved snow tussock (*Chionochloa rigida* (Raoul) Zotov) was the dominant cover before and after burning (Figs. 2–5). The topography is gently rolling (Figs. 2–5), but the catchment outlets tend to be incised, with steep banks. Wetlands occupy the valley bottoms, particularly in the upper parts of the catchments.

The catchments on the top of the Lammermoor Range are quite exposed. Strong dry northwesterly winds are often followed by cold fronts from the southerly quarter. The rainfall regime consists of many small events of long duration and low intensity (Murray *et al.*, 1990). Annual precipitation is between 1000 mm and 1200 mm, with a little under half of this arriving as snow during May to October.

Both catchments were instrumented with Leupold and Stevens digital water-level recorders behind sharp-crested 120° V-notch weirs. Current meter and volumetric gaugings confirmed the theoretical ratings for the weirs. Each catchment had a network of three storage raingauges and a recording raingauge (Fig. 1).

Water-level recording started in both catchments in 1980, and the instrumentation was removed from Deep Creek in mid-January 1994.

Flow is perennial in both catchments, but snow up to 2 m deep lies for several months each winter; access to these remote catchments during these months is difficult and dangerous. During this period water-level recorders cannot be serviced properly and precipitation measurements are unreliable because of the difficulty of measuring snowfall. Analysis was therefore restricted to months without snow (November to April, called 'summer' in the paper) to avoid the effects of unreliable records and the influence of snowmelt. In some years, significant snowmelt occurred in November. These occurrences are noted in the paper and were excluded from the analysis. Monthly runoff is spread evenly throughout the year, apart from September and October, which have about twice the runoff of other months, and November, which has 30%–40% more runoff than other months. July flows are lowest.

In September 1988, 70–80% of the Deep Creek catchment was burnt. The rest of the catchment was covered by residual snowdrifts or wetlands and was untouched. The tussock recovered rapidly and, in the absence of grazing stock, had the visual appearance of its pre-burn condition within 3 to 4 years. A photograph taken immediately before burning shows a dense cover of snow tussock 0.6 m to 1 m high with many dead tillers (Fig. 2). The ground between tussocks was covered with a thick mat of dead tillers. Immediately after the burn, a repeat photograph shows blackened tussock stumps with a cover of unburnt dead tillers between

Figure 2 – Mature snow tussock at Deep Creek immediately before burning (26/9/1988).

Figure 4 – Recovering snow tussock at Deep Creek four months after burning (18/1/1989).

Figure 3 – Burnt snow tussock at Deep Creek soon after burning (2/10/1988).

Figure 5 – Recovering snow tussock at Deep Creek seven months after burning (24/4/1989).

them (Fig. 3). A photograph taken four months later shows fresh green tillers up to 0.4 m long sprouting from each stump, with an inter-tussock cover of predominantly dead tillers, but there were some short grasses and herbs (Fig. 4). Seven months after burning, a repeat photograph (Fig. 5) shows further substantial growth, with tillers from adjacent tussocks beginning to touch, but the tussocks have a lower stature and density than the original cover.

Results

Changes in summer water yields

Summer (November to April) rainfall and runoff for each catchment are shown in Table 1. Catchment rainfall was calculated using data from both the recording and manual raingauges. Before Deep Creek was burned, runoff from Deep Creek averaged 35 mm (9%) more than from Elbow Creek and after burning it averaged 12 mm (3%) less than from Elbow Creek. Mean catchment rainfall for Deep Creek averaged 7 mm (1%) more than for Elbow Creek for pre-burn summers and averaged 14 mm (2%) less for post-burn summers. Post-burn summer rainfall averaged 4% (Deep Creek) to 8% (Elbow Creek) more than pre-burn summer rainfalls, but the post-burn range in summer rainfalls was less than for pre-burn summers. A double mass curve of accumulated summer rainfall (not shown) from Elbow Creek versus accumulated summer rainfall

Table 1 – Summer rainfall and runoff for Elbow and Deep Creeks for 1980/81 to 1993/94. November 1992 data are excluded from1992/93 totals, and 1993/94 includes data to mid-January 1994.

Summer	**Summer rainfall**		**Summer runoff**	
	Elbow Creek (mm)	**Deep Creek (mm)**	**Elbow Creek (mm)**	**Deep Creek (mm)**
80/81	547	576	262	274
81/82	494	537	251	278
82/83	886	940	614	710
83/84	410	453	368	424
84/85	488	430	229	218
85/86	801	736	418	472
86/87	867	855	485	516
87/88	592	616	360	372
88/89	642	590	318	303
89/90	576	524	296	243
90/91	864	741	399	372
91/92	732	820	446	469
92/93	612	679	419	443
93/94	380	351	288	264
Mean (80/81–92/93)	655	654	374	392

from Deep Creek shows no breaks in slope, suggesting that the two catchments have very similar rainfall regimes. The consistency of the rainfall climate between the catchments and with time increases the likelihood that any differences in runoff characteristics between pre- and post-burn periods is due to changes in processes rather than changes in rainfall climate.

To examine the effect of burning the tussock and then leaving it ungrazed to regrow, a linear regression describing the relationship between the summer water yields between the two catchments for the pre-burn calibration period (1980/81 to 1987/88) was developed (Fig. 6). Water yields in the burnt catchment were predicted using the regression equation, and the effect of burning calculated as the difference between predicted yields and measured yields (Fig. 7). The departure during the first summer after burning was greater than for any calibration period summer, indicating a small (41 mm) decrease in runoff. In the second and third summers after burning, the departures were greatest and amounted to reductions in runoff of 74 mm (32%) and 69 mm (19%) respectively. By the fourth and fifth summers the water yield from the burnt catchment had returned to the range within the calibration period, but was still lower than the average for the pre-burn period. Data for the fifth summer excludes data from November 1992, when there was substantial snowmelt runoff from both catchments. For the sixth summer (November 1993 to 12 January 1994 when measurements ceased at Deep Creek) flow from the burnt catchment was again lower

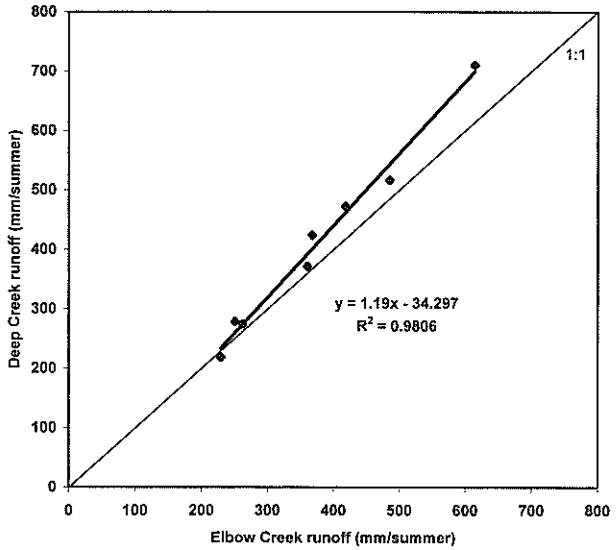


Figure 6 – Relationship between Elbow Creek and Deep Creek summer flows during the calibration period.

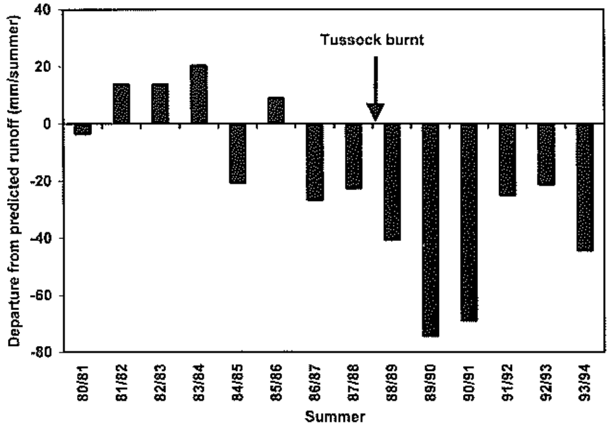
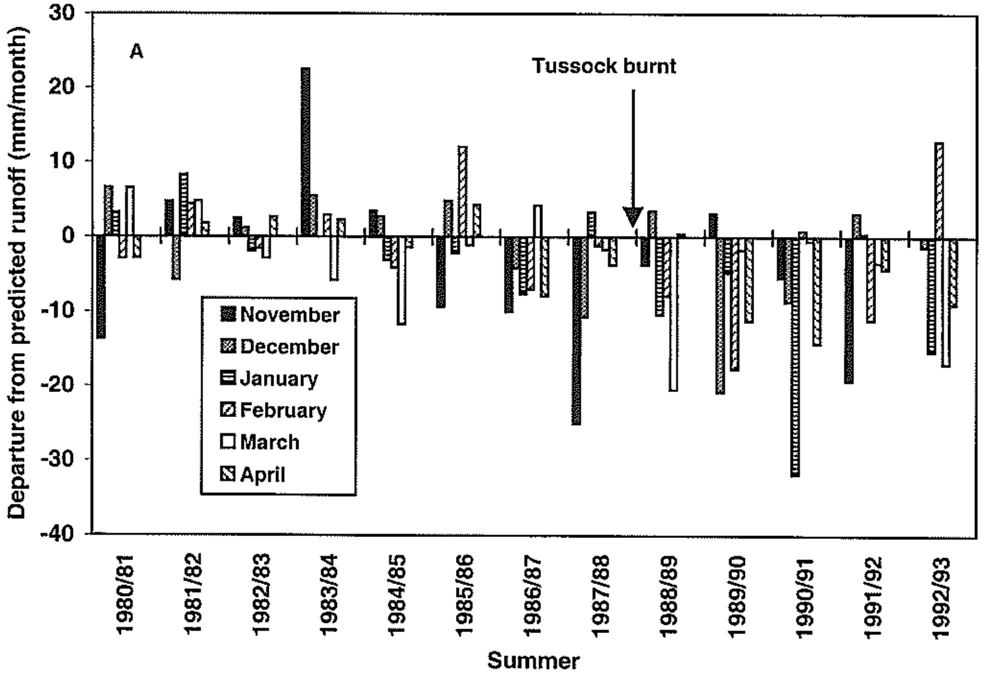


Figure 7 – The differences between measured runoff from Deep Creek and predicted runoff from Deep Creek using the relationship shown in Figure 6. The data for 1992/93 excludes November 1992 data that was predominantly snowmelt runoff. The data for 1993/94 finishes on 12 January 1994 when records from Deep Creek ceased, and should be treated with caution.

than during the calibration period. However as the measurement period for this summer was less than half as long as most previous summers, the 1993/94 result should be treated cautiously.

Monthly runoff

The effect of the burning on monthly water yield was examined in a similar way to that for annual water yield, i.e., by developing a linear regression describing the relationship between the monthly water yield for each summer month (November to April) between the two catchments for the pre-burn calibration period (1980/81 to 1987/88). Water yields for each month in the burnt catchment were predicted using the regression equation. Any difference between measured yields and predicted yields (Fig. 8A) after burning, greater than the largest difference before burning, was attributed to the burning and was assumed to be significant. In all cases the data covered a wide range of runoff and the coefficients of determination ranged from 0.88 to 0.98. The slopes of the regression lines (1.10 to 1.45) indicate that the southeast-facing Deep Creek normally has a higher water yield for each summer month than the northwest-facing Elbow Creek. The water yield differences for individual summer months following burning were not as clear-cut as the differences in water yield for the entire summer. For most months after burning the differences were within the range of values calculated for the calibration period (Fig. 8A). For the first



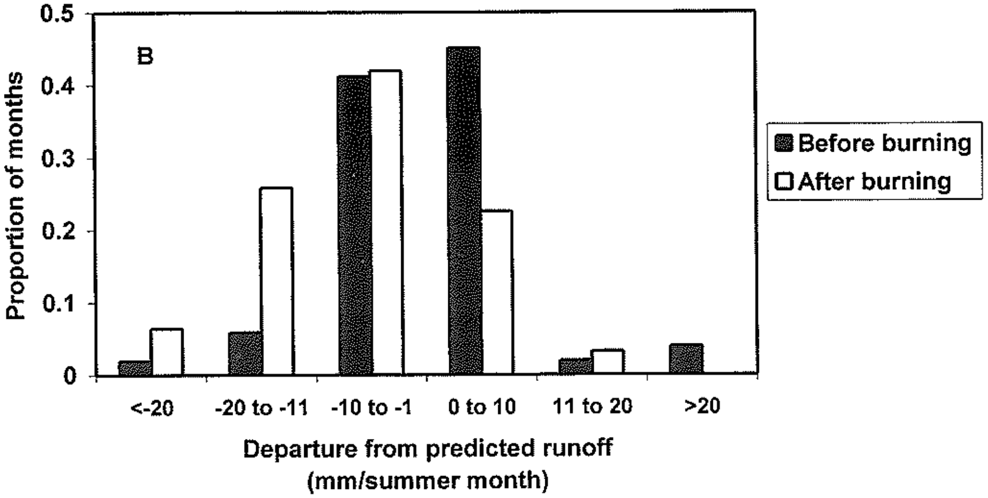


Figure 8 – A) The difference between measured and predicted summer month runoff. B) Proportion of months in summer month runoff departure categories before and after burning.

summer after burning only January, February and March flows in Deep Creek were less than predicted for the corresponding calibration period months. This was when the tussocks were photographed as having vigorous new tillers up to 0.4 m long. For the second summer when the greatest annual reduction was measured, December, February and April had less runoff than predicted for the corresponding calibration period months. For the third summer December, January and April had less runoff than predicted for the corresponding calibration period months. For the fourth summer, November and February had lower runoff than predicted for the corresponding calibration period months. However, in the fifth (1992/93) summer, November flows from Deep Creek were very much higher than predicted due to snowmelt, but in January, March and April they were less than predicted. There were very large snowfalls in the spring of 1992 and there was some residual snow pack at the beginning of November. As Elbow Creek has a northwesterly aspect, compared to the southeasterly aspect of Deep Creek, it could be expected to lose water from the snow pack earlier than Deep Creek. Thus at the end of the spring Deep Creek could be expected to be yielding more runoff than would normally be expected. As this runoff is unrelated to tussock cover, the November 1992 data have been excluded from the analysis. The months with the greatest reductions in flow (March and December 1989, February 1990 and January and November 1991), were those with large runoff values.

The lower March flows from Deep Creek in the first summer following burning are consistent with transpiration and interception losses coinciding with maximum growth and biomass in the tussocks.

The total summer flow reductions from the burnt catchment show a consistent pattern of lower flows in the first three years after burning, but the monthly flows do not, with only a few months in each of those summers showing significant reductions in flow. However, almost every month during that period shows reduced flow from Deep Creek (Fig. 8A), and the sum of those flows for each summer shows a significant reduction. The differences in the departures of summer water yield before and after burning are more clearly shown in Figure 8B, where after burning there is a shift in the proportion of months in most categories to increased negative departures (i.e., lower runoff).

Low flows

The same methods (departure from pre-treatment linear regression) were used to test for significant changes to the minimum flows during each summer month. The slopes of the regression lines of 1.18 to 1.47 indicate that the specific low flows from the southeast-facing unburnt Deep Creek catchment would normally be larger than from Elbow Creek. The regression coefficients lie between 0.82 and 0.97 and indicate reasonable relationships between the flows in the two catchments.

Inspection of plots of the monthly low flow departures (not shown) showed that few departures during the post-burn period were larger than those during the calibration period. The main trend was for most months in 1989 to 1991 to have negative departures, indicating smaller low flows than would have been expected. However, there were unexpected large positive departures for most months during the 1992/93 summer. These were attributed to higher than normal soil moisture and groundwater recharge from the large 1992 snowfalls.

The 7-day-average annual minimum flows were calculated and they show (Fig. 9) departures no larger than those of the calibration period, except in 1991, which was a wet summer. There is a tendency for the 7-day minimum flows from the burnt catchment to be higher than the average for the calibration period, especially in 1990/91.

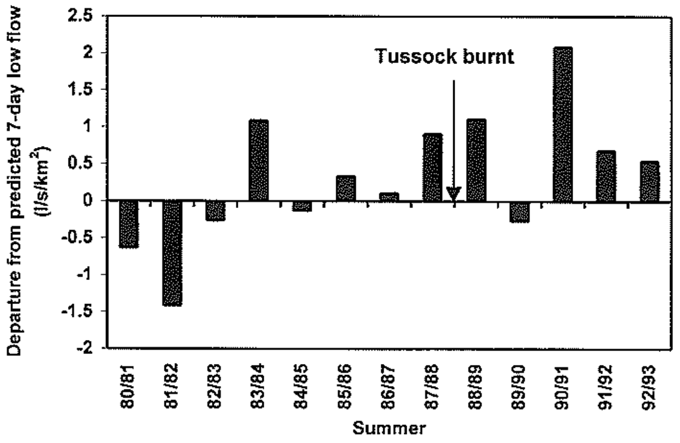


Figure 9 – The difference between measured and predicted summer 7-day minimum flow.

The flow duration curves (December to April) for each catchment before and after burning (Fig. 10) show that flows exceeded more than about 50% of the time were unaffected by burning the tussock (November data was excluded because some November flows were dominated by snowmelt, which varied between the catchments). At flows higher than those exceeded 50% of the time, Elbow Creek had greater discharges after burning than it did before burning, indicating some sort of climatic shift. However, discharges from Deep Creek in the same range did not respond as dramatically as did those from Elbow Creek, possibly indicating some effect of the tussock burning.

Quickflow

Summer quickflow

The summer flow record from each catchment was separated into quickflow and delayed flow using the method of Hewlett and Hibbert (1967), using their separation slope of 0.15186 ml/s/km^2/s. The same method as used elsewhere in this study, departure

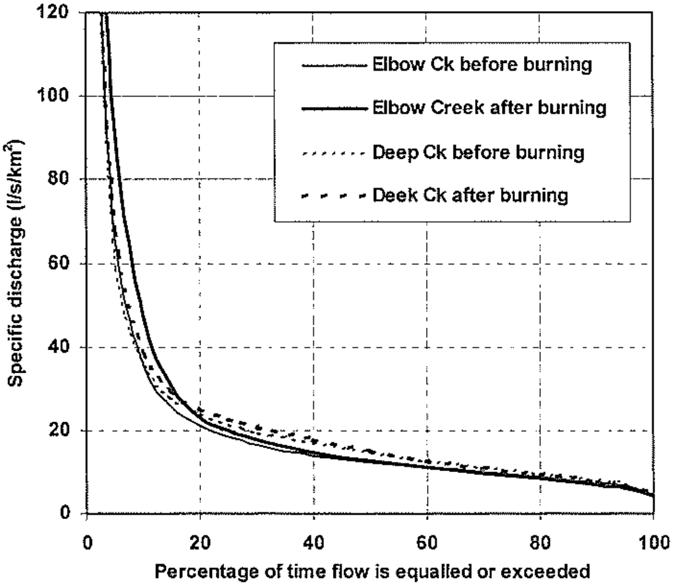


Figure 10 – Flow duration curves of summer (December to April) flows for Elbow Creek and Deep Creek before and after burning.

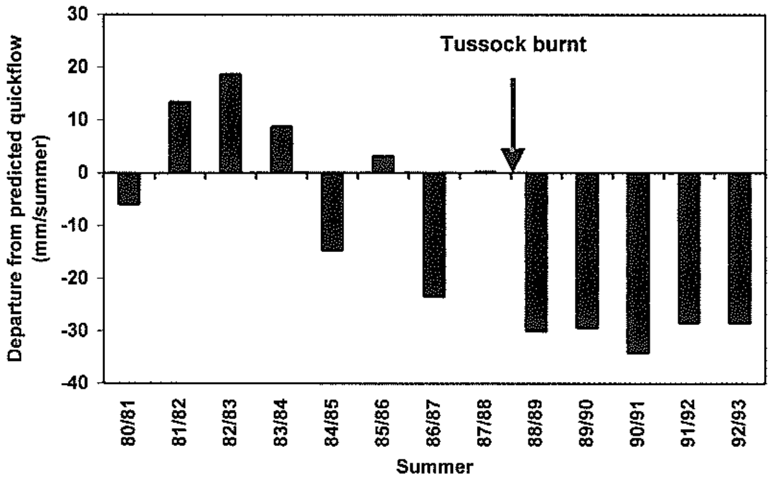


Figure 11 – The difference between measured and predicted summer quickflow.

from linear regression, was used to test for significant changes to summer quickflow. The slope of the regression line was close to one (1.07), indicating that the catchments responded similarly to quickflow-producing storms before Deep Creek was burnt. The regression coefficient of 0.97 indicates that the relationship is reliable. Figure 11 shows that following burning there was a reduced amount of quickflow from the burnt catchment; this reduction persisted for 5 years.

The base flow index for all summer flow data (0.63 and 0.70 for Elbow and Deep Creeks respectively) shows that quickflow was between 37 and 30% of total runoff. This

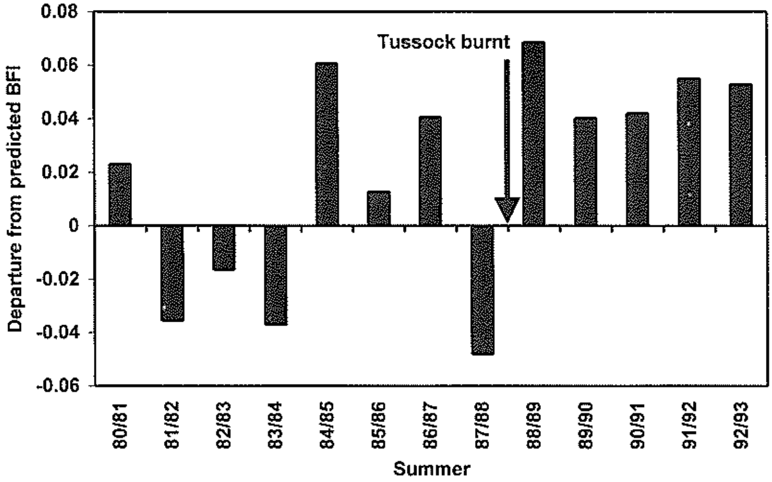


Figure 12 – The difference between measured and predicted base flow index (BFI).

value is similar to the 30% found by Pearce *et al.* (1984) and Fahey and Watson (1991) at the nearby Glendhu catchments. Figure 12 shows that after burning, the baseflow index of Deep Creek was consistently larger than it was before burning.

Storm peak flows and quickflows

The effect of burning Deep Creek on storm quickflows and associated peak flood flows was examined for two size classes of floods (Table 2). All storms producing more than 5 mm runoff were selected for analysis. Before and after burning, Deep Creek produced fewer small floods (5 to 9.9 mm runoff) than Elbow Creek, but the peaks and quickflow volumes from both catchments were similar.

Deep Creek produced more large floods (>10 l/s/ha), which were larger than those from Elbow Creek before Deep Creek was burnt, whereas after burning the two catchments produced an equal number of large flood peaks and the difference in size was smaller. Before Deep Creek was burnt it produced slightly fewer floods with more than 10 mm runoff than Elbow Creek, but they produced more runoff. After Deep Creek was burnt it produced relatively fewer large floods than Elbow Creek and they were similar in size to those before burning relative to those from Elbow Creek. None of the differences in average storm quickflow or average peak flow before and after burning, in any size class, are significant at the 5% level using a t-test.

Discussion

The hydrological behaviour of both catchments was similar before burning, although Deep Creek did have more runoff and produced more large floods with higher peak flows and discharge volumes than Elbow Creek. The burning of Deep Creek resulted in a reduction in summer runoff that persisted for at least three years and possibly longer. Analysis of the summer low flows and inspection of the summer flow-duration curves showed that low flows hardly changed. After burning there was a reduction in the amount of quickflow from Deep Creek. This was reflected in a reduction in the number of flood peaks and their size relative to those in Elbow Creek. While some of the changes in floods are small and not significant, their direction is consistent.

The expectation from the experiment was that burning of the tall tussock cover would reduce interception loss and reduce transpiration, leading to increased soil moisture, increased runoff, increased flood peaks and volumes, and higher and more persistent low flows. However, the opposite appears to have occurred, with a decrease in runoff, primarily from reductions in flows

Table 2 – Average storm peak flows and associated quickflows for Elbow and Deep Creeks in two storm size classes, before and after burning Deep Creek. The analysis was for all storms with more than 5 mm runoff. "n" is the number of floods in each size class and catchment.

Period	Size class (l/s/ha)	n	Peak flows Elbow Ck (l/s/ha)	n	Deep Ck (l/s/ha)	Size class (mm)	n	Quickflows Elbow Ck (mm)	n	Deep Ck (mm)
1980-88	5-9.9	66	4.3	45	4.1	5-9.9	36	6.3	21	7.2
	>10	4	13.7	6	19.1	>10	34	20	30	24.7
1988-93	5-9.9	48	4.3	34	4.3	5-9.9	21	7.3	15	7.2
	>10	3	11.7	3	15.5	>10	30	18.5	22	22.8

higher than the median flow. This appears to have occurred because the period of depleted cover was only a matter of months, as vigorous new tillers quickly emerged from the burnt tussock stumps (Fig. 4) and the canopy had recovered to a remarkable degree by the end of the summer (Fig. 5). This vigorous response to burning of narrow-leaved snow tussock has been previously observed by Payton and Brasch (1978), Payton and Mark (1979) and Payton *et al.* (1986), who report that the maximum growth of tussock tillers after fire occurs in years 1 and 2, and by year 3 growth rates are in decline. Rapid vegetative growth in many crops is associated with high transpiration rates and narrow-leaved snow tussock is unlikely to be different. Stimulation of flowering in the second year after burning was attributed by Mark (1965) and Rowley (1970) to the induction of floral primordia during the summer immediately after spring burning due to increased temperatures brought about by the blackened tussock crowns. The increased temperatures within the canopy may have also contributed to increased transpiration. Fire can remove litter and cause soil temperatures to rise during the day—this may promote higher soil evaporation rates, especially in the absence of the mulching effect of the litter, although bare ground was not evident in photographs taken immediately after burning (Fig. 3). Thus a large part of the interception capacity of the former cover was quickly regained, and we speculate that the new tillers had much higher transpiration rates than those in mature tussocks. The post-burn photographs confirm the recollections of staff that exotic grasses or other species were rare, so the apparent increased transpiration cannot be attributed to their higher transpiration rate. If the reduction in runoff was primarily an effect of increased transpiration, then maximum effect would be in Years 2 and 3, during the period of most rapid growth. During year one, when the tussock is recovering from burning and tillers were small and fewer in number, transpiration would be less than during years 2 and 3 when the tussocks have more tillers (Fig. 5). Growth, and hence transpiration, would slow as plants neared their mature height and density in year 4. This pattern is reflected in the changes to runoff found in Figure 7.

Possibly contributing to increased transpiration and interception rates after burning was the lack of dead tillers in the canopy, leading to a less shaded and less dense canopy. Meurk (1978), measured the phytomass and primary productivity of the tussock grasslands of Central Otago, including the study area, and noted that dead tillers and standing litter contributed about 69% of the total tiller weight of unmodified narrow-leaved snow tussock (Fig. 2) and that tillers had an average life span of about 3 years. Thus most of the tillers in the burnt catchment would have been alive post-burning and freely transpiring. The more open canopy would have allowed downward pulses of dry air easier access into the canopy and facilitated the displacement from within the canopy of air, moist from transpiration and evaporated intercepted water. The mean post-burning runoff reduction was 46 mm/summer. This amount spread over a 150-day summer is only 0.3 mm/day and amounts to an increase of about 10% of the 2.4 to 3.3 mm/day transpiration from mature snow tussock in mid-summer measured nearby by Campbell and Murray (1990).

The reduced runoff at higher flows is attributed to increased, more efficient, interception of rainfall and a greater soil moisture deficit, due to the higher transpiration and reduced net rainfall, that needed to be replenished before substantial flows could occur. The lack of change in low flows could be attributed to their source in the wetlands that made up the 20-30% of the catchment that was not burnt. However, Fahey *et al.* (1998) concluded, from study of a small headwater catchment at Glendhu, that low flows could not be sustained from the wetlands alone and unsaturated flow from adjacent hillsides was required to account for the observed outflow. Pearce *et al.* (1984) noted that delayed flow at the nearby Glendhu catchments appeared to be discharged from shallow unconfined groundwater. Bonell *et al.* (1990), also working at Glendhu, used isotopic analysis to show that recession flows were 'old' water derived from shallow groundwater. Bowden *et al.* (2001), in a comprehensive study of runoff generation in a small headwater catchment at Glendhu, confirmed much of the earlier hydrometric, soils and isotopic observations. Their work suggested that rainfall quickly saturates the surface soils of the hillslopes, after which quickflows are generated when further rainfall moves as interflow through the surface layer of mosses, litter and roots. Moisture appears to move slowly into the deeper mineral soil, but sufficient water moves there to sustain baseflow for long periods and supplements moisture in the wetlands that are too small to sustain low flows. These runoff mechanisms are consistent with the results of this study. The increased transpiration and more effective interception would result in the surface soils having a higher soil moisture deficit than would have occurred before burning. This deficit would have to be recharged before quickflows could be generated, thus reducing the relative size of floods. However, deeper moisture sources are probably out of the direct influence of vegetation. In the study catchments the seasonal snowmelt, regular rainfall and relatively low evaporative demand is likely to result in the deep soils and regolith being saturated at the start of summer and being replenished with moisture throughout the summer, leading to sustained low flows barely unchanged by the burning of the tussock.

In a study of land-use change in tussock grasslands, in which pasture was replacing tussock, Fahey and Jackson (1991) attributed reduced summer water yield to a lack of physiological controls on transpiration from pasture. In this study we believe that increased transpiration from the vigorous tiller growth may have been partly responsible for the reductions in water yield from the burnt catchment.

An alternative explanation for the flow reduction following burning could be the reduction in catch of fog precipitation due to the loss of tillers in the burn. If this were the case, the greatest effect would have been apparent in the summer immediately after the burn when there were fewer and smaller tillers, yet there appears to be a greater reduction in water yield in years 2 and 3. Fewer fog events in the 1988/89 summer compared with subsequent summers might explain this variability in reduction of water yield. However, if fog can augment water yield, this would most likely be seen by an increase in low flows and not in quickflows, as was the case here. Also Campbell and Murray (1990) and Fahey *et al.* (1996) have shown that precipitation of fog on snow tussock is a small proportion of total precipitation. Thus the explanation of reduction in fog catch must be discounted.

In this experiment stock were excluded after the burn, but this does not reflect typical management of burned tussock land. Under normal management, stock grazing would have maintained a lower tussock height, which would have increased the exposure of under-tussock plant species and soil, perhaps increasing drying of the soil and encouraging the growth of plants with different transpiration characteristics to snow tussock. The effects on flows of stocking after burning depend on the balance between the increased transpiration of exotic grasses and reduced transpiration and interception caused by stock grazing fresh tussock shoots after the burn. Stock would have also trampled wetlands and riparian areas. With repeated burning and continued stocking it is unlikely that the tendency towards restoration of the initial flow regime would have occurred, and characteristics of the flow regime of the second and third years after burning, with reduced overall water yield, would have persisted.

The grassland and water management implications of this study are that burning tall tussock grassland reduces water yield in the short term. It can be implied from this and other studies that if burning and grazing persist, then so will reductions in water yield. On the other hand, this study shows that if tall tussock cover is allowed to recover and returns to its former state, then water yields will tend to recover.

Acknowledgements

We thank Mr Arthur Borrell, retired of Queenstown, and formerly of the remote Branch Station in the Shotover River catchment, for his interest in tussock management, his dogged encouragement, and his financial support, without which the paper would not have been completed. Support was also received from FRST Contract C01X0304. Thanks also to the dedicated field staff of the Ministry of Works and Development for collecting the data, often in appalling conditions. Their reward would have been the beauty, tranquillity and the uplifting of spirit that comes from visiting such landscapes when the weather is kind.

We also thank the reviewers whose comments have improved the paper.

References

Bonell, M.; Pearce, A.J.; Stewart, M.K. 1990: The identification of runoff-production mechanisms using environmental isotopes in a tussock grassland catchment, Eastern Otago, New Zealand. *Hydrological Processes 4*: 15-34.

Bowden, W.B.; Fahey, B.D.; Ekanayake, J.; Murray, D.L. 2001: Hillslope and wetland hydrodynamics in tussock grassland, South Island, New Zealand. *Hydrological Processes 15*: 1717-1730.

Campbell, D.I. 1987: Evaporation, energy and water balance studies of narrow-leaved snow tussock in Otago, New Zealand. PhD thesis, Department of Geography, University of Otago, New Zealand.

Campbell, D.I. 1989: Energy balance and transpiration from tussock grassland in New Zealand. *Boundary Layer Meteorology 46*: 133-152.

Campbell, D.I.; Murray, D.L. 1990: Water balance of snow tussock grassland in New Zealand. *Journal of Hydrology 118*: 229-245.

Fahey, B.D.; Bowden, W.B.; Smith, J.; Murray, D.L. 1998: Hillslope-wetland hydrological linkages in the headwaters of a tussock grassland catchment at Glendhu, South Island New Zealand. In: Hydrology, Water Resources, and ecology of headwaters, Proceedings of the Headwater'98 Conference, Meran/Merano, Italy, IAHS Publication no. 248: 157-164.

Fahey, B.D.; Jackson, R.J. 1991: Effects of land-use change on water yields from Dunedin's water supply catchments. Abstracts of New Zealand Hydrological Society Symposium, Wellington. 6-8 November.

Fahey, B.D.; Murray, D.L.; Jackson, R.M. 1996: Detecting fog deposition to tussock by lysimetry at Swampy Summit, near Dunedin, New Zealand. *Journal of Hydrology (New Zealand) 35(1)*: 87-104.

Fahey, B.D.; Watson A.J. 1991. Hydrological impacts of converting tussock grassland to pine plantation, Otago, New Zealand. *Journal of Hydrology (New Zealand) 30*: 1-15.

Hewlett, J.D.; Hibbert A.R. 1967: Factors affecting the response of small watersheds to precipitation in humid areas. In: Sopper, W.E. and Lull, H.W. (*eds.*) *Forest Hydrology*, Permagon: 275-290.

Mark, A.F. 1965: Effects of management practices on narrow-leaved snow tussock, *Chionochloa rigida. New Zealand Journal of Botany 3*: 300-319.

Mark, A.F.; Rowley, J.; Holdsworth, D.K. 1980: Water yield from high-altitude snow tussock grassland in central Otago. *Tussock Grasslands and Mountain Lands Institute Review*: 3821-33.

McKellar, I.C. 1966: Geological map of New Zealand 1:250,000 Sheet 25, DSIR, Lower Hutt, New Zealand.

Meurk, C.D. 1978: Alpine phytomass and primary productivity in Central Otago, New Zealand. *New Zealand Journal of Ecology 1*: 27-50

Murray, D.I.; Jackson, R.M.; Fahey, B.D. 1990: Tall tussocks and water yield. In: Kearsley, G. and Fitzharris, B. (*eds.*) *Southern landscapes: Essays in Honour of Bill Brockie and Ray Hargreaves*. Department of Geography, University of Otago: 181-197.

New Zealand Soil Bureau 1968: General Survey of the Soils of South Island, New Zealand. Soil Bureau Bulletin 27. New Zealand Department of Scientific and Industrial Research, Wellington.

Payton, I.J.; Brasch, D.J 1978: Growth and non-structural carbohydrate reserves in *Chionochloa rigida* and *C. macra* and their short-term response to fire. *New Zealand Journal of Botany 16*: 435-460.

Payton, I.J.; Lee, W.G.; Dolby, R.; Mark, A.F. 1986: Nutrient concentrations in tussock (*Chionochloa rigida*) after spring burning. *New Zealand Journal of Botany 24*: 529-537.

Payton, I.J.; Mark, A.F. 1979: Long-term effects of burning on growth, flowering, and carbohydrate reserves in narrow-leaved snow tussock (*Chionochloa rigida*). *New Zealand Journal of Botany 17*: 43-54.

Pearce, A.J.; Rowe, L.K.; O'Loughlin, C.L. 1984: Hydrology of mid-altitude tussock grasslands, upper Waipori catchment: II – water balance, flow duration, and storm runoff. *Journal of Hydrology (New Zealand) 23*: 60-72.

Rowley, J. 1970: Effects of burning and clipping on temperature, growth and flowering of narrow-leaved snow tussock. *New Zealand Journal of Botany 8*: 264-82.

Manuscript received 24 August 2004; revised; accepted for publication 11 October 2004