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The application of a water balance model to assess the role of fog in water yields from catchments in the east Otago uplands, South Island, New Zealand

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Abstract

The degree to which fog interception can augment water yields from snow tussock grasslands in the uplands of east Otago has been debated for over 40 years. Initially, the discussion centred on conflicting results from lysimetry-based studies. More recently, results from a stable isotope analysis suggest that fog and rain may contribute to the soil and groundwater stores in approximately equal proportions, raising the possibility that fog deposition may add as much to stream discharge as rainfall. To test this notion, we compare the mean annual water yield measured from five catchments in the east Otago uplands ranging in size from 1.2 to 60 km^2 (Glendhu, Elbow Creek, Deep Creek at Muster Huts, Deep Creek, and Upper Deep Stream) with predicted water yield using the WATYIELD water balance model. Because the model makes no allowance for fog input in its water balance calculations, our hypothesis is that any excess in measured over modelled water yield may at the outset be assigned to fog. Deep Creek and Upper Deep Stream were the only catchments to show any excess. For Deep Creek the excess averaged 30 mm a year, which is less than the error with which the average annual water yield of 836 mm is measured for this catchment. At Upper Deep Stream the excess averaged 230 mm per year over a 7-year period, which is approximately 15% of the catchment area rainfall. However, not all of this can be automatically attributed to extra input from unmeasured fog. Rain gauge under-catching, and suppressed transpiration, may also explain some of this difference. Thus, while fog, under some circumstances, may be capable of contributing to annual water yield at the catchment scale, it is not doing so in approximately equal proportions with respect to rainfall in the examined catchments.

Keywords

Fog interception, water balance, water yield hydrological models

Introduction

The debate over the role of fog interception in sustaining water yields from catchments with an extensive cover of snow tussock grassland in the uplands of east Otago has been ongoing for over 40 years. Mark and Rowley (1969, 1976) used small non-weighing lysimeters to measure the water balance of five cover types over a 6-year period on the Rock and Pillar Range. They found that those containing snow tussocks had substantially higher water yields (63% of the mean annual precipitation of 1348 mm) than those with blue tussock (49%) or bare soil (56%). They concluded that high water yield from snow tussock grassland could be explained by a combination of low transpiration and interception gains from fog.

Mark and Rowley's (1969) study was extended to two more sites on the Rock and Pillar Range, and four on the upper slopes of the Lammerlaw Range by Holdsworth and Mark (1990). Over a 2-year period (March 1977 to February 1979), lysimeters containing snow tussock plants at a site on the south-west-facing flank of the Lammerlaws generated the highest water yields (91 mm per month or 80% of rainfall), whereas one to the north yielded only 36 mm per month (26% of rainfall). Mean water yields from the various treatments showed that those from snow tussock grassland were all significantly greater than those from blue tussock and from bare soil. This led them to conclude that a cover of unmodified snow tussock will produce significantly greater water yields than a short cover of blue tussock or even bare soil. They attributed this situation to a combination of low transpiration rates by tussocks and a high incidence of fog, but they regarded the latter as the most important factor.

Campbell and Murray (1990) used a large weighing lysimeter to measure the water balance of snow tussock grassland as part of an ongoing study in the Glendhu experimental catchments in the Waipori Basin, east Otago uplands. They found that gains from fog interception contributed no more than 1% to water input, and attributed the high water yields from this cover type to low transpiration. However, they did not rule out the possibility that fog could be a more important component of the water balance at locations with a higher incidence of fog. The weighing lysimeter was subsequently moved, with its soil monolith intact, to a more fog-prone site on Swampy Summit near Dunedin, but the results showed that over a 3-year period, total fog measured by the lysimeter added less than 2% to the measured rainfall (Fahey *et al.*, 1996).

Ingraham and Mark (2000) adopted an alternative approach to assessing the importance of fog in the water balance. Because fog has a higher proportion of the heavy stable isotopes of hydrogen and oxygen than rain, they proposed that their concentrations (i.e., δD and $\delta^{18}O$) could be used to trace the movement of fog into groundwater. They collected rain and fog at three sites in the east Otago uplands, and sampled soil drainage from two of these, and stream water from the third. They found that water from fog was more enriched than rain water, whereas the isotopic composition of soil and stream water fell between those of fog and rain. They interpreted this result as showing that sub-surface water must be a mixture of fog and rain in what they termed 'sub-equal' proportions, from which they concluded that fog interception by snow tussock grassland has the potential to make a substantial contribution to water yield.

Davie *et al.* (2006) reviewed and discussed the relative importance of the two mechanisms thought to be responsible for sustaining high water yields from snow tussock grasslands in upland east Otago (low evaporation rate and fog interception). They highlighted the difficulties associated with interpreting the results of water balance investigation using lysimeters and in using isotopic chemistry to assign hydrological mechanisms. They offered other explanations to account for Ingraham and Mark's (2000) conclusion that sub-surface water may contain sub-equal proportions of fog and rain. These include the possibility that the isotope ratio has been enriched through exchange and evaporation (Stewart *et al.,* 1975), and that water resided in the soil profile for longer than the rainfall collection period, making it likely that the soil water in the lysimeter was recharged before the rain and fog was collected.

Ingraham *et al.* (2008) defend their interpretation of the isotopic signatures in fog, rain, and sub-surface water, and their conclusion that fog must be a major contributor to water yield from snow tussock grasslands in the east Otago uplands. They asserted that the use of stable isotope analysis of the relevant components of the water balance provides a more critical and thorough approach to assessing the role of fog than lysimetry, and reiterated that the sub-surface water at their three sites was derived from fog and rain in approximately equal proportions.

Apart from a short discussion in Davie *et al.* (2006) and a comparison of data from lysimeters and catchments in the southern Lammermoor Range by Mark (1998), no attempt has been made to establish whether there is any evidence to indicate that fog interception by tussock is actually contributing to water yield at the catchment scale. One way of addressing this issue is through the use of hydrological models that predict catchment runoff on the basis of water balance calculations. According to Beven (1989) one of the aims of simulation models is to explore the implications of making certain assumptions about the nature of the real-world system. If we treat a model as a mathematical representation of our hydrological understanding for a catchment, then a comparison of simulated versus measured flows gives us some idea of the reality of our understanding. None of the readily available and widely used hydrological models make allowances for fog deposition in their calculations. Therefore they assume it is not an important mechanism. We hypothesize that if rainfall and fog are contributing to stream discharge in sub-equal proportions in the east Otago uplands, then any modelled predictions based on the rainfall alone should

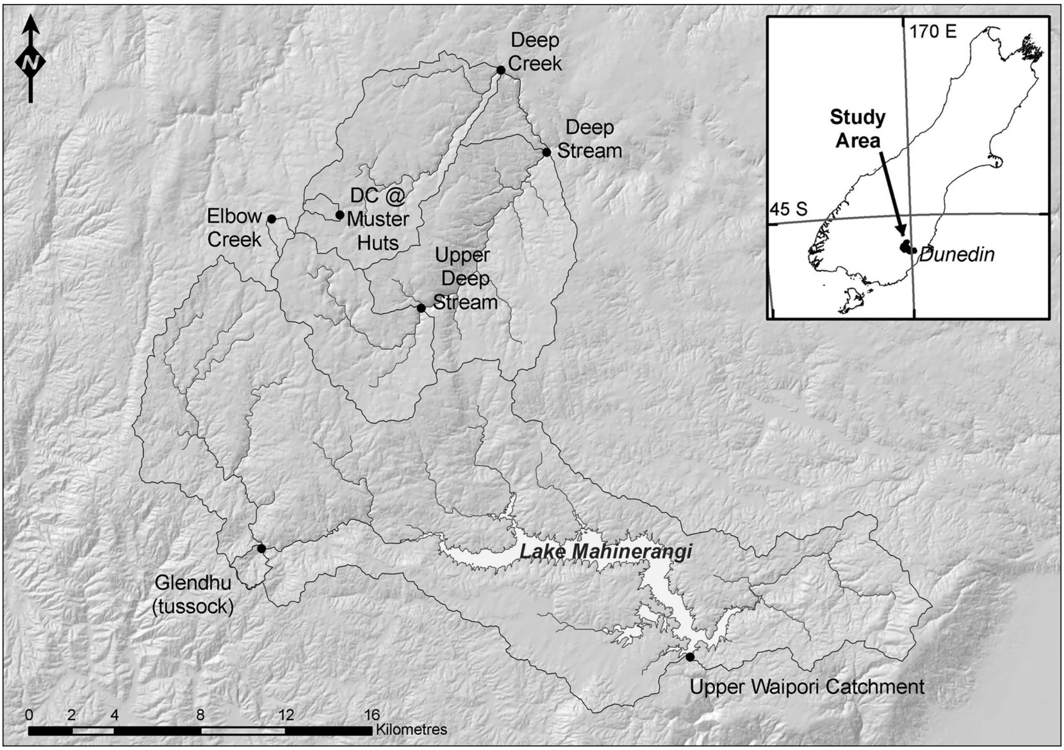

Figure 1 – Map and location of catchments used in the study.

underestimate actual water yields by as much as 50%.

In this paper we use the WATYIELD model, which was developed in New Zealand for use in situations where there is a limited amount of data on climate, soil, and vegetation cover (Fahey *et al.*, 2004, 2010). WATYIELD is a water balance model that requires the calculation of the soil water balance from a daily rainfall time series and an estimate of evapotranspiration for the site. The model has been recently calibrated, validated, and tested against flow data from one of the Glendhu experimental catchments (GH1 in tussock) located in the upper Waipori river basin in upland east Otago (Fig. 1). Fahey *et al.* (2010) reported on its ability to predict annual water yields to within ±5% of measured values from catchments with a variety of land covers, and at a range of spatial scales in New Zealand.

Model description and application

The WATYIELD model permits a catchment to be divided into a maximum of 10 sub-areas based on features that distinguish those areas and are likely to influence water yield, e.g., cover type, soil characteristics, and rainfall. The minimum data requirements are daily rainfall totals from a local rainfall station, and average monthly reference evapotranspiration from a climate station. This is equivalent to potential evaporation for an extensive surface of short grass under well-watered conditions (Allen *et al.*, 1998). The same daily rainfall series is used for all sub-areas. However, the daily rainfall series can be scaled up or down for each sub-area, if additional rainfall information justifies this. Likewise, different reference evapotranspiration totals can be assigned to one or more sub-areas.

Spatial representation in WATYIELD is at the whole catchment scale. Thus, as the scale increases, any underlying assumptions about spatial uniformity may begin to break down. To circumvent this problem, individual water yields can be calculated for selected areas, which can then be summed or weighted to estimate the total catchment water yield.

Statistical measures of goodness-of-fit were used to calibrate the model and to identify the most sensitive model parameters (Fahey *et al.*, 2010). Each input parameter was changed over a specified range (up to 50%) while other parameters were kept constant The most important parameters in order of decreasing sensitivity were: the interception fraction (the proportion of rainfall lost through interception); the crop coefficient (a value that converts the reference evapotranspiration to a loss equivalent to transpiration for the cover type); the recession coefficient, which defines the rate of base-flow recession from the base-flow store; and the base-flow index (the proportion of total flow that appears as base flow). Changes in total available and readily available soil water showed only small changes in model efficiency.

For testing the model against measured discharge from the tussock catchment at Glendhu (2.18 km^2, elevation 460-650 m) the following input parameters were chosen: an interception fraction of 0.2 (based on measurements made by Campbell and Murray (1990)), a crop coefficient of 0.3 (based again on water balance calculations by Campbell and Murray (1990)), a recession coefficient of 0.98 (calculated according to the procedure described by Martin (1973)), and a base-flow index of 0.65 (calculated from the flow record using a separation procedure described by Hewlett and Hibbert (1967)). The estimated reference evapotranspiration for Glendhu is 656 mm (Fahey *et al.*, 2010). More background on these parameters and their derivation is provided by Fahey *et al.* (2004, 2010). The model output was then compared against the daily flow record available for the tussock catchment at Glendhu for the period 1980-2007. The measured average annual water yield was 828 mm whereas the modelled value was 866 mm, a difference of 38 mm (5% of the measured discharge), which is about the accuracy with which annual discharge can be measured at the 120° V-notch weir (Pearce *et al.*, 1984).

Application of WATYIELD to fog-prone catchments

No long-term measurements of fog frequency or duration are available for upland east Otago, but it is expected that the incidence of fog will increase with elevation. Thus, the next step was to apply the model to nearby catchments with a snow tussock grassland cover that are at a higher elevation than Glendhu, in order to see whether WATYIELD underestimates actual water yield, and if so whether any excess could be attributable to fog deposition. Four catchments were selected: Elbow Creek, Deep Creek at Muster Huts, Deep Creek, and Upper Deep Stream (Fig. 1; Table 1)

Elbow Creek and Deep Creek at Muster Huts

Duncan and Thomas (2004) analysed flow data from two small catchments located approximately 15 km north of Glendhu (Fig. 1), Elbow Creek (1.24 km^2) and Deep Creek at Muster Huts (1.54 km^2), to investigate the hydrological importance of fire as a land management option. Deep Creek at Muster Huts should not be confused with the much larger Deep Creek, of which it is a tributary (Fig. 1). Discharge at both catchments was measured to an accuracy of ±3% with sharp-crested 120° V-notch weirs. The tussock grassland cover at Elbow Creek was retained without change as the control, and Deep Creek at Muster Huts was subject to burning as the treated counterpart. The catchments are located within 3 km of each other on opposite sides of the Lammermoor Range divide (Fig. 1). They range in elevation from 900 to 1100 m, and are thus well within the altitudinal zone where fog is thought to be common.

There are marked environmental similarities between Glendhu and these two catchments. They have a comparable geology, and are both characterised by headwater and riparian wetlands. The rainfall regime is also similar, consisting of many small events of long duration and low intensity. In addition Waugh (2005), based on a comparison of flow duration curves, concluded that all three catchments have similar flow characteristics.

Table 1 – Summary of catchment information. Details on the tussock catchment at Glendhu have been added for comparison.

Catchment	Area (km^2)	Orientation	Elev. range (m)	Geology	Main soils [a]	Predom. vegetation [b]	Precip. (mm y^{-1})	Potential evapotrans. (mm y^{-1})
Glendhu Tussock	2.18	NNE	460-650	Schist	Acid brown	Tall tussock grassland	1350	650
Elbow Creek	1.24	NW	900-1100	Schist	Acid brown	Tall tussock grassland	1100	500
Deep Crk at MH	1.54	E	950-1120	Schist	Acid brown	Tall tussock grassland	1100	500
Deep Creek	60	NNE	700-1150	Schist	Acid brown	Tall tussock grassland	900-1500	490-530
Upper Deep Stream	40	SE	750-1150	Schist	Acid brown	Tall tussock grassland	1300-1600	490-530

[a] Based on information obtained from the National Soil Database and the New Zealand Soil Classification (Hewitt, 2010);
[b] based on information obtained from the Land Cover Database (LCDB2).

Elbow Creek and Deep Creek at Muster Huts, however, have much more snowfall that makes access difficult, and precipitation and discharge measurements unreliable in the winter. Snow tussock (*Chionochloa rigida*) is the dominant cover in both cases. Soils are thinner than at Glendhu, but they display similar textural properties (silt and stony loams).

The WATYIELD model was used to predict water yields from Elbow Creek (the control catchment), and Deep Creek at Muster Huts up to the time the tussock cover was burnt, and the results were compared with the measured flows listed by Duncan and Thomas (2004). In the modelling exercise, the same interception factor (0.2) and crop coefficient (0.3) listed for Glendhu were used at Elbow Creek and Deep Creek at Muster Huts. The recession coefficient was calculated as 0.96 (Martin, 1973) and the base-flow index was set at 0.65 for Elbow Creek and 0.70 for Deep Creek at Muster Huts (Duncan and Thomas, 2004). Brash and Murray (1980) used the Priestly-Taylor equation to calculate the actual evapotranspiration for the Taieri catchment which includes Deep Creek and Deep Stream. This has been adjusted to provide an estimate of the potential or reference evapotranspiration for Elbow Creek and Deep Creek at Muster Huts (500 mm per annum). Actual and potential evapotranspiration are assumed to decrease with elevation in the study area, in accordance with the increased incidence of cloud and fog. This assumption is supported by the observed decrease in potential evapotranspiration from Dunedin airport at sea level 100 km to the east and Lake Mahinerangi at 396 m elevation (New Zealand Meteorological Service, 1986; R. Jackson, pers. comm.)

Table 2 – Measured rainfall and water yield for Elbow Creek and Deep Creek at Muster Huts for the summer months (November to April) of 1980/81 to 1991/92 and 1980/81 to 1987/88 respectively (data from Duncan and Thomas, 2004), and the predicted water yield for both using WATYIELD. The rainfall and water yield record for the tussock catchment at Glendhu is included for comparison.

Summer	Rainfall (mm)			Measured water yield (mm)			Modelled water yield (mm)		
	Elbow Crk	Deep Crk	Glendhu	Elbow Crk	Deep Crk	Glendhu	Elbow Crk	Deep Crk	Glendhu
80/81	547	576	562	262	274	319	331	346	300
81/82	494	537	530	251	278	268	347	338	301
82/83	886	940	1000	614	710	517	724	707	711
83/84	410	453	745	368	424	470	371	369	471
84/85	488	430	534	229	218	232	309	221	309
85/86	801	736	654	418	472	282	508	486	340
86/87	867	798	968	486	516	557	618	501	561
87/88	592	597	695	360	372	369	449	379	411
88/89	642	*	722	318	*	347	441	*	424
89/90	576	*	611	296	*	278	376	*	313
90/91	864	*	721	399	*	384	371	*	394
91/92	732	*	672	446	*	403	463	*	385
Mean	**658**	**633**	**701**	**371**	**408**	**368**	**442**	**418**	**410**

Flow data supplied by the National Institute for Water and Atmospheric Research for 12 consecutive summers (1980/81 to 1991/92) were used in the modelling exercise for Elbow Creek. The rainfall record for 1992/93 and 1993/94 is incomplete, and these years have been excluded from the analysis. For Deep Creek at Muster Huts, eight consecutive summers of rainfall and flow data (November-April) were available up to the time of treatment (September 1988). To avoid any initialisation errors associated with the application of the model to a situation involving only part of a year, the daily rainfall record for the whole year was included in the model run for estimating summer water yield at both catchments. Some gaps in the record outside of the November-April period were filled (without adjustment) with rainfall data from Glendhu.

Over the period of record for Elbow Creek, measured summer water yield averaged 371 mm while the modelled values averaged 442 mm (Table 2). For Deep Creek at Muster Huts the average measured value for the pre-treatment period was 408 mm, and the average modelled value was 418 mm.

Deep Creek

Deep Creek (60 km^2) (Fig. 1) flows into Deep Stream and these two catchments supply almost 50% of the average daily water used by the city of Dunedin. Much of the original tussock cover survives in the headwaters, but downstream, large tracts have been modified by burning, oversowing, and grazing. Landcare Research conducted a survey in the two catchments for the Dunedin City Council to map and assess the condition of the tussock cover in the catchments above the pipeline intakes (Fahey *et al.*, 1991). The degree of tussock cover depletion (nil to severe) and vigour of growth based on tiller length (very poor to strong) was identified and mapped in both catchments, based on field observations and air photo interpretation. Five mapped units representing various combinations of tussock depletion and vigour were identified for the Deep Creek catchment above the pipeline intake. They ranged from severe depletion and very poor vigour to nil depletion and strong vigour.

Daily flow data for the catchment collected from a broad-crested weir at the pipeline intake (DCC Site No.7440), originally used in the preparation of reports for the Dunedin City Council (Fahey, 1996), were available for the period 1989-1995. The quality of the flow record is estimated at ±5% (McKerchar, 1994). The average daily pipeline abstraction (100 L s^{-1}) was added to the daily flow. The input data for the model are listed in Table 3. Precipitation data are available for the Upper Deep Creek catchment for the period (Fahey, 1996) but the daily record is incomplete, and close to half the precipitation falls as snow (Duncan and Thomas, 2004). Thus it was decided to use the daily rainfall record at Glendhu (mean annual total for the period 1989-1995 of 1291 mm) as input for the model.

As a check on the validity of this decision, the Glendhu rainfall totals for the summers of 1980/81 to 1991/92 were compared with those for Elbow Creek (Table 1). If we omit the data for 1983/84, summer rainfall totals at Elbow Creek are only 2% below those recorded at Glendhu, suggesting that the rainfall record for Glendhu can be safely used in the modelling exercise as a proxy for that at Elbow Creek (Table 1). It was weighted according to average annual rainfall isohyets mapped for the Taieri catchment water resources inventory (Otago Catchment Board, 1983). These data show a marked reduction in rainfall from the headwaters of Deep Creek (≈1600 mm) to the weir (≈1000 mm). Similarly, the Glendhu reference evapotranspiration (656 mm) was adjusted on the basis of data in Brash and Murray (1980) to take into account the higher elevation range

Table 3 – Information on mapped units identified in Deep Creek, including condition of tussock cover, annual rainfall, annual reference evapotranspiration, and model input parameters (interception fraction and crop coefficient), for calculating the mean annual water yield using WATYIELD over the 7-year period 1989-1995.

Mapped unit	Tussock depletion	Tussock vigour	Area (km²)	Prop. of total area	Precip. wghting factor[a]	Precip.[a] (mm)	Interc. fraction	Ref. evap.[b] (mm)	Crop coeff.	Modelled water yield (mm)
1	Slight	V. poor	14.7	0.24	1.15	1500	0.10	490	0.7	970
2	Slight	Strong	9.3	0.16	1.1	1400	0.20	510	0.3	971
3	Nil	Strong	5.4	0.09	1.0	1300	0.20	520	0.3	860
4	Slight	Poor-med.	23.7	0.39	0.8	1025	0.15	530	0.3	711
5	Mod.-sev.	Poor	7.0	0.12	0.7	900	0.05	530	0.7	514
Catchment			**60.0**		**0.95**	**1209**[c]	**0.14**[c]	**518**[c]	**0.45**[c]	**806**

[a] Mean annual totals for each unit estimated from isohyetal data (Otago Catchment Board, 1983);
[b] based on data in Brash and Murray (1980); [c] values weighted according to proportion of area of each mapped unit.

of the Deep Creek catchment (700-1150 m) compared with Glendhu (460-650 m). Soils and bedrock are comparable to those already described for Glendhu (predominantly sandy and silt loams and schist respectively). The base-flow index used for Glendhu (0.65) was retained for Deep Creek. The recession coefficient (0.96) was estimated from the daily flow record following the procedure based on Martin (1973) described above.

Given the size of the catchment, water yields were calculated for each of the five mapped units and their input weighted and summed to produce an overall yield (Table 3). This approach takes advantage of the specific information available for each unit, thus ensuring that the characteristics likely to affect water yields from the various units are taken into consideration in the water balance calculations. This is particularly important when accounting for the strong south-to-north rainfall gradient observed for the Deep Creek catchment. Table 4 lists the measured and modelled values for the period 1989-1995 for Deep Creek. The estimated mean annual water yield for Deep Creek above the pipeline intake is 806 mm, and the measured value is 836 mm, a difference of 30 mm.

Table 4 – Measured and modelled annual water yields for Deep Creek and Upper Deep Stream, 1989-1995.

	Deep Creek (mm)		Upper Deep Stream (mm)	
Year	Measured	Modelled	Measured	Modelled
1989	532	604	1044	941
1990	664	599	1052	796
1991	858	863	1418	1130
1992	1025	921	1533	1206
1993	869	857	1291	1125
1994	978	886	1486	1160
1995	924	912	1310	1169
Mean	**836**	**806**	**1305**	**1075**

Upper Deep Stream

Flow data from reports prepared by Landcare Research for the Dunedin City Council (Fahey, 1996) are also available for Deep Stream immediately above the point where water is diverted into Lake Mahinerangi, referred to here as Upper Deep Stream (40 km²; elevation range 750-1150 m) (Fig. 1). According to the information supplied by the Otago Regional Council, flow for Deep Stream above the diversion is calculated from the flow record at the point of diversion into

Table 5 – Information on mapped units identified in Deep Stream above the Mahinerangi diversion, including condition of tussock cover, annual rainfall, annual reference evapotranspiration, and model input parameters (interception fraction and crop coefficient), for calculating the mean annual water yield using WATYIELD over the 7-year period 1989-1995.

Mapped unit	Tussock depletion	Tussock Vigour	Area (km^2)	Prop. total area	Precip. wghting factor	Precip.[a] (mm)	Interc. fraction	Ref. evap. (mm)[b].	Crop coeff.	Est. water yield (mm)
1	Severe	V. poor	12.5	0.31	1.2	1580	0.05	490	0.8	1020
2	Slight	Poor-med.	10.3	0.26	1.1	1420	0.15	530	0.3	1051
3	Slight-mod.	Poor-med.	14.5	0.36	1.2	1550	0.10	510	0.5	1142
4	Slight	V. poor	0.3	0.07	1.0	1300	0.15	520	0.4	894
Catchment			**40.2**		**1.13**	**1510**[c]	**0.11**[c]	**506**[c]	**0.53**[c]	**1075**

[a] Mean annual totals for each unit estimated from isohyetal data (Otago Catchment Board, 1983);
[b] based on data in Brash and Murray (1980);
[c] values weighted according to proportion of area of each mapped unit.

the Mahinerangi race (DCC Site 7444) plus flow over the main weir, but the accuracy of the discharge calculations is unknown (M. Simpson pers. comm.).

A total of four mapped units defining the degree of depletion and vigour of the tussock cover were identified for the area above the diversion point (Table 5). Water yields were calculated for each of these units and the weighted values summed to provide annual water yields for the whole catchment. Input data used in the modelling exercise are listed in Table 5. The daily rainfall totals for Glendhu were again used as the basis for the rainfall input to each mapped unit, and weighted according to available isohyetal information (Otago Catchment Board, 1983). The Glendhu reference evapotranspiration was used, but adjusted downwards to account for the higher elevation of the Deep Stream catchment on the basis of mapped evapotranspiration (Brash and Murray, 1980). Values for the interception fraction and the crop coefficient were assigned to each mapped unit according to the state of the tussock cover (Table 5). The same base-flow index and recession constant used in modelling flow from Deep Creek were used for Upper Deep Stream (0.65 and 0.96 respectively). The annual measured and modelled water yields for Upper Deep Stream are listed in Table 4. The modelled annual water yield for the 7-year period was 1075 mm, whereas the measured value was 1305 mm, a difference of 230 mm.

Discussion

The annual water balances for the five catchments considered in this study are summarised in Table 6 and Figure 2. Table 6 also includes an estimate of the extent to which fog may be contributing to the water yield, calculated as the difference between measured and modelled water yield. Table 6 and Figure 2 show a close match between the measured and modelled values except at Upper Deep Stream, where the model under-predicts the amount of water yield. It is possible that this under-prediction is due to the model not accounting for fog deposition.

The lack of any apparent contribution from fog deposition to the water yield from Elbow Creek and Deep Creek at Muster Huts is contrary to the views of Ingraham *et al.* (2008). They refer to a study conducted

Table 6 – Summary of the annual water balances for the five catchments in the east Otago uplands for which detailed information on stream discharge is available. Estimated water yield using the WATYIELD model is also listed, together with the potential contribution of fog to the water yield (measured minus modelled water yield). Note that for Elbow Creek and Deep Creek at Muster Huts, data are for 6 months only (November-April).

Catchment	Area (km^2)	Data period	Mapped units	Precip. (mm)	Intercept. (mm)	Trans.[b] (mm)	Measured water yield (mm)	Modelled water yield (mm)	Potential fog input (mm)
Glendhu Tussock	2.18	1980-2006	1	1326[a]	265[a]	233	828 (±40)[e]	865	0
Elbow Creek	1.24	1980/81-1991/92	1	658[a]	132[c]	155	371 (±10)	442	0
Deep Crk @ MH	1.54	1980/81-1987-88	1	633[a]	127[c]	98	408 (±10)	419	0
Deep Creek	60	1989-1995	5	1209[d]	169[d]	204	836 (±40)	806	30
Upper Deep Stream	40	1989-1995	4	1510[d]	166[d]	30	1305 (±130)	1075	230

[a] Measured;
[b] calculated as a residual;
[c] based on measurements at Glendhu;
[d] weighted value.
[e] Apart from Upper Deep Stream (see text) error estimates are based on the reported accuracy with which stream discharge is measured at the respective weirs.

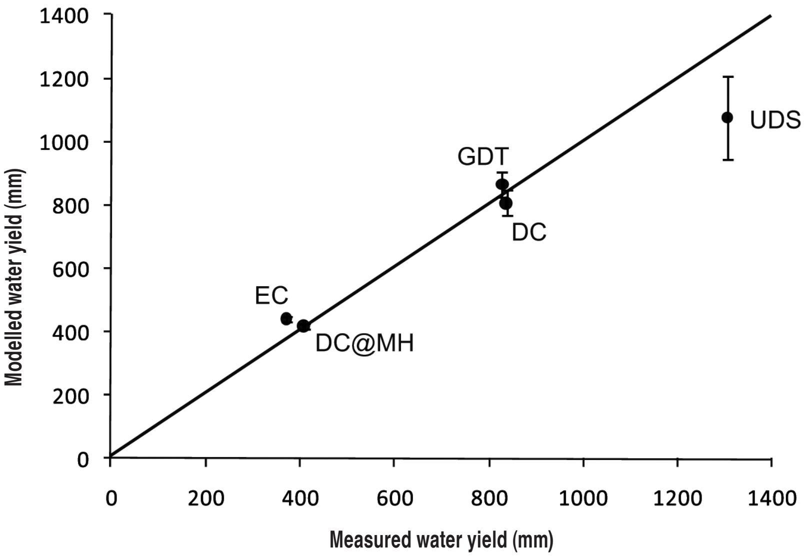

Figure 2 – Measured versus modelled water yield for the catchments listed in Table 6: Glendhu Tussock (GDT), Elbow Creek (EC), Deep Creek at Muster Huts (DC@ MH), Deep Creek (DC), Upper Deep Stream (UDS). The line is 1:1 rather than fitted. Error bars were calculated using information from Table 6.

by Mark (1998) close to Elbow Creek in which water yield was measured from simulated snow tussock, comprising silicon-coated snow tussock tillers mounted in the orifice of a recording rain gauge. Based on measurements from this gauge, and some supporting micrometeorological data, Mark (1998) concluded that fog deposition had the potential to contribute 166 mm to a unit area of snow tussock grassland over a 6-month snow-free period (November-April). This represents a 22% addition to the measured rainfall of 755 mm (averaged over 4 years), and implies that the combined summer precipitation input from rain, snow, and fog, at the site where his simulated snow tussock experiment was undertaken, could be as much as 900 mm.

For the same two summers used by Mark (1998) in his analysis of fog interception by simulated tussock, Elbow Creek recorded rainfall of 642 mm and 576 mm, and water yields of 318 mm and 296 mm respectively (Table 2), leaving an average of 300 mm in each summer to be partitioned between interception loss and transpiration. If we assume the interception loss to be 20% of gross precipitation (121 mm), this leaves approximately 170 mm to be lost through transpiration, which is not unreasonable. Thus the evidence from Elbow Creek and Deep Creek at Muster Huts is that there is no significant interception gain from fog deposition contributing to runoff at the catchment scale.

Table 6 shows, based on the difference between measured and modelled water yield, that fog may be contributing an extra 30 mm (or 4%) to the water yield of Deep Creek. However, this must be viewed in the context of the accuracy with which runoff is measured for this catchment, which is thought to be no better than ±40 mm.

For Upper Deep Stream, the difference between measured and predicted water yield is substantial (230 mm). However, not all of this can be automatically assigned to fog deposition. Firstly, given the nature of the rainfall regime (many events of low to moderate intensity), the rainfall totals used for preparing the isohyetal maps upon which the WATYIELD rainfall input is based may suffer from gauge under-catching. Indeed, turbulence around the orifice can cause gauges to under-catch by as much as 15% (Rasmussen and Halgreen, 1978; Allerup and Madsen, 1980). The effect is greatest for snow and small raindrop sizes (Rodda, 1967) and increases with wind speed (Dreaver and Hutchinson, 1974). This could be a factor with all the catchments discussed above, but it would be particularly crucial for Upper Deep Stream because of its exposure to wind and rain from the south-west. Secondly, we have already commented on the likelihood of inaccuracies in calculating the discharge for Upper Deep Stream at the point where water is diverted into Lake Mahinerangi. In Table 6, we have assumed the error to be ±10% (130 mm), but we concede that this is nothing more than an educated guess.

Part of the considerable difference between measured and predicted water yield for Upper Deep Stream may also be explained by low transpiration from the tussock cover (Davie *et al.*, 2006). It is unlikely that transpiration from the tussock grassland cover in Upper Deep Stream would be lowered to the extent required to make up the balance between precipitation and measured discharge (30 mm in Table 6), but it could account for some of the 230 mm difference. For example, the ratio of intercepted rainfall to transpiration in the water balance calculations for all catchments other than Upper Deep Stream is approximately 1-to-1 (Table 6). If we assume that losses from transpiration and intercepted rainfall occur in approximately equal amounts from Upper Deep Stream and re-calculate the water balance, an excess of about 130 mm is left to be assigned to input from fog (9% of the estimated catchment area rainfall).

If the interpretation of the isotopic data in Ingraham *et al.* (2008) were correct, that there is a substantial contribution by fog to the soil water store, there is still little evidence in the water balance data to suggest that this water eventually ends up as part of the catchment water yield (apart from, possibly, at Upper Deep Stream). This interpretation is implicit in the comparison made by Mark (1998) of lysimeter and catchment water yields in Elbow Creek and Deep Creek at Muster Huts. Over a 4-year period (1988-1991), data from pairs of non-weighing lysimeters containing snow tussocks showed that 92% of the rainfall was being converted to water yield, whereas the catchment data for the same four summers at Elbow Creek showed only 52% of the summer rainfall appearing as discharge (Table 2). Coincidentally, over the same four summers at Glendhu, where fog is rare, the percentage of rainfall converted to discharge was also 52% (Table 2).

There is general agreement that streams draining the uplands of east Otago, with catchments that retain a healthy cover of tussock grassland, show strong and sustained base flow, even in dry years. Waugh (2005) attributed this to a combination of factors, including the gradual release of large amounts of stored water in the regolith and the loess mantle, low transpiration by tussock, and the possibility of fog interception adding to the soil water store. We do not know the relative importance of these factors, but a recent investigation of runoff-generating mechanisms at Glendhu, using tritium to estimate mean transit time (Stewart and Fahey, 2010), shows that slow release from groundwater reservoirs within the schist bedrock constitutes an important water source.

Conclusions

This study demonstrates that, overall, fog does not make a significant contribution to water yields in the east Otago uplands at the catchment scale. The results from Upper Deep Stream suggest that, in special circumstances determined by catchment aspect and exposure to prevailing fog-bearing winds, fog may contribute up to an extra 15% over and above that from rainfall. However, in this case other factors such as gauge under-catching and reduced transpiration may also help explain the difference between measured and modelled water yield. We conclude that there is no evidence in the hydrological records of the examined catchments that fog adds anything like as much input as rainfall to the water yield.

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References

Allen, R.G.; Pereira, L.S.; Dirk, R.; Smith, M. 1998: Crop evapotranspiration: guidelines for computing crop requirements. FAO Irrigation and Drainage Paper 56. Rome, United Nations Food and Agricultural Organization.

Allerup, P.; Madsen, H. 1980: Accuracy of point precipitation measurements. *Nordic Hydrology 11*: 57-70.

Beven, K. 1989: Changing ideas in hydrology – the case of physically-based models. *Journal of Hydrology 105*: 157-172.

Brash, D.N.; Murray, D.L. 1980: Indirect methods for estimation of catchment precipitation. *New Zealand Geographer 36(2)*: 57-67.

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

Davie, T.J.A.; Fahey, B.D.; Stewart, M.K. 2006: Tussock grassland and high water yield: a review of the evidence. *Journal of Hydrology (NZ) 45*: 83-94.

Dreaver, K.R.; Hutchinson, P. 1974: Random and systematic errors in precipitation at an exposed site. *Journal of Hydrology (NZ) 13*: 54-63.

Duncan, M.J.; Thomas, M.B. 2004: Hydrological effects of burning tall tussock grassland on the Lammermoor Range, East Otago, New Zealand. *Journal of Hydrology (NZ) 43*: 125-139.

Fahey, B.D. 1996: Water yields from the Deep Stream and Deep Creek catchments. Contract Report LC9697/029, Landcare Research, Lincoln.

Fahey, B.D.; Jackson, R.J.; Davie, T.J.A. 2004: User's guide for the Land Use Change Water Balance Model (WATYIELD). Contract Report LC0203/185, Landcare Research, Lincoln.

Fahey, B.D.; Jackson, R.J.; Sutcliffe, C. 1991: Water yields and land-use in the Deep Creek and Deep Stream catchments. Contract Report FEW 91/51, Forest Research Institute, Rotorua.

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 (NZ) 35*: 85-102.

Fahey, B.D.; Ekanayake, J.; Jackson, R.J.; Fenemor, A.; Davie, T.J.A.; Rowe, L.J. 2010: Using the WATYIELD water balance model to predict catchment water yields and low flows. *Journal of Hydrology (NZ) 45*: 39-58.

Hewitt, A.E. 2010. New Zealand Soil Classification (3rd ed.) Manaki Whenua Press, Lincoln New Zealand. 136 p.

Hewlett, J.D.; Hibbert, A.R. 1967: Factors affecting the response of small watersheds to precipitation in humid areas. Pp. 527-543 in Sopper, W.E.; Lull, H.W. (*eds*.). *International Symposium on Forest Hydrology,* Pergamon Press, New York.

Holdsworth, D.K.; Mark, A.F. 1990: Water and nutrient input: output budgets: effects of plant cover at seven sites in upland snow tussock grasslands of Eastern and Central Otago, New Zealand. *Journal of Royal Society of New Zealand 20*: 1-24.

Ingraham, N.L.; Mark, A.F. 2000: Isotopic assessment of the hydrologic importance of fog deposition on tall snow tussock grass on southern New Zealand uplands. *Austral Ecology 25*: 402-408.

Ingraham, N.L.; Mark, A.F.; Frew, R.D. 2008: Fog deposition by snow tussock grassland on the Otago uplands: response to a recent review of the evidence. *Journal of Hydrology (NZ) 47*: 107-122.

Mark, A.F. 1998: The role of snow tussocks in maximising water yield from upland snow tussocklands of the Taieri catchment and its relevance to land management. Pp. 28-32 in: Hamel, J. (*ed.*) *Research in the Taieri catchment.* University of Otago Ecology Research Group Occasional Paper no 1. University of Otago, Dunedin.

Mark, A.F.; Rowley, J. 1969: Water yield of low-alpine snow tussock grassland in Central Otago. *Journal of Hydrology (NZ) 15*: 59-79.

Mark, A.F.; Rowley, J. 1976: Hydrological effects in the first two years following modification of snow tussock grassland. Pp.188-202 in: *Proceedings of Symposium on Watershed Management*, Paper in Water Resources 8. Lincoln University, Lincoln.

Martin, G.N. 1973: Characterization of simple exponential baseflow recessions. *Journal of Hydrology (NZ) 12*: 57-62.

McKerchar, A.I. 1994: Analysis of Deep Stream discharge data. NIWA Christchurch Miscellaneous Report No. 163.

New Zealand Meteorological Service 1986: Summaries of water balance data for New Zealand stations. *New Zealand Meteorological Service Miscellaneous publication 189.*

Otago Catchment Board 1983: Taieri River catchment water resource inventory. Otago Catchment Board, Dunedin.

Pearce, A.J.; Rowe, L.K.; O'Loughlin, C.L. 1984: Hydrology of mid-altitude tussock grasslands, Upper Waipori Catchment, Otago II – Water balance, flow duration and storm runoff. *Journal of Hydrology (NZ) 23*: 60-72.

Rasmussen, K.R.; Halgreen, C. 1978: Some errors in precipitation measurements. *Nordic Hydrology 9*: 145-160.

Rodda, J.C. 1967: The rainfall measurement problem. Proceedings of the Bern Assembly. *IAHS Publication 78*: 215-231.

Stewart, M.K. 1975: Stable isotope fractionation due to evaporation and isotopic exchange of falling water drops: Applications to atmospheric processes and evaporation of lakes. *Journal of Geophysical Research 80(9)*: 1133-1146.

Stewart, M. K.; Fahey, B.D. 2010: Runoff generating processes in adjacent tussock grassland and pine plantation catchments as indicated by mean transit time estimation using tritium. *Hydrology and Earth System Sciences 14*: 1021-1032.

Waugh, J.R. 2005: Water resources of tussock grasslands in the upper Taieri catchment. Report prepared for the Department of Conservation, Opus International Consultants, Timaru, New Zealand.

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