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HYDROLOGY OF MID-ALTITUDE TUSSOCK GRASSLANDS, UPPER WAIPORI CATCHMENT: II — WATER BALANCE, FLOW DURATION AND STORM RUNOFF

A. J. Pearce, L. K. Rowe, C. L. O'Louglin

Protection Forestry Division, Forest Research Institute, Christchurch, New Zealand

ABSTRACT

The average annual water balance of two catchments in narrow-leaved snow tussock grassland for the period 1980–1982 was:

Precipitation = Interception + Quickflow + Delayed flow + Transpiration
1305 mm = 260 mm + 250 mm + 585 mm + 210 mm

Flow was sustained at moderate levels for extremely long periods compared with catchments with other vegetative covers; the 90th percentile of the runoff-duration curve was 0.9 mm/day, and runoff did not fall below 0.6 mm/day. Low-flow rates are 4–6 times greater than those described from other regions with similar rainfall climates but different vegetation. Transpiration during summer, estimated using a daily water balance model, is about half that predicted by Penman or Priestley-Taylor methods, averaging about 1.6 mm/day. Estimated winter transpiration averages about 0.4 mm/day and is similar to Penman estimates. Quickflow production (30% of total runoff and 20% of total rainfall) is similar to that in moderately responsive indigenous forest regions, but the catchments respond more slowly to storm rainfall than indigenous forests in higher rainfall regions.

INTRODUCTION

Few data exist on the water balance or hydrologic regime of tussock grassland areas except on the scale of large (10^2–10^4 km^2) catchments over which there are often substantial rainfall gradients and a mixture of land uses. The data reported here appear to be the first assessment of the water balance, flow frequency and storm runoff production for first or second order catchments in largely unmodified tussock grassland. Estimation of the main components of the water balance for the Glendhu catchments is of major importance to the study outlined in Part I (O'Loughlin *et al.*, 1984) (this issue), both to characterise the status quo and to identify those components which may be most likely to change significantly on afforestation of tussock grasslands in eastern Otago.

INSTRUMENTATION

Precipitation

Precipitation was recorded at three Alter-shielded, Belfort weighing-bucket precipitation gauges on an altitudinal transect along the ridge dividing the

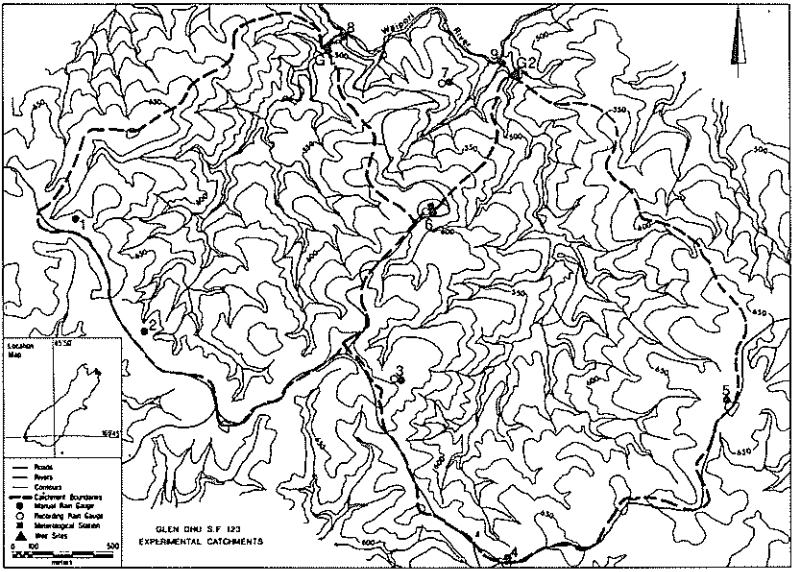

FIG. 1: Location, topographic map and instrument locations, Glendhu State Forest experimental catchments.

two catchments. Recordings by these gauges were routinely scaled to standard 127 mm check gauges set at 305 mm above ground which were read weekly or more frequently. Another six standard 127 mm gauges set out in the network shown in Figure 1 were read weekly or more frequently. Snowfall is included in the recorded winter precipitation because of the 200 mm diameter gauge orific which is fully open during winter months, but the percentage of snow is not well known. Fresh snowfall depth was measured at 14 permanent snow poles after each snowfall.

Runoff

Both streams were gauged at broad-crested concrete "V" weirs of 2:1 side slope (see Holtan *et al.*, 1962). The flow cross-section 3.05 m (10 feet) upstream of each weir was deliberately constricted by the walls of the stilling-pond sediment-trap in order to obtain as steep a rating curve as possible from the ratings given by Holtan *et al.* (1962). Ratings for the two weirs were slightly modified on the basis of volumetric gaugings and dye dilution gaugings at flows corresponding to the range of stage heights between 150 mm and 250 mm, which were recorded for ~ 90% of the flow duration. During weir construction, the sites were excavated to fresh bedrock over the complete extent of the weir and sediment trap/stilling pond to ensure the structures were water-tight. We are confident that no flow bypassed the measuring structures.

Water levels were recorded to ± 1 mm using Belfort FW-1 recorders at a distance of 3 m upstream of the weir wall, i.e., more than five times the maximum recorded head. The combination of recording methods and close checking of a limited part of the rating curve which covers 90% of the flow duration suggests that monthly and annual runoff quantities are probably known to about ± 5% (± *c.* 40 mm annually).

ESTIMATION OF CATCHMENT WATER BALANCE

Precipitation

Variation among gauges in weekly and monthly totals was moderate but unsystematic. Over a 3-year period, the highest monthly total exceeded the lowest total for the same month by amounts ranging from 8% to 96%, but the descrepancy was 15% to 30% for 70% of months. Annual variability for the 3-year period 1980–1982 was much less, with the highest gauge total for 1980–82 exceeding the lowest total by only 10%.

Accumulated fresh snowfall totalled between 40 and 80 cm in each of the three study years. This snow is equivalent to 60 to 120 mm of rainfall, if mean fresh snow density was as high as 0.15. Density measurements indicate typical fresh snow densities of 0.1 to 0.12. Based on these data, snowfall contributed less than 10%, and possibly as little as 5%, of annual precipitation.

Catchment average precipitation was estimated by Thiessen weighting of five gauges for each catchment. Areas represented by individual gauges range from 10% to 31% of catchment area, but in each catchment three of the five gauges each represent areas between 17% and 23%. Catchment precipitation was also estimated by stratifying the gauges by elevation and weighting by proportions of catchment area in each elevation band. This method produced monthly and annual estimates that were typically within 1–2% of the Thiessen weighted estimates. Over a 3-year period the total precipitation estimated using the two methods differed by less than 1%.

Monthly precipitation estimated for the two catchments by Thiessen weighting differs by 0.2% to 10.8%, with estimates for catchment 1 exceeding those for catchment 2 in 70% of months during 1980–82. The 1980–82 estimated total for catchment 1 exceeded that for catchment 2 by less than 2%. These discrepancies are well within the precision of individual gauge measurements, thus the two catchments are considered to have identical annual precipitation.

Monthly precipitation ranged from 25 to 265 mm during 1980–82 with a mean monthly precipitation of about 115 mm. Annual precipitation averages for the two catchments was 1455 mm in 1980, 1080 mm in 1981 and 1385 mm in 1982. Mean annual precipitation for the period was 1305 mm. Snowfall water equivalents are included in these monthly and annual values, but separate precise estimates are not available.

Maximum rainfall intensities during the study period were moderate (Table 1) and were dominated by intensities measured during two large storms of 17 January 1980 and 24 October 1982.

Fog is infrequent at the study site compared with the sites at 700 m to 1400 m on the Lammerlaw and Rock and Pillar Ranges studied by Mark and Rowley (1976) and Mark and Holdsworth (1979). Interception gains from fog are considered minor, as found by Mark and Holdsworth (1979) at their low-elevation (500 m) study site.

TABLE 1: Maximum rainfall intensities (mm/h) for various durations observed during 1980–1982.

Duration	30 min.	1 h	2 h	6 h	12 h	1 d	3 d
Intensity	26.4	26.4	20.6	9.2	5.9	3.3	2.3

Runoff

Monthly runoff ranged from 30 to 185 mm during 1980–82. Annual runoff averaged for the two catchments was 955 mm in 1980, 725 mm in 1981 and 835 mm in 1982. Differences between the two catchments in montly runoff are typically < 1 to 5 mm, but in exceptional instances, when storms overlap between months, discrepancies range as high as 15 mm/month. Differences greater than 10 mm between the two catchments occur in six out of 46 months of record. For the period 1980–82, differences in annual runoff between the two catchments were in the range 10–20 mm, which is much less than the uncertainty of the runoff measurements.

The continuous hydrograph has been separated into quickflow (storm runoff) and delayed flow using the method of Hewlett and Hibbert (1967). Catchment 1 yielded 325 mm of quickflow in 1980, 180 mm in 1981 and 260 mm in 1982. These amounts correspond to 34%, 25%, and 31% of total runoff, averaging 30% of runoff over the combined period. Catchment 2 yielded 330 mm of quickflow in 1980, 180 mm in 1981 and 235 mm in 1982, corresponding to 35%, 25%, and 28% of total runoff in each year and an average of 30% of total runoff for the combined period.

Interception

Interception loss is extremely difficult to measure for low to moderate height, multi-stemmed vegetation such as tussock grasses. Direct measurement of interception during either rainfall or fog has not thus far been attempted. Rather, interception loss was estimated from the water balance of winter periods of 2–3 months between storms of sufficient size that regolith moisture storage was almost certainly fully recharged at the beginning and end of the period. For example, the period June 5 to August 9, 1981 followed a 25 mm rainfall on June 2 and 13 mm of rainfall on June 4, and was terminated by 43 mm of rainfall on August 9–11. Catchment storage is assumed to have been fully recharged at the beginning and end of this 65-day period. During the 65 days, 247 mm of rain fell in 220 hours on 42 days. Runoff during the period was 191 mm, thus, assuming complete recharge at beginning and end of the period and no drainage to deep groundwater, evaporation was 56 mm. If all the evaporation was by interception, interception loss would be 23% of gross rainfall. If the evaporation from interception storage occurred predominantly during rainfall, rather than after rainfall ceased, implied evaporation rates from wet foliage would average *c.* 0.25 mm/hour. Penman evaporation estimates for the region suggest winter transpiration of about 10 mm/month, thus transpiration during the 65-day period might have been as much as 20 mm. This indicates that interception losses may have been as low as 15% of gross rainfall and that evaporation rates from wet foliage averaged *c.* 0.16 mm/hour.

The above estimates indicate the probable upper and lower limits of interception loss. Mean interception loss was assumed to be 20% (± 5%) of gross rainfall, with wet canopy evaporation rates averaging *c.* 0.2 (± 0.05) mm/hr. Interception loss was estimated as 290 mm in 1980, 215 mm in 1981 and 275 mm in 1982.

Transpiration

Transpiration was estimated for each year and for shorter periods between major rainfalls which recharge catchment storage, as a residual in the water balance. Estimated transpiration for these periods includes all errors in measurement and estimation of other water balance components and any error in the assumption that the catchment is water-tight. Transpiration was estimated as 210 mm in 1980, 140 mm in 1981, and 275 mm in 1982.

Catchment Water Balance

An estimated average annual water balance for the period 1980–82 is as follows:

Precipitation = Interception + Quickflow + Delayed flow + Transpiration
1305 mm = 260 mm + 250 mm + 585 mm + 210 mm

If interception loss were 15% of gross rainfall (the lower likely limit estimated above), the interception and transpiration components of the average water balance would be 195 mm and 275 mm respectively.

FLOW DURATION AND RECESSION CHARACTERISTICS

Flow is sustained at moderate levels for very long periods. The minimum flow recorded was 0.07 *l*/sec/ha (0.6 mm/day), and flow was sustained at ≥ 0.1 *l*/sec/ha (0.86 mm/day) for 96% of the observed period of record. Figure 2 shows the flow duration curve compared with those of catchments in two undisturbed indigenous forest areas. Despite the difficulties of comparing catchments of very different size, the comparison indicates that sustained low flows from these tussock grasslands were 5–6 times greater than those from indigenous forests (0.1–0.15 mm/day) in both similar (Big Bush)and much higher (Maimai) rainfall climates. Sustained low-flow rates from a 250 ha catchment at Maimai are very similar to those of the small subcatchments shown in Figure 2.

In McKerchar and Waugh's (1976) comparison of flow-duration curves for 25 representative basins throughout New Zealand, only three catchments draining high rainfall areas (Ahaura, Hutt, Te Tahi) and two other catchments where flow was sustained by glacier and snow melt (Ivory, Ahuriri) sustained flows of ≥ 0.1 *l*/sec/ha for more than 90% of their record. For nine of the 10 catchments with mean annual rainfall in the range 1000–1600 mm studied by McKerchar and Waugh (1976), the 90th percentile of the flow duration curve lay in the range << 0.01 to 0.025 *l*/sec/ha (<< 0.1 to 0.22 mm/day). These comparisons indicate that the Glendhu study catchments sustain unusually high rates of flow between episodes of storm runoff, possibly because of the low transpiration demand exerted on the soil water by tussock.

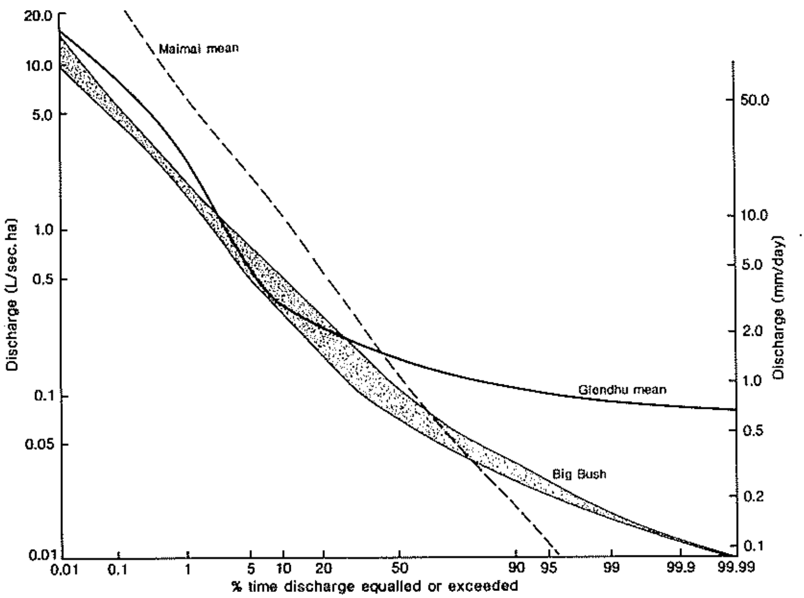

FIG. 2: Flow duration curves 1980–82, Glendhu catchments, compared with flow duration curves for two areas of indigenous forest (Big Bush data from Pearce *et al.*, 1982, Maimai data from Pearce *et al.*, 1976).

The high flow rates during delayed runoff are reflected in gently, very unifrom recession curves during both winter and summer. The uniformity of the recession characteristics (except on infrequent occasions involving snow melt) makes the plotting of a master recession curve worthwhile. Figure 3 shows a composite or master recession curve plotted from six storms and includes the longest single recession period (17 days) so far observed. The six events plotted are highly representative of hydrographs uncomplicated by snow melt or by rain during the recession limb. The hydrographs were typical of medium to large events in the available data set except that they had long recession durations. In Figure 3 two distinct recession segments are apparent; a steep recession for the first 12–14 hours after peak flow, followed by a sharp transition to a slower recession at a flow rate of about 0.3 *l*/sec/ha (2.6 mm/day). About 11% of the flow duration occurred during the rising limbs of storm hydrographs and during the first recession segment. Nearly 90% of the flow duration occurs during the slower recession, which appears to be a recession from regolith storage (shallow, unconfined groundwater storage).

Most of the volume of quickflow (QF) computed using the standard separation slope (0.0055 *l*/sec.ha.hour; Hewlett and Hibbert, 1967) has occurred before the transition to the second recession segment occurs, but quickflow does not usually end until some hours after the change in recession slope on may larger hydrographs. In 270 of 350 hydrographs yielding more than 0.025 mm of quickflow, the elapsed time between the hydrograph peak and the end of quickflow was less than 14 hours. Essentially all quickflow occurred during the rising limb and the first recession segment of these hydrographs. Typical quickflow yields were less than 8 mm, but two much larger hydrographs (15 mm and 22 mm quickflow) were also in this group.

Some 40 hydrographs had durations, from peak flow to the end of quickflow, in the range 14–18 hours. Given the flow rate at the start of the second recession segment (2.7 mm/day), the maximum difference between computed quickflow and the runoff generated before the transition between recession segments is less than 0.5 mm per hydrograph. These hydrographs typically yielded 2 to 12 mm quickflow, so that the difference between computed quickflow and quick runoff that could be defined by a separation line similar to that of Hewlett and Hibbert, but which intersects the break in slope of the recession, would average about 10%.

In another 40 hydrographs, computed quickflow lasted for 19 to 80 hours after peak flow, but in only seven of these did quickflow persist for more than 36 hours after peak flow. In those hydrographs where computed quickflow persisted for ~ 1 day after the recession transition point (c. 36 hours after

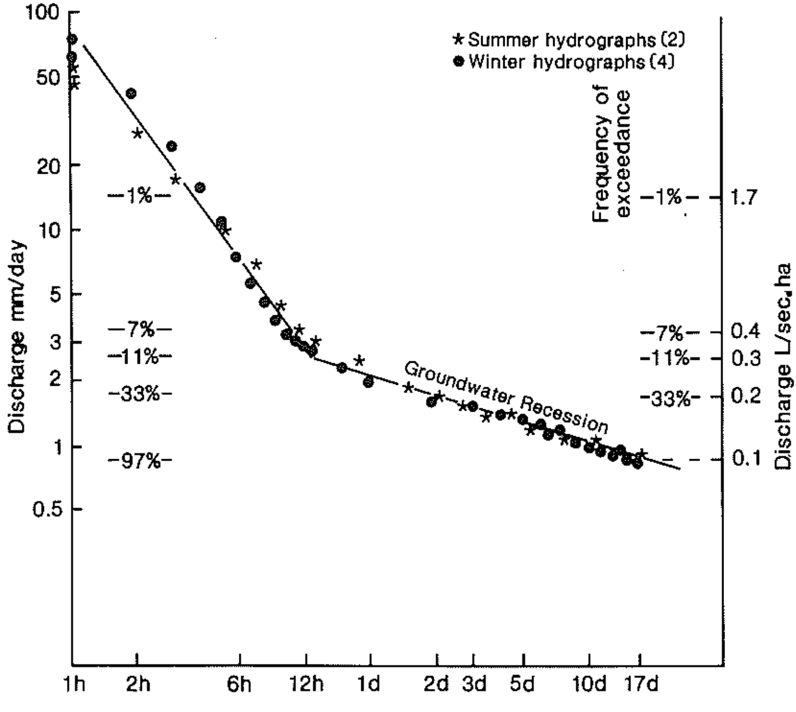

FIG. 3: Master recession curve for storm hydrographs not involving snow melt, Glendhu catchments.

the peak), the discrepancy between computed quickflow and that defined by a Hewlett and Hibbert-type separation intersecting the recession transition was c. 2.5 mm, or about 10% of the volume of quickflow. In the one hydrograph where computed quickflow persisted for 80 hours after peak flow, or for c. 3 days after the transition between recession segments, the discrepancy between computed quickflow and that defined by a separation line intersecting the recession transition is c. 7 mm, or about 18% of the computed volume.

For quickflow volumes computed by Hewlett and Hibbert's method to agree almost exactly with quick runoff defined by the two recession slopes, the hydrograph separation slope needs to be steeper than the standard slope. Most hydrographs start from flow rates in the range 0.1 to 0.2 *l*/sec/ha, averaging about 0.15 *l*/sec/ha, and few hydrographs have rising limbs (time from initial rise to peak flow) longer than 12 hours. Of 350 hydrographs, 27 had rising limbs > 12 hours and only 16 were 24 hours or longer. For the separation line to intersect most recessions at about the transition between recession slopes, or somewhat before the transition, delayed flow must increase from about 0.15 to 0.3 *l*/sec/ha in about 24 hours, i.e., about 0.0063 *l*/sec/ha/hour; about 15% faster than the standard separation line.

STORM RUNOFF RESPONSE

Over the calendar years 1980–82, storm runoff estimated by quickflow separation using the standard slope averaged 30% of total runoff and 19% of gross rainfall. Compared with most of the catchments studied by Pearce and McKerchar (1979), this storm runoff response is moderate to low, particularly the ratio of quickflow to total runoff. For example, at Hut Creek, in the Craigieburn Range, a modified tussock grassland/exotic pasture catchment with about 20% forest vegetation and mean annual rainfall of 1500 mm, quickflow (QF) was about 50% of total runoff and 25% of gross rainfall. Undisturbed indigenous forests can be substantially more responsive than the Glendhu tussock grasslands, e.g., Maimai catchments where quickflow was 65% of runoff and 40% of gross rainfall (Pearce and McKerchar, 1979); or rather similar in responsiveness, e.g., Big Bush catchments, where quickflow was 35% of runoff but only 13% of gross rainfall (Pearce *et al.*, 1982); Ngahere catchment, Kaweka Range, quickflow was 25% of runoff and 16% of gross rainfall (Pearce and McKerchar, 1979). Developed exotic pasture catchments on other than gentle terrain or deep pumice soils and bedrock were more responsive than the Glendhu catchments in the proportion of runoff yielded in quickflow, e.g., Pukewaenga, quickflow was 44% of runoff and 21% of rainfall; Makara, quickflow was 41% of runoff and 11% of rainfall; Moutere 5, quickflow was 40% of runoff and 10% of rainfall (Pearce and McKerchar, 1979). The low ratio of quickflow to total runoff at Glendhu reflects a high yield of delayed flow rather than a limited production of quickflow. The proportion of rainfall yielded in quickflow at Glendhu is similar to that for many of the forested and grassland catchments studied by Pearce and McKerchar (1979).

Figure 4 shows the relationship between yield of quickflow and the ratio of quickflow to gross storm rainfall (quickflow response ratio) for both catchments. In events yielding 1–2 mm of quickflow, the quickflow response

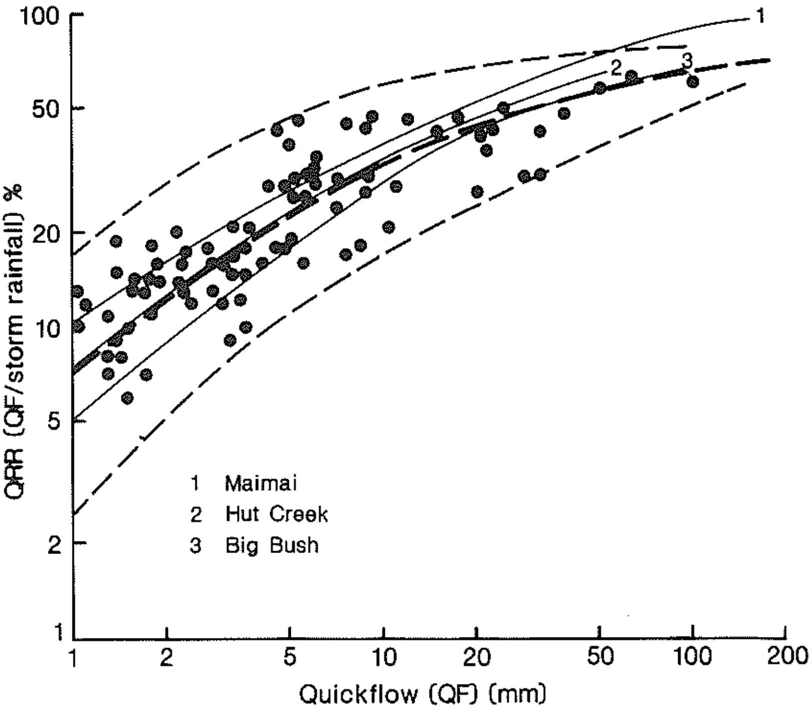

FIG. 4: Quickflow response of Glendhu catchments (mean response of G1 and G2 plotted), compared with responses of other regions in modified tussock grassland and indigenous forest. QRR = quickflow response ratio.

ratio was typically 2–15% but increased rapidly to values of 20–50% in events yielding 10–20 mm of quickflow. In events yielding from about 25 mm to more than 100 mm of quickflow, quickflow response ratios increase gradually from about 40% to 60%. In the largest recorded events, quickflow is equivalent to 60% of gross rainfall, or 75% of estimated net rainfall. In events yielding more than 5 mm of quickflow the quickflow response ratio was 25% or greater. The average response curve is very similar to those for Hut Creek (tussock/pasture) and Big Bush (beech forest) (Pearce and McKerchar, 1979; Pearce *et al.*, 1982).

Mechanisms of storm runoff generation are not easy to discern. Rainfall onto stream channels and other wetland areas (saturation overland flow) probably accounts for the small hydrographs yielding less than about 5 mm quickflow. Channels and saturated areas frequently cover 10–15% of the total area and may include up to about 20% of catchment area at times. Hydrographs yielding more than about 5 mm of quickflow or with quickflow response ratios greater than about 25% must have had substantial volumes of flow delivered by subsurface routes as extensive Horton overland flow was not observed. It would appear from the recession shape that at least two mechanisms or pathways contribute runoff. One of these mechanisms delivers much of the calculated volume of quickflow at rates that exceed Hewlett and Hibbert's (1967) distinction between quick and delayed flow. The second, slower mechanism appears to be dicharge of a shallow, unconfined, groundwater body which supplies the second part of the recession and the delayed flow.

The contribution of groundwater outflow to the rate of rise of the combined hydrograph and peak flow, and the lag between the peak of the combined hydrograph and the peak flow rate from the groundwater body are difficult to determine solely from hydrograph analysis. If the groundwater recession is extrapolated under the combined hydrograph to a time 1 hour after the combined hydrograph peak (i.e., the ordinate of Fig. 3), the maximum probable peak flow rate of the groundwater hydrograph is *c.* 5 mm/day (0.6 *l*/sec/ha), or 7–10% of the peak flow rate of the combined hydrograph. The sharp transition between the two differently-sloped recession segments suggests, however, that the peak of the groundwater outflow hydrograph is probably quite close to the transition point, rather than being under the combined hydrograph peak. Thus a peak groundwater outflow of between 3 and 4mm/day is more likely. The time lag from the combined hydrograph peak to the groundwater hydrograph peak is probably 10–12 hours, corresponding roughly with the period from peak flow to the transition between the two recession segments.

A MODEL OF DAILY WATER BALANCE

The consistent shape of storm hydrographs, the relative ease of separation of quick and delayed runoff based on recession shape, and the persistence of easily-modelled groundwater discharge throughout the longest recorded period of delayed flow, suggest the possibility of a simple conceptual model of daily water balance. Such a model can be fitted to observed rainfall and flow records, and can be used to estimate average daily transpiration for periods between storms which fully recharge catchment storage, with the observed groundwater recession providing closure to the water balance.

Gross daily rainfall enters an interception store from which 80% of gross rainfall drains to become net rainfall and the remaining 20% is evaporated as interception is loss. Net rainfall enters a single regolith store which is initially assumed full after a major rainfall event. The regolith storage capacity is not specified; rather, storage deficits are calculated for each day. Surplus rainfall, after the deficit reaches zero, becomes storm runoff on the day of rainfall and the deficit is reset to zero. Discharge from the regolith store to delayed flow is obtained from the master recession curve, assuming that storage deficit S is zero at the transition between the two recession curves (when daily discharge is 2.7 mm).

The equation for groundwater discharge (GWD) in Figure 5 is the groundwater recession of Figure 3 where GWD is daily groundwater discharge and t is day number (day 1 is the day on which the hydrograph peak occurs). A linear regression in logarithms of daily groundwater discharge on t is GWD $= 2.67\ t^{-0.3996}$ ($r^2 = 0.997$). Transpiration is permitted from the regolith store, on days with less than 1 mm net rainfall, at a selected but fixed daily rate for each period between recharging storms.

To initiate calculations it is necessary to use a single large storm that recharges the regolith store to an assumed deficit of zero. Storms yielding more than *c.* 5 mm quickflow are considered to have fully recharged the regolith store, as quickflow yields are usually $\geq 25\%$ of gross rainfall. Between such events, the daily transpiration value in the model can be fitted by iteration to match the model calculation of storm runoff at the end of the period, with the total of quickflow plus delayed flow during quickflow calculated from the observed hydrograph. Such fitting can usually be achieved in one to three iterations. The model is simple enough to be run efficiently in a programmable pocket calculator for one or two periods, but for multiple periods using many iterations, it is more convenient to run the model on a computer where the daily rainfall sequence can be stored for re-use in each iteration.

Model runs for winter periods indicate that a typical average daily transpiration rate of 0.4 mm/day permits fitting of the observed and model storm runoff quantities to better than 10%. Winter transpiration estimated by the model is typically 5–10 mm/month since transpiration is only permitted

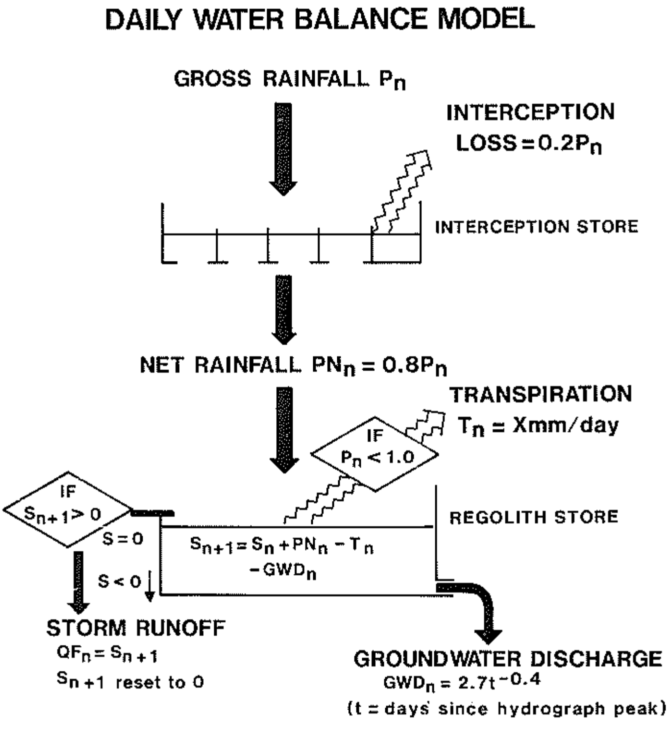

FIG. 5: Daily water balance model, Glendhu catchments.

on ("dry") days with less than 1 mm rainfall. These values agree quite closely with Penman estimates for winter transpiration in this region (Coulter, 1973; N.Z. Meteorological Service, unpublished water balance calculations for Mahinerangi Dam).

Average daily transpiration rates for summer periods between major storms vary from 1.4 mm to 2.0 mm/day and do not appear to exceed 2 mm/day. Overall, summer transpiration rates average about 1.6–1.7 mm/day. These values are about half those estimated from Penman's equation. Monthly transpiration totals rarely exceed 30 mm and are less than half Penman monthly estimates (N.Z. Meteorological Service, unpublished data). The low estimated transpiration is in keeping with the low productivity of these tussock grasslands, the high ratio of dead to live biomass (Meurk, 1978), and the probable high light interception by the dead portions of the tussock cover. The low model-estimates of transpiration are also consistent with the observed water balance and high proportions of delayed runoff.

Deficits of regolith storage rarely exceed 25 mm. This is consistent with the large volume of delayed runoff and qualitative observations of high soil water content throughout summer and autumn periods.

SUMMARY

Water balances over 3 years in two catchments in largely unmodified narrow-leaved snow tussock indicate that evaporative losses are substantially smaller than would be predicted from Penman or other methods of estimation. Runoff, particularly delayed runoff, is high in comparison with other vegetative covers in either similar or substantially wetter rainfall climates. Interception losses, at *c.* 20% of gross rainfall, are somewhat higher than anticipated for vegetation of this type and stature, and are comparable with scrub vegetation or low-density forest stands. Transpiration on a daily, monthly, or annual basis, except in winter months, is much less than would be predicted by Penman's or Priestley and Taylor's equation. The low transpiration values are also consistent with the observed high, persistent rates of delayed runoff from shallow, unconfined groundwater storage, indicating that upward fluxes of soil water to transpiration do not compete effectively with drainage of the groundwater to delayed runoff.

Storm runoff responses are moderate and are comparable to areas of indigenous forest with similar rainfall climates in terms of the ratio of quickflow to storm rainfall over a wide range of event sizes. Quickflow as a proportion of total runoff is less than in most areas studied in detail in New Zealand, but this reflects the persistence of high rates of delayed flow, rather than small yields of quickflow.

A simple conceptual model of daily water balance with an interception store and regolith store discharged by transpiration and drainage is capable of fitting the major components of the water balance to a precision of better than 10%. This model, however, does not identify precisely the mechanisms by which either quickflow or delayed runoff are generated.

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