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HYDROLOGIC REGIME OF UNDISTURBED MIXED EVERGREEN FORESTS, SOUTH NELSON, NEW ZEALAND

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ABSTRACT

Data from a 3-year calibration period of a 4-catchment study indicate little variaton among catchments except in delayed flow and in losses to shallow groundwater. For a water year beginning September 1st the water balance is:

$$\begin{array}{lllllllllll} \text{Rainfall} & = & \text{Inter-ception} & + & \text{Quick-flow} & + & \text{Delayed flow} & + & \text{Ground-water loss} & + & \text{Trans-piration} \\ 1480\text{ mm} & = & 435\text{ mm} & + & 190\text{-}205\text{ mm} & + & 340\text{-}400\text{ mm} & + & 40\text{-}195\text{ mm} & + & 320\text{-}360\text{mm} \end{array}$$

Sustained summer low flows are in the order of 0.15 mm/day. The duration of higher summer flow rates is determined mainly by the distribution and amount of summer rainfall. Storm hydrographs are remarkably consistent among catchments for individual events but vary greatly in shape for different events depending on rainfall volume, antecedent wetness and rainfall intensity. Quickflow generation (32-37% of runoff) is moderate compared to other studied areas of similar forest because of the storage available in the thick regolith. Rapid-response runoff mechanisms generate small hydrographs, but much of the storm runoff in large events (and 50-75% of the annual total quickflow) is generated by slower response mechanisms, so that much storm runoff delivered to the stream channels lags 6-24 hours after storm rainfall.

INTRODUCTION

Evergreen forests of mixed hardwoods and softwoods with *Nothofagus* spp. as important components are, or were, widespread in New Zealand, western South America, Tasmania and parts of Melanesia. There have been few studies of the hydrologic regime of these forests in their undisturbed state (e.g. Pearce *et al.*, 1976). In New Zealand, despite extensive modification and clearing of these forests, very little is yet known of the hydrologic consequences of forest removal (e.g. O'Loughlin *et. al.*, 1980; Pearce *et al.*, 1980a). Here we describe the water balance, flow frequency, summer low flows, and storm runoff response of four small catchments covered with undisturbed *Nothofagus* spp.-podocarp-hardwood forest in south Nelson. We also compare the hydrologic regime of these catchments with that of other small catchments, covered with a similar forest association in a much higher rainfall zone in north Westland.

PHYSICAL SETTING

Four small catchments ranging from 4.8 ha to 20.2 ha in area located in Big Bush State Forest (Figure 1) have been studied since late 1975. The study catchments are in the headwaters of Donald Creek, a tributary of Tadmor River, approximately 5 km north of the divide separating catchments draining north to Tasman Bay from those draining south and west to the Tasman Sea. The study catchments are typical of an extensive area of dissected hill terrain underlain by lithified early Pleistocene conglomerate, the Moutere Gravel Formation, which is moderately weathered and has a tightly compacted silty- clay matrix. Mean catchment elevation is approximately 550 m asl, and the four catchments have a north-west aspect. Local relief ranges from 100 to 250 m, slopes are up to 500 m long and slope angles range from 15° to 35°, averaging 28°. The soils are shallow and stony (Humults and Dystrochrepts), and vary from non-podsolised (Donald series) through moderately podsolised (Perth series) to podsolised yellow-brown earths of the Hope series (G. Mew and I. B. Campbell, pers. comm.). Organic (L, F and H) horizons average 8 cm in thickness. The main stream channels are incised nearly vertically into the bedrock to depths as great as 5 m.

Hard beech *(Nothofagus truncata)* and red beech *(N. fusca)* are the dominant forest species, with kamahi *(Weinmannia racemosa)*, miro *(Podocarpus ferrugineus)*, rimu *(Dacrydium cupressinum)* and silver beech *(N. menziesii)* as subdominant species.

Rainfall gradients across the terrain underlain by Moutere Gravel are quite large; annual rainfall normals range from about 1130 mm to 1650 mm (NZ Meteorological Service, 1973a). The nearest station with a long-term reliable record is Kaka (NZ Meteorological Service Station G12561), 5 km northwest of the study catchments at 396 m asl, for which monthly and annual rainfall normals are given in Table 1. The nearest long-term climatological station is Golden Downs Forest (Station G12581), 13 km northeast at 274 m asl (NZ Meteorological Service, 1973b). Rainfall normals and 20th and 80th percentile rainfalls for Golden Downs are also given in Table 1. Mean annual temperature at Golden Downs is 10.4°C, with monthly means ranging from 4.6° (July) to 15.8° (February). On average, screen frosts and ground frosts are recorded on 74 days/year and 117 days/year, respectively. The average number of rain days is 113/year and snow falls on 2 days/year. Mean wind speed is 1.7 m/s. Further detail of the climate of the region is given by de Lisle and Kerr (1965).

MEASUREMENT OF WATER BALANCE COMPONENTS

Precipitation

Precipitation is measured with two recording natural-siphon gauges at the uppermost and lowermost elevations of the study catchments (Figure 1), and with a network of five standard rain gauges (127 mm orifice, 300 mm above ground level), read weekly. Monthly differences between the upper and lower recording gauges are typically 2 to 3 mm and have never exceeded 10 mm. The differences average 3% of the mean of the two

TABLE 1—Rainfall normals and percentiles (mm) for stations near Big Bush experimental catchments (N.Z. Meteorological Service 1973a, 1979).

	J	F	M	A	M	J	J	A	S	O	N	D	YEAR
Kaka													
Normal	109	114	124	147	170	140	152	150	140	142	135	130	1653
Golden Downs Forest													
Normal	94	97	99	119	132	107	114	119	114	119	117	112	1343
20 Percentile*	38	32	34	70	59	53	55	68	56	65	69	74	1158
80 Percentile	150	135	147	190	178	167	158	182	130	154	155	149	1453

* Golden Downs percentiles are for period 1929-1978.

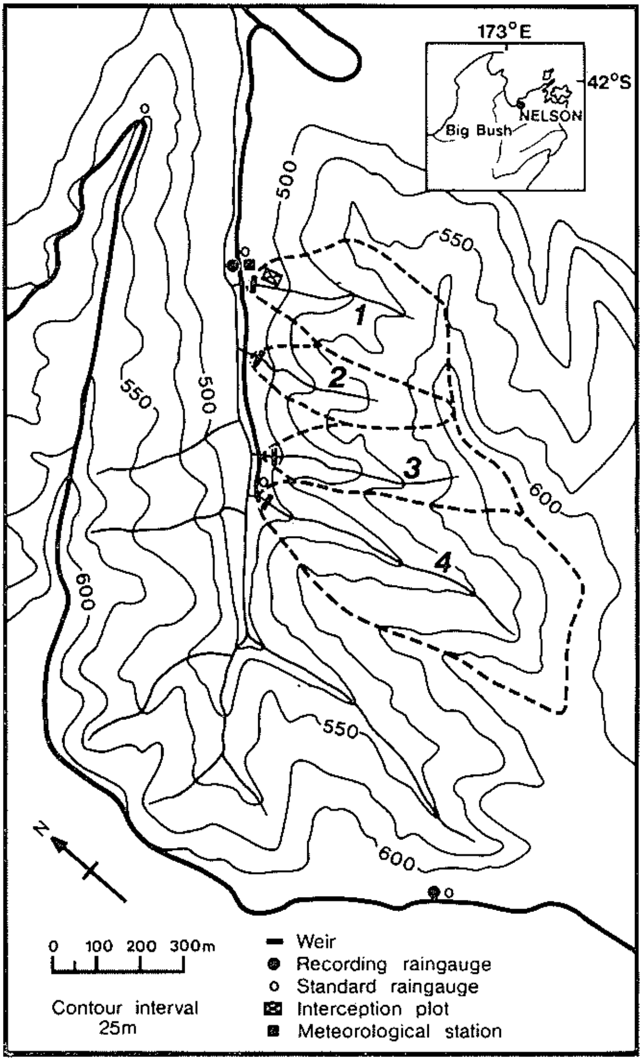

FIG. 1—Location and topographic map of experimental catchments, Big Bush State Forest.

gauges and exceed 6% of the mean in only 2 of 67 months of rainfall records from November 1975 to May 1981. Over the 67 months, the upper gauge total exceeded the lower gauge total in 34 months and the reverse occurred in 27 months. A 3-year data period (April 1977-March 1980) is used for calibration of the catchments because other water balance components are either unavailable or are of low precision outside this period. The upper gauge monthly total exceeded the lower gauge total 18 times and the reverse occurred 14 times in the 3-year calibration period. The largest discrepancy is 13% of the mean of the two gauges in February 1978, when more than half the monthly rainfall fell in an intense local thunderstorm of 45 minutes duration with a substantial difference in rainfall at the two gauges.

Over 67 months rainfall record, the upper gauge total is 8526 mm and the lower gauge 8500 mm; for the 3-year calibration period, the respective totals are 4648 mm and 4653 mm. The close agreement between the two recording gauges and between the recording gauges and the standard rain gauges permits us to use the mean of the two recording gauges as mean catchment rainfall for monthly and annual water balances. Detailed analysis of storm hydrographs may sometimes require evaluation of storm rainfalls for individual catchments.

Light snow has fallen on at least 1 day in each winter since the study began, but has remained on the ground for more than 24 hours in only one instance.

Interception

Throughfall has been measured near catchment 1 since March 1977 with a fixed trough system similar to that used in other interception studies in beech-podocarp-hardwood forest in New Zealand (Rowe, 1979). The trough area is approximately 9 m^2, laid out in a grid fashion, and the throughfall collected is channelled to a storage tank where water level is recorded to ± 1 mm. A large ratio of trough area: tank area (6:1) permits measurement of throughfall to a precision better than ± 0.2 mm. Gross rainfall for comparison with throughfall is taken from the lower recording raingauge, located about 50 m from the throughfall plot. Stemflow in the study stand is assumed to be 1.5% of gross rainfall in keeping with the data of Rowe (1979) for a very similar beech-podocarp-hardwood stand.

Runoff

Runoff is measured at 90° sharp-crested weirs fitted to concrete stilling ponds. Free drops of at least 20 cm in height at the stilling pond inlets, floating leaf/trash traps at the weir plate, and a free fall from the weir notch that is normally 2 to 10 times the head of water, all contribute to high accuracy of the flow measurement. Stage-heights were measured to ± 5 mm from November 1975 to March 1977. Throughout the calibration period, since April 1977, water levels have been recorded to ±1 mm at a distance at least 4 times the maximum recorded head upstream of the weir plate. Field volumetric rating of the weirs at heads less than 10 cm indicate discrepancies from the standard rating equation of the order of 1%

THE WATER YEAR

Monthly rainfall, interception and runoff data for the period April 1977-March 1980 are plotted as means for the 4 catchments in Figure 2 together with 3-month running mean plots of the residual of rainfall minus interception and runoff. Values of the residual are plotted at the

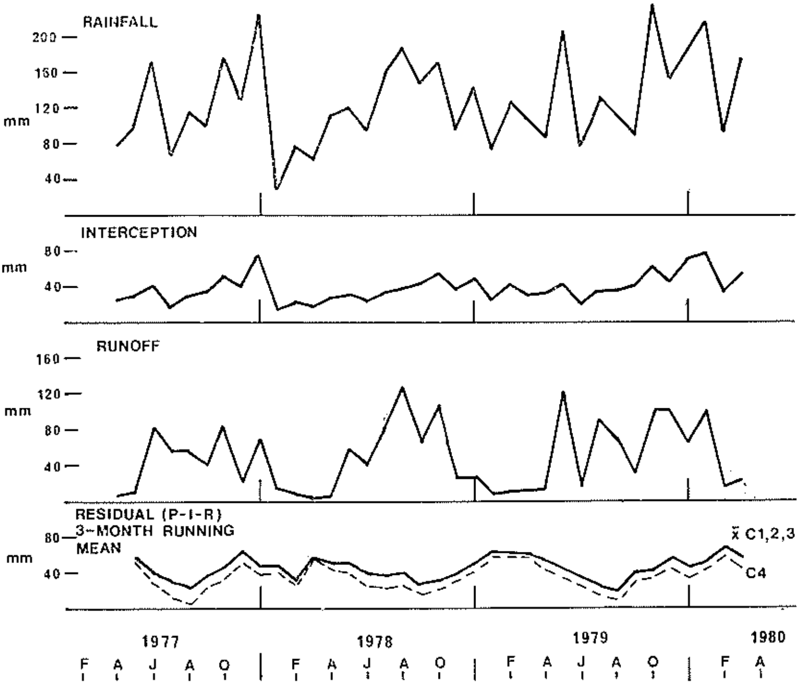

FIG. 2—Seasonal course of water balance components during calibration period (April 1977-March 1980), Big Bush experimental catchments.

centre of each 3-month period. The residual is the sum of transpiration, losses to shallow groundwater and changes in storage. The smoothed residual should be less influenced by fluctuations in storage than a plot of monthly values and should principally reflect the seasonal course of combined transpiration and seepage to groundwater. Residuals are plotted as a mean for catchments 1 to 3 and separately for catchment 4 because of significantly greater runoff and delayed flow for catchment 4 (see Runoff and Groundwater loss sections). Figure 2 reveals a consistent seasonal trend in the size of the residuals, with lowest values being reached in mid-August of 1977 and 1979 and mid-September of 1978. The consistency of the seasonal trend and the limited range of values for the annual minima (4-27 mm/month, and averaging 17 mm/month for the four catchments in three winters) suggest that: (1) soil moisture storage tends to be fully recharged in late winter; (2) changes in storage (ΔS) from year to year for a water year beginning about September 1 will be minimal; and (3) the catchments are not fully watertight, but annual losses to seepage will be relatively small taking the loss rates in late winter as an indication of average loss rates. Data for the main water balance components are therefore presented for the water years 1.9.77 to 31.8.78 and 1.9.78 to 31.8.79.

WATER BALANCE COMPONENTS

Rainfall

Monthly rainfall values averaged between the two gauges varied from 28 to 227 mm. Annual totals were 1476 mm and 1487 mm, respectively, for the 1977-78 and 1978-79 water years. Rainfall in these 2 years at Kaka was 94% and 99%, respectively, of the 1941-70 normal rainfall, suggesting that a corresponding normal rainfall for the study catchments lies in the range 1500-1550 mm.

Interception loss

Monthly values of interception loss ranged from 15 to 75 mm, strongly reflecting monthly variations in rainfall. Annual interception losses were 416 and 456 mm in 1977-78 and 1978-79, respectively, or 28% and 31% of gross rainfall in the two water years. Mean monthly interception loss is 31% (± 1.5%, 1 S.E.). Monthly values varied from 19% to 51% but only 3 of 24 months had interception losses outside the range 22-38% of gross rainfall. Seasonal variations in interception loss are also apparent, with higher losses in the months October-March (34.6 ± 2.1%) than in April-September (27.3 ± 1.5%) (see also Rowe, 1979).

Runoff

Monthly runoff is strongly influenced by monthly rainfall except during the period December to March when high evaporative losses appear to override rainfall distribution (Figure 2). In late summer, runoff falls to 1-2 mm/month in catchments 1, 2 and 3, but not less than 4 mm/month in catchment 4. In the wettest months, runoff depths of 120-130 mm on catchments 1 to 3, and up to 140 mm on catchment 4 were recorded. Catchments 1, 2 and 3 have remarkably similar runoff production on monthly and annual bases, with mean annual runoff depths of 526 (± 6) mm and 539 (± 23) mm in 1977-78 and 1978-79, but catchment 4 produced significantly greater runoff of 644 mm in 1977-78 and 641 mm in 1978-79.

The continuous hydrograph for each catchment has been separated into quickflow (storm runoff) and delayed flow by the method of Hewlett and Hibbert (1967). The four catchments produce similar quantities of quickflow, ranging from 190 to 220 mm in 1977-78 and from 180 to 190 mm in 1978-79. Catchment 4 produced significantly more quickflow (218 mm) than the mean of catchments 1, 2 and 3 (196 ± 5 mm) in 1977-78 but did not produce significantly more quickflow in 1978-79 (190 mm vs 186 ± 4 mm).

In both water years catchment 4 produced 95 to 100 mm more delayed flow than the mean of the other three catchments (about 20 to 25 times the standard error of the mean for catchments 1 to 3). This difference is not an artefact of the standard separation slope (0.0055 $l\ s^{-1}\,ha^{-1}\,h^{-1}$). Halving or doubling the separation slope changes the apportioning between quick and delayed flow by about 50 mm in each catchment, but catchment 4 always yields about 95 mm more delayed flow than catchments 1 to 3. Forest-stand inventory data indicate that the density or species composition of the forest in the four catchments are not sufficiently different for annual interception losses in catchment 4 to be smaller by 100 mm. The similarity of the forest stands also suggests that smaller transpiration losses in catchment 4 are not involved. Rather, the larger area of catchment 4 (20.2 ha versus a mean of 7.1 ha for the other three), implies a substantially greater channel length, which could receive subsurface flow via moderately deep flow paths to a greater extent than in the smaller catchments.

Groundwater loss

Losses to deep groundwater within the Moutere Gravel are probably insignificant because of the low porosity and permeability of this formation (Johnston, 1979). The thick regolith (up to 5 m, Pearce *et al.*, in press) provides some storage, and pathways within the regolith may allow shallow groundwater from a small part of each catchment to bypass the gauging structures laterally. These losses are best analysed separately for catchment 4 and for catchments 1 to 3 grouped together because of the apparent differences in delayed flow response. The lowest segment of Figure 2 shows the residual of rainfall-interception-runoff plotted separately for catchment 4 and the mean for catchments 1 to 3. The similarity in seasonal trend is remarkable but the mean of catchment 4 losses is 9 (± 0.7) mm/month smaller than the grand mean of monthly losses for catchments 1 to 3 during the 1977-78 and 1978-79 water years. Differences between the residuals for catchment 4 and for the other three catchments range from 2 to 15 mm/month. Residual values for catchment 4 fall to 4-16 mm/month in late winter, but for the other catchments remain in the range 15-27 mm/month (0.5-1.0 mm/day, which is probably too great for winter transpiration rates).

The likely range in annual losses to shallow groundwater can be estimated assuming that there is negligible change in watershed storage from the end of one winter to the next ($\triangle S_{annual} = 0$), and that groundwater loss rates are constant through the year. If transpiration in the 3 months spanning the end of the water year is assumed to be zero, maximum groundwater losses in catchment 4 are estimated from the average value of rainfall-interception-runoff at the end of the water year as *c.* 110 mm/a. Maximum groundwater losses in catchments 1 to 3 are about 270 mm/a. If transpiration in late winter is estimated as 10% of summer rates (summer rates are indicated by the mid-summer values of rainfall-interception-runoff to be *c.* 60 mm/month), annual groundwater losses are *c.* 40 mm/a in catchment 4 and are *c.* 195 mm/a in catchments 1 to 3. The variation with catchment area suggests that the losses in catchments 1 to 3 are a measure of shallow groundwater bypassing the weirs to enter Donald Creek further downstream.

Transpiration

Transpiration has been estimated as a residual in the water balance only for the complete water year, using the separate estimates of groundwater loss for catchment 4 and for catchments 1 to 3. Transpiration from catchment 4 was estimated to be 375 mm in 1977-78 and 350 mm in 1978-79. For catchments 1 to 3 the average transpiration was estimated to be 340 mm in 1977-78 and 295 mm in 1978-79. Because transpiration values are estimated by difference they include all errors in the measurement and estimation of other components of the water balance. The difference between transpiration estimates for catchment 4 and for the other catchments is smaller than the range of the estimates for groundwater loss alone, and is smaller than combined uncertainties in the measured components of the water balance. (Rainfall is probably known to about ± 5% (75 mm/a), runoff to about ± 3% (15 mm/a) and interception loss to about ±3% (15 mm/a)).

Catchment water balances

An average annual water balance for the 2 water years 1977-79 for ctchments 1 to 3 is as follows:

Rainfall	= Interception	+ Quickflow	+ Delayed flow	+ Groundwater loss	+ Transpiration
1480 mm	= 435 mm	+ 190 mm	+ 340 mm	+ 195 mm	+ 320 mm

For catchment 4 the average annual water balance for the 2 water years 1977-79 is:

Rainfall	= Interception	+ Quickflow	+ Delayed flow	+ Groundwater loss	+ Transpiration
1480 mm	= 435 mm	+ 205 mm	+ 440 mm	+ 40 mm	+ 360 mm

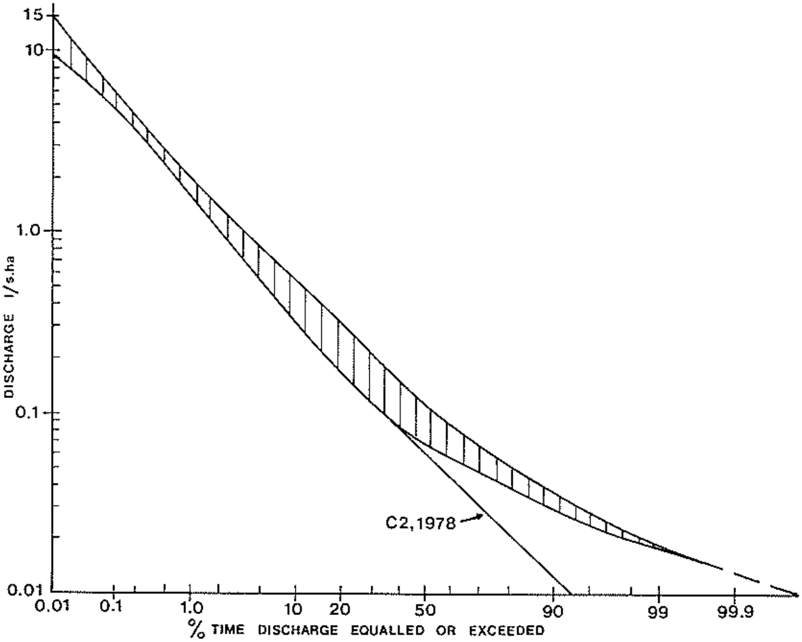

FIG. 3—Range of instantaneous flow-duration curves for individual catchments and individual calendar years of calibration period. All curves plot within the shaded zone except the low-flow part of the catchment-2 curve in 1978. Variation of curve position within the shaded zone is dominated by year to year differences.

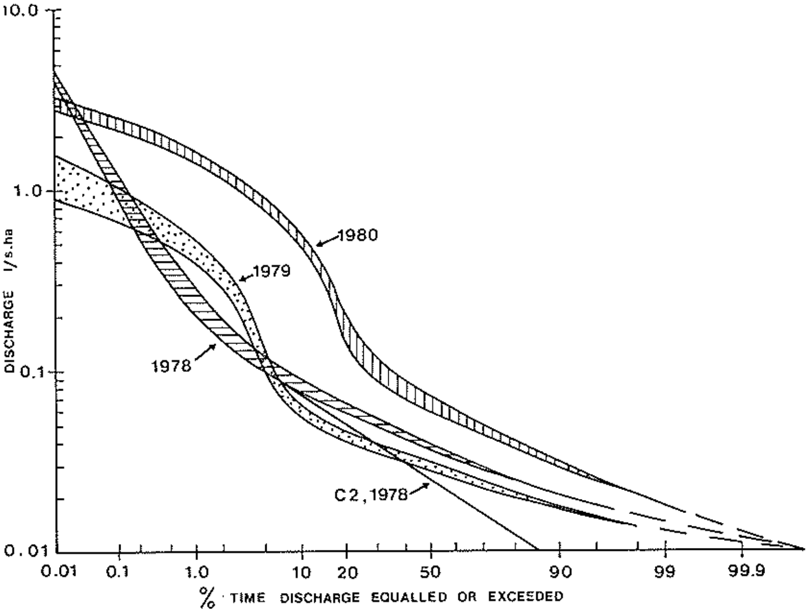

FIG. 4—Range of instantaneous flow duration curves for all catchments in the January-March periods of 1978, 1979, 1980. All curves plot within the shaded zones except for the catchment 2 in 1978 which departs from the other catchments at flows less than 0.1 *l* $s^{-1} ha^{-1}$.

FLOW DURATION AND SUMMER LOW FLOWS

The flow frequency distributions for all catchments are very similar and differences in the instantaneous flow-duration curves for separate catchments are smaller than variations between flow-duration curves plotted for different years. Figure 3 shows the narrow range within which all flow-duration curves fall. Flow exceeds 2 *l* $s^{-1} ha^{-1}$ only 1% of the time and exceeds 0.075-0.1 *l* $s^{-1} ha^{-1}$ 50% of the time. Only catchment 2 has any period of zero flow, 7% of 1978, thus zero flow is expected about 2.5% of the time based on the whole calibration period. High flow rates in the range 10-15 *l* $s^{-1} ha^{-1}$ persist for less than 0.05% of the total flow duration.

Mean annual specific discharge is 0.17 *l* $s^{-1} ha^{-1}$ for catchments 1, 2 and 3, and is 0.20 *l* $s^{-1} ha^{-1}$ for catchment 4. Scarf (1972) gives a mean annual specific discharge of 0.26 *l* $s^{-1} ha^{-1}$ for Donald Creek near its junction with Tadmor River. His estimate for the headwaters of 0.3 *l* $s^{-1} ha^{-1}$ is based largely on an estimated water balance using Thornthwaite's method for estimating evapotranspiration (Scarf, 1972, Figure 6 and p. 111). His evapotranspiration estimate (*c.* 600 mm/a, his Figure 3) is substantially smaller than the actual evaporation (755-795 mm/a) by both transpiration and interception found in this study. Using the measured evaporation data, Scarf's estimate would be reduced to about 0.24 l s^{-1} ha^{-1} for the Donald Creek headwaters, still 20-30% larger than the mean annual specific discharges we have measured.

Flow duration curves for the summer period of low flow (Jan-Mar) are of great importance to horticultural water users downstream, and data for these are shown in Figure 4. The influence of the rainfall distribution in each summer period is far greater than the differences between catchments in each year. The flow-frequency distributions for summer periods are distinctly non-log normal, partly reflecting the distribution and size of storms within this 3 month period of each year. For all catchments in all years, summer flow rates were less than 0.15 l s^{-1} ha^{-1} (1.3 mm/day) for 75% of the time. Flow rates were less than this rate more than 95% of the time in 2 of the 3 summers. Flow rates exceeded 0.15 mm/day (0.0175 l s^{-1} ha^{-1}) in 90% of all the summer periods, except in catchment 2, which did not flow for 15% of the 1978 January-March period (5% of the combined period). If these catchments are typical of native forest areas underlain by Moutere Gravel Formation, sustained summer low flows in the order of 0.15 mm/day can be expected from such areas in most summers.

STORM HYDROGRAPHS

Streamflow responses to storm rainfall are moderate in these catchments. Quickflow forms from 32% to 37% of total runoff, slightly more than estimated for the same catchments by Pearce and McKerchar (1979) from 15 months of flow data (Nov 75 - Jan 77). Figure 5 shows

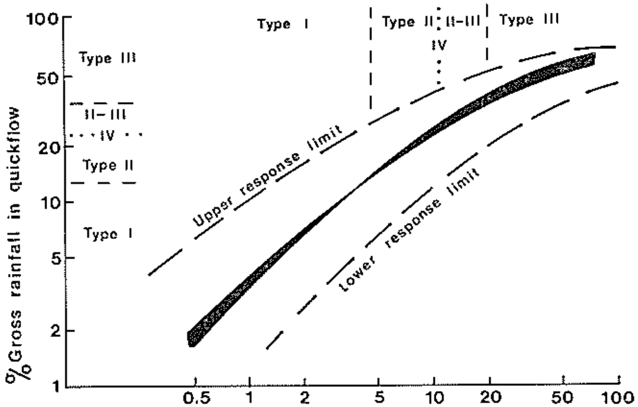

FIG. 5—Quickflow response of Big Bush experimental catchments (April 1977-March 1980 data). Eye-fitted average response for each catchment lies within the shaded zone. Different storm hydrograph shapes (Figure 6) are roughly correlated with event size as shown.

the range and average quickflow response to storm rainfall with changing size of event. The upper and lower response limits are for all catchments. Average responses for each of the four catchments lie within the shaded zone, the narrow range indicating that all catchments have remarkably similar quickflow response.

As indicated by Pearce and McKerchar (1979), storm runoff in events producing less than 2 to 5 mm of quickflow could be produced entirely by saturation overland flow or by other rapid-response mechanisms in wet areas near the channels. Field surveys indicate that the maximum extent of such wetlands occupies between 4% and 6.5% of total area in the four catchments. In all runoff events yielding more than about 5 mm quickflow, contributions of runoff from large fractions of catchment area are required to generate the observed hydrographs. During 1977-79, runoff events yielding more than 30 mm quickflow produced 44-47% of the total quickflow volume, and runoff events yielding more than 15 mm quickflow produced 70-75% of total quickflow in each catchment. In a typical event yielding 15 mm of quickflow (Fig. 5), the quickflow volume is equivalent to 30% of gross rainfall (*c.* 43% of net rainfall). The corresponding figure for an event yielding 30 mm of quickflow is 42% of gross rainfall (*c.* 60% of net rainfall). These figures for equivalence of net rainfall and quickflow volumes indicate that 70-75% of total annual quickflow volume is produced by events ($\geqslant$ 15 mm quickflow) in which quickflow must be generated from *at least* 40% of the catchment area, and nearly half the annual quickflow is produced by events in which quickflow must be generated from at least 60% of the catchment area. The large quickflow volumes, low rainfall rates compared with hydraulic conductivity of the regolith (Pearce and McKerchar, 1979), and the areal extent of quickflow generation required to produce the observed hydrographs strongly indicate that rapid infiltration of rainfall induces lateral subsurface flow, (1) through permeable horizons, (2) above permeability contrasts such as stratifications within the regolith and the regolith- bedrock contact, and (3) possibly through inter-connected porous zones such as former root channels.

Hydrograph types

Peak flow rates, rising-limb and recession-limb slopes and shapes, and quickflow volumes are strongly influenced by varying combinations of rainfall amount, antecedent moisture conditions, and rainfall intensity. None of these variables considered in isolation has any clear influence on hydrologic response. Most storm hydrographs can be qualitatively grouped into one of four shape classes (Figure 6), but there are many hydrographs that are transitional between shape classes. Variations in the timing and shape of storm hydrographs among the four catchments for any one storm are negligible compared with the different hydrograph responses of each catchment to different storms (Figure 7).

Type I hydrographs have rapid, steeply curved recessions, apparently a single recession from storage. They are typical of summer periods or dry antecedent conditions, and of small rainfall amounts irrespective of antecedent conditions. Rapid recession begins immediately on cessation

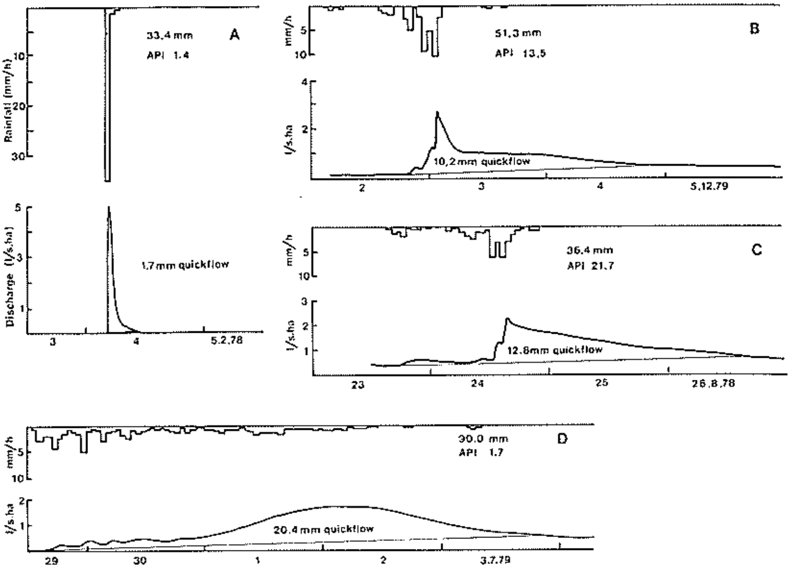

FIG. 6—Storm hydrograph types produced by varying combinations of rainfall amount, antecedent wetness (API) and rainfall rate. 30-day API value shown defined by $\mathrm{API} = \sum_{i=1}^{30} P_i/i$, where i is number of days preceding event.

Runoff value shown is quickflow volume defined by separation line.

A: Type I hydrograph
B: Type II hydrograph
C: Type III hydrograph
D: Type IV hydrograph

of rain or a major reduction in rainfall rate. Small hydrographs of this type may be superimposed on the recession of other larger hydrographs of very different shape. About 50 such hydrographs were recorded during 1977-79, most of which yielded only a small percentage of rainfall in quickflow. The example shown in Figure 6, resulting from a short-duration high intensity storm of 33 mm total rainfall, produced less than 2 mm of quickflow (5% of rainfall or 7% of net rainfall).

Type II hydrographs exhibit two distinct recession segments. The first is similar in shape and timing to the early recession of Type I hydrographs. The second is of much lower slope, is much less curved, and can be nearly flat. The example shown in Figure 6 was produced by a 50 mm storm in conditions of moderate antecedent wetness and low to moderate rainfall intensities typical of the winter and spring events which produce this type of hydrograph. In general, 15 to 20% of gross rainfall is

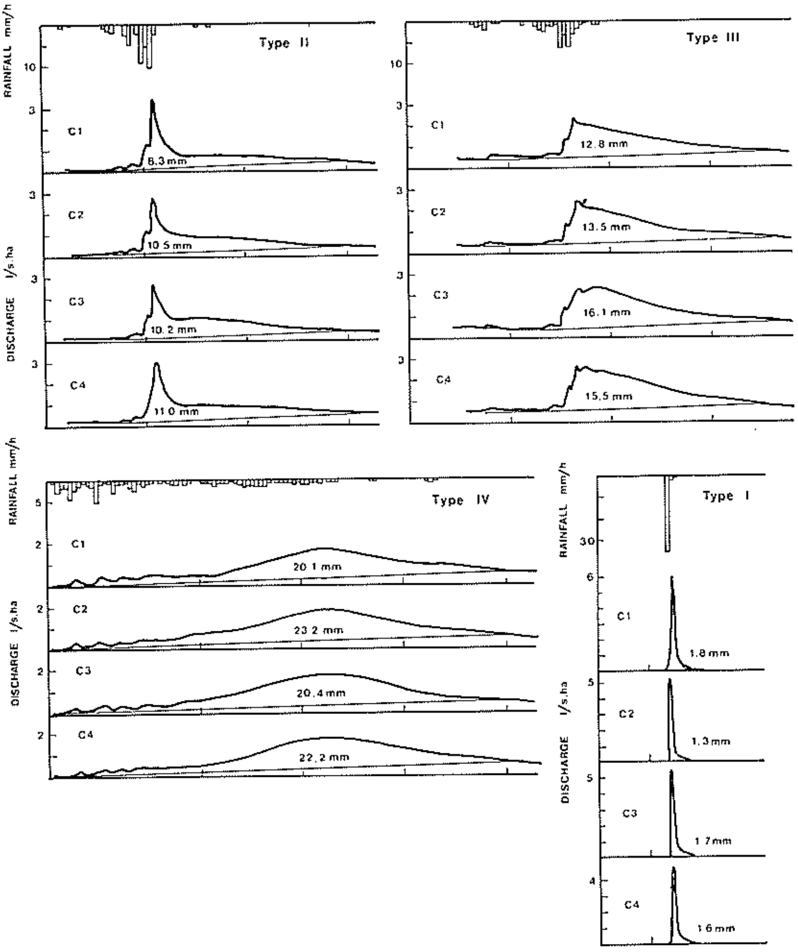

FIG. 7—Hydrographs plotted on the same time base for all catchments for the four events shown in Figure 6. Variation among catchments is negligible within each event.

yielded in quickflow (20-30% of net rainfall). About 35 Type II hydrographs were recorded during 1977-79.

Type III hydrographs have nearly straight recession limbs and are typical of moderate storms in wet antecedent conditions (such as the example in Figure 6) and of most large winter events. Such hydrographs typically yield more than 35-40% of gross rainfall in quickflow (50-55% of net rainfall). About 15 such hydrographs were recorded in 1977-79.

About 15 further hydrographs were recorded from rainstorms and antecedent wetness conditions intermediate between those for Type II and Type III responses. In these transitional hydrographs, an initial peak and rapid recession is followed by a smaller hydrograph peak with gentle rising and recession limbs. The recession limb of the second peak typically has a slope similar to Type III recessions and the second part of Type II hydrograph recessions. On several occasions over periods of up to 10 days, sequences of hydrographs have been recorded which progress from Type II to 2-peaked transitional shapes to Type III as antecedent wetness increases. Distinct quantitative combinations of rainfall amount, rainfall intensity, and conditions of antecedent wetness that would discriminate between Types II and III hydrographs have not yet been determined.

Only one Type IV hydrograph (Figure 6) has been recorded. It was the response to a long-duration, low-intensity storm following a long mid-winter period with little rain. The major flow peak lags at least 24 hours after the centre-of-mass of rainfall. The recession slope is similar to that in Type III hydrographs and the later parts of Type II hydrographs. Both rising and receding limbs have slopes similar to those in the second peak of hydrographs transitional between Types II and III. This hydrograph yielded about 25% of gross rainfall or about 35% of net rainfall in quickflow.

Response mechanisms and their contribution to annual quickflow totals

The four groups of hydrographs and the transitional shapes between groups suggest several hypotheses relating to storm runoff mechanisms. Type I hydrographs are probably produced by saturation overland flow, by a rapid, transient groundwater response (Sklash and Farvolden, 1979) on near-channel wetlands, or by other rapid-response subsurface flow. In these hydrographs, the volume of net rainfall falling on near-channel wetlands is sufficient to supply all the quickflow generated. The early part of Types II, III and II-III transitional hydrographs appears to be generated by the same rapid-response mechanism. The later parts of these hydrographs appear to be generated by a slower response mechanism, presumably subsurface transmission of net rainfall through the regolith matrix, rather than through rapid transmission zones. In Type II-III transition hydrographs, the second peak lags 12 to 24 hours after the peak of the Type I part of the hydrograph; shorter lag times appear associated with wetter antecedent conditions. In type III hydrographs, the lag time between the two responses has been greatly reduced (to perhaps 4-6 hours), so that the Type I recession and the hydrograph of the second flow mechanism combine to produce a nearly-straight recession from the hydrograph peak. Small peaks on the rising limb of Type IV hydrographs are probably produced by the Type I response mechanism but the main volume of quickflow is produced by the slower response mechanism, peaking at least 24 hours after the centre-of-mass of rainfall. In all other hydrographs, peak flow lags only a few hours from the centre-of-mass of rainfall.

Quickflow generated by Type I response accounts for much less than half the total quickflow, and possibly for as little as one-quarter. Most of the quickflow volume in Type II, III, and IV hydrographs and in transitional hydrographs is generated by slower response mechanisms with mean transmission times in the order of 12-24 hours for path lengths of 100 m or more. Between 50% and 75% of total annual quickflow is generated by these mechanisms. The large volume of regolith storage, the degree of regolith stratification, and the porosity and permeability of some regolith horizons appear to be significant factors in determining the relative importance of rapid-response and slower-response storm runoff mechanisms in these catchments. Very rapid-reponse storm runoff mechanisms are much less important in the production of large volumes of storm runoff in the Big Bush catchments than in other similar catchments studied by Pearce and McKerchar (1979) and by Mosley (1979).

COMPARISON WITH OTHER SIMILAR FORESTED CATCHMENTS

Small catchments near Reefton of comparable size, covered with very similar forest, and underlain by the regional equivalent of the Moutere Gravel Formation have been studied since 1974 (Maimai Catchments, Pearce *et al.* 1976, 1980a; O'Loughlin *et al.*, 1978, 1980). The Maimai catchments are steeper (35° average slope), with shorter slopes, and receive a higher annual rainfall (2600 mm) than the catchments at Big Bush. Principal differences in the hydrologic behaviour of the Maimai catchments compared with Big Bush are:

—greater runoff generation (60% vs. 40% of rainfall)
—much greater production of quickflow (65% vs. 35% of runoff)
—higher peak-flow rates
—steeper hydrograph recessions
—only one major hydrograph shape type, similar to Type I Big Bush hydrographs.

Similarities in the hydrologic behaviour of the two study areas are mainly confined to the evaporative components of the water balance. Interception losses as a fraction of gross rainfall are very similar, as is expected from the similarity of forest types (Rowe, 1979; Pearce and Rowe, 1979; Rowe, in prep.). At Big Bush, interception loss is about 30% of gross rainfall; at Maimai it is about 26% of gross rainfall. Seasonal variation in interception loss is significant in both areas. Transpiration losses estimated from water balance residuals lie between 300 and 360 mm/a in both areas. The different between the two areas in estimated transpiration is within the probable uncertainty on the estimates.

Mean specific discharge at Maimai is 0.5 l s^{-1} ha^{-1} (Pearce *et al.*, 1976), three times greater than at Big Bush, and high specific discharges are more frequent. At low specific discharges the Big Bush flow-duration curve are very similar to those for the Maimai catchments (Pearce *et al.*, 1976, Fig. 4), but the slope of the Maimai curves is greater than that of the Big Bush flow-duration curves. Thus, the flow rate exceeded 1% of the time in the Maimai catchments is about 6 l s^{-1} ha^{-1}; three times greater than that at Big Bush.

The greater annual runoff at Maimai partly reflects the greater annual rainfall, but the higher proportion of net rainfall yielded in runoff (*c.*

75-80% vs. 50-60% at Big Bush) partly reflects the more limited storage in the Maimai catchments. The regolith at Maimai (generally 0.5-1.0 m, McKie, 1978) is much thinner than at Big Bush (average *c.* 2.5 m) and does not contain the extensive zones of very porous angular gravels found at Big Bush (Pearce *et al.*, in press). The more limited storage and shorter, steeper slopes at Maimai combine to ensure that more than 50% of the annual net rainfall is transformed into quickflow compared with slightly less than 20% at Big Bush. Larger rainfall amounts and higher rainfall frequency at Maimai mean that antecedent moisture conditions are generally wetter than at Big Bush and this partly accounts for the more efficient generation of quickflow. The small watershed storage is frequently filled completely, or nearly so, so that the Maimai catchments are extremely responsive in terms of quickflow production. At Big Bush, where more regolith storage is available, and is less frequently recharged, much of the net rainfall is stored temporarily and discharged later as delayed flow, which accounts for 35-40% of net rainfall. At Maimai only about 27% of net rainfall appears in delayed flow.

Storm hydrographs at Maimai generally have higher peak flow rates than at Big Bush, essentially a combined effect of the smaller catchment storage and larger rainfall amounts at Maimai. Rainfall intensities do not vary greatly between the two areas, but on their own would not be expected to influence peak flow rates greatly (Hewlett *et al.*, 1977; Taylor and Pearce, in press). Hydrograph recessions at Maimai are similar to Type I hydrograph recessions at Big Bush irrespective of storm size, antecedent wetness or rainfall intensity. Hydrograph shapes such as those of Big Bush hydrograph Types II, III and IV have never been recorded in 7 years of flow records and several hundred storm hydrographs from the Maimai catchments. Storm runoff responses at Maimai are apparently generated either by a single process-pathway combination, or by overlapping process and pathways that have similar response times, lag times, and similarly limited opportunities for storage. The thin, rather uniform, unstratified regolith of the Maimai catchments presents few alternative pathways for transmission of subsurface flow and little storage opportunity that would permit the development of time lags between rainfall inputs and flow output.

OVERVIEW

Under natural forested conditions, the dissected hill country underlain by Moutere Gravel is only moderately hydrologically responsive compared with similar forested terrain in higher rainfall climates, e.g. Maimai catchments. The influence of the evergreen forest is most predominant in the evaporative components of the water balance, and then principally in the high losses by evaporation of intercepted rainfall. Nearly 30% of gross rainfall is evaporated from interception; data from similar stands (Pearce *et al.*, 1980b) indicate that 80-85% of the interception loss (the net interception) is completely lost to the ground phase of the hydrologic cycle. Of the estimated 1550 mm mean annual rainfall about 375 mm is cycled between only the exterior of the tree canopy and the atmosphere.

Estimated annual transpiration forms only 40-45% of the total annual evaporation and is less than the annual net interception loss.

The thick, stratified regolith, which provides substantial catchment storage, plays an important role is apportioning net rainfall between quickflow and delayed flow, and is probably the major factor in moderating the storm runoff response of the Big Bush catchments compared to that in other similar forests. Regolith properties and storage also seem important in producing an extremely wide range of hydrograph responses from storms with varying rainfall, antecedent conditions and intensities. Variations in the response of each of the study catchments to different storms are vastly greater than variations among the catchments in individual storms.

Mechanisms for generating rapid-response runoff are important in small hydrographs and in the early parts of most large hydrograph responses, but such processes yield much less than half the annual quickflow from the Big Bush catchments and possibly as little as one quarter of the annual quickflow. Most of the annual quickflow and most of the quickflow in large storm hydrographs is generated by slow-response mechanisms, with the major streamflow response lagging 6 to 24 hours after storm rainfall.

Despite small differences in estimated groundwater losses between catchment 4 and catchments 1 to 3, the hydrologic behaviour of the four catchments studied is remarkably consistent. Between-catchment variations in the major water balance components on monthly or annual bases are slight, and hydrograph responses to storm rainfall reveal insignificant variation among catchments. The consistency of hydrologic response of the four catchments makes them nearly ideal for testing the consequences of various wood harvesting and forest replacement methods, using classical treatment and control catchment methods.

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