A FIELD LYSIMETER TO STUDY WATER MOVEMENT AND NUTRIENT CONTENT IN A PUMICE SOIL UNDER *PINUS RADIATA* FOREST

II — DEEP SEEPAGE AND NUTRIENT LEACHING IN THE FIRST 12 YEARS OF TREE GROWTH

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ABSTRACT

A field lysimeter was used to record the seasonal incidence of deep seepage in a yellow-brown pumice soil planted with **Pinus radiata** D. Don. The volume of water which percolated to a depth of 2.7 m was recorded daily; bulked weekly samples were analysed for nutrient content. The study covers two separate periods of observations:

(1) 1962-64 (begun within a year of establishment of a second pine crop when the ground was still largely bare), and

(2) 1967-73 (initiated soon after canopy closure, by which time a litter layer had accumulated over the entire soil surface).

The deep seepage which invariably occurred each year indicates that the soil mantle is fully recharged annually. The lysimeter discharged percolate in September and October of each year and, more often than not, in August and July; discharge in the January to April period was unusual. The lysimeter index of deep seepage, which ranged from 54 to 573 mm, was closely correlated with gross annual precipitation; differences in the latter accounted for 99.8% and 65% of the variation in lysimeter discharge for the earlier and later periods respectively. Differences between gross annual rainfall and yearly deep seepage ranged from 973 to 1577 mm for the first period and from 1118 to 1555 mm for the second, and may be accounted for by evapotranspiration and changes in soil moisture stored.

Average annual leaching losses, based on the 7 years of data relating to established stand conditions, were (kg/ha): Si 39, Na 12.5, Ca 5.7, Cl 5.6, K 4.2, Mg 1.6, and P <0.01; no loss of inorganic nitrogen was detected.

INTRODUCTION

Construction details of a lysimeter built in central Kaingaroa Forest have been given by Will (1977), together with an outline of the principles underlying the choice of the design. The lysimeter was built in 1961; measurements of rainfall and of drainage flow and its nutrient content began in 1962. After an initial 3-year period, measurements were discontinued for 2 years and resumed in 1967; by that time the trees (*Pinus radiata* D. Don) planted after the construction of the lysimeter had grown sufficiently to give a closed canopy forest over the lysimeter and the surrounding area.

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This paper gives the results obtained during the initial 3 years after construction and tree planting (1962-64), and during 7 years after tree canopy closure (1967-73).

Over the period reported here, the cover crop had grown from yearling seedlings to sizeable trees. By 1973, basal area was equivalent to 42 m^2/ha, and average diameter at breast height 1.4 m (d.b.h.) was 18.6 cm, or, excluding suppressed trees with d.b.h. of 15 cm or less, 22.4 cm. Predominant mean height in February 1974 was 18 m. The trees in the immediate vicinity of the lysimeter were low-pruned (2 m) and slasher-thinned in 1971 to remove markedly suppressed trees; stocking after this thinning was equivalent to 1340 stems/ha. The disposition of trees within a 10-m radius of the centre-point of the lysimeter is shown in Fig. 1. Trees located either directly above or

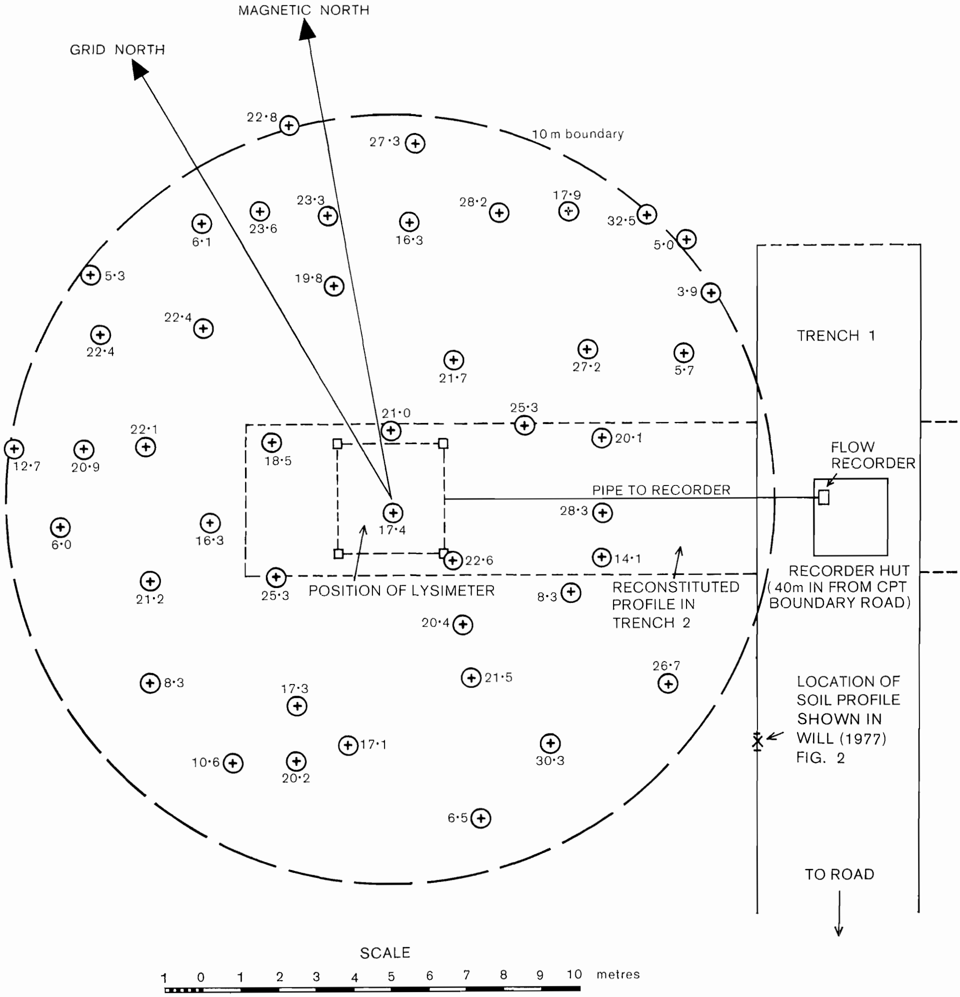

FIG. 1—Plan of the lysimeter area showing the disposition of stems within a 10-m radius of the lysimeter centre. Figures by each stem represent individual tree d.b.h. (cm) measured in 1973.

on the periphery of the lysimeter appear to have grown normally and are of near-average d.b.h. and height.

During the initial 3-year period of measurements, the surface of the ground in the lysimeter area was for the most part bare and this possibly resulted in some run-off losses. By the time measurements were resumed in 1967, however, the crowns of the 6-year-old trees had merged to form a forest canopy, and a layer of litter had accumulated to a depth of about 25 mm over the entire forest floor. These developments would undoubtedly have considerbly modified the amounts of rain, solar radiation, and nutrients reaching the forest floor. Experience has shown that, at this stage of development, the tree root systems have merged and a continuous mat of fine mycorrhizal feeding roots has occupied the topsoil. This enables the trees to intercept a large proportion of the moisture and dissolved nutrients on their passage through this part of the soil profile, and makes the efficient recycling of nutrients possible.

METHODS

Rainfall Measurements

Prior to canopy closure, rainfall measurements were made in a small clearing inside Compartment 69 located about 15 m from the lysimeter. Latterly, precipitation was recorded at a point about 60 m to the south of the lysimeter in a specially-cleared area alongside the boundary road in the adjacent compartment. Daily rainfall was recorded by a tipping-bucket rain-gauge, and annual gross precipitation by a 12.7-cm (standard New Zealand Meteorological Service) copper rain-gauge; the gauges were located within 3 m of each other.

Lysimeter Flow Measurements

Drainage water from the lysimeter travelled by natural fall through a pipe to a recording device in a small hut about 10 m away. During periods of discharge, the percolate trickled into a polythene vessel fitted with an automatic siphoning device. The frequency with which the vessel (1350 ml) emptied and filled in the course of a week was recorded as a trace on a chart fitted around a clockwork-driven revolving drum.

Sample Collection

After discharge from the flow-recording device, the water was funnelled into a 35-litre plastic storage drum. Each week the drum was emptied and a sample taken for laboratory examination. From 1968 onwards, all samples were stored in plastic containers at *c.* 4°C until analyses were completed. The containers were thoroughly cleaned with a laboratory surfactant (Decon 75 or 90) before use. Although it is possible that some sorption of phosphate could have occurred onto the surfaces of the plastic containers, occasional spot checks, wherein samples were collected in glass and analysed on return to the laboratory, failed to reveal higher levels of phosphate.

Water Analysis — see Appendix

RESULTS AND DISCUSSION

Rainfall

Total rainfall measured in the clearing near the lysimeter gives an index of the water input into the immediate forest area. Precipitation was almost entirely in the form of rain. Data on nutrient input in precipitation in the study area are very limited. Knight (1970) reported that rainfall collected in the open over a 12-month period (midwinter 1968 to midwinter 1969) at a site less than 1 km from the lysimeter, represented an input (kg/ha/yr) of Na 9.6, K 7.6, Ca 1.6, and Mg 1.4; no data for total N and P were recorded. Attempts to record nutrient input at tree-top level were unsuccessful; the precipitation was found to have become considerably enriched in ammonium-N, phosphate, and potassium—presumably through prior contact with the forest canopy occasioned by the turbulence at this level.

The relevance of the results of this study to a wider area than the immediate study site hinges in part on the degree of spatial variability in gross precipitation in forest areas with similar soil profile and topography. Gross annual rainfall totals recorded at the study site and the two nearest climatological stations — Wairapukao Forest 4 km to the south (Table 1) and Kaingaroa Forest headquarters 9 km to the north—bear a reasonably constant relationship to each other. For the 10 years that rainfall measurements were made at the lysimeter site, the mean annual rainfall averaged 1.06 (s.d. ± 0.05) times that at Wairapukao and 0.93 (s.d. ± 0.04) times that at Kaingaroa. Based on the limited data available, the least squares estimate of annual rainfall at the lysimeter site is given by the equation:

$$Y = 151 + 0.452\ X_k + 0.435\ X_w \quad (r^2 = 0.98^{***})$$

where X_k = annual rainfall at Kaingaroa

X_w = annual rainfall at Wairapukao

Based on this regression equation, the rainfall normal at the lysimeter site would be 1466 mm. Not only is the rainfall at the study site closely related to these climatological stations, but rainfall isohyets for the standard period 1941-70 (Fig. 2) show that most of the extensive forests on yellow-brown pumice soils in the Rotorua-Taupo districts receive similar annual rainfall.

Depth and Incidence of Deep Seepage

In Table 1, the depth* of percolate (D_o) discharged in each year of the study, and other relevant data, are shown in relation to gross annual precipitation (P_g). Although deep seepage occurred in each year, the actual amount recorded varied appreciably from year to year, ranging from 54 to 573 mm over the study period. As a percentage of P_g, deep seepage ranged from 3.9 to 26.7%. The number of days on which discharge was recorded also differed markedly from year to year, ranging from approximately 26 to 322 days.

As can be seen in Table 1, P_g ranged from 0.85 to 1.52 of the rainfall normal for Wairapukao climatological station (1413 mm — Anon, 1973). Differences in P_g accounted almost entirely for the variation in D_o in the first brief observation period

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* For purposes of comparison, it is convenient to express the lysimeter index of deep seepage (D_0) in the same linear units as precipitation (mm) by dividing the volume of percolate discharged (litres) by the surface area of the lysimeter (8.532 m²).

TABLE 1—Summary of lysimeter yearly drainage data shown relative to gross annual rainfall and yearly deviation from Wairapukao rainfall normal*

Year	Gross Precipitation Data			Lysimeter	P_g-D_o	$100. \frac{P_g\text{-}D_o}{P_g}$	Cumulative Drainage Time	
	Annual total P_g (mm)	Diff. from norm. P_g-P_n (mm)	Fraction of norm. $\frac{P_g}{P_n}$	Index of drainage D_o (mm)	(mm)	(%)	Total† (days)	Proportion of year (%)
1961‡	1231	—182	0.87	- -	- -	- -	- -	- -
1962	2150	+737	1.52	573	1577	78.3	322	88
1963	1179	—234	0.83	206	973	82.5	122	33
1964	1606	+194	1.14	354	1252	78.0	163	45
1965‡	1444	+ 32	1.02	- -	- -	- -	- -	- -
1966‡	1628	+215	1.15	- -	- -	- -	- -	- -
1967	1673	+260	1.18	118	1555	92.9	96	26
1968	1440	+ 27	1.02	211	1229	85.3	126	34
1969	1370	— 43	0.97	54	1316	96.0	31	8
1970	1616	+203	1.14	214	1402	86.8	93	25
1971	1891	+478	1.34	385	1506	79.6	194	53
1972	1315	— 98	0.93	110	1205	91.6	86	23
1973	1195	—218	0.85	77	1118	93.6	26	7
Ranges								
1962-64 max.	2150	+737	1.52	573	1577	82.5	322	88
min.	1179	—234	0.83	206	973	78.0	122	33
1967-73 max.	1891	+478	1.34	385	1555	96.0	194	53
min.	1195	—218	0.85	54	1118	79.6	26	7

- - No data

* Rainfall normal for Wairapukao Forest (B86551) is 1413 mm (Anon, 1973).

‡ Rainfall data for Wairapukao climatological station (B86551) located 4 km south of study site.

† An estimate of the cumulative total; because of the extremely slow rate of discharge which always preceded complete cessation of flow, the exact date of termination of discharge could not always be ascertained.

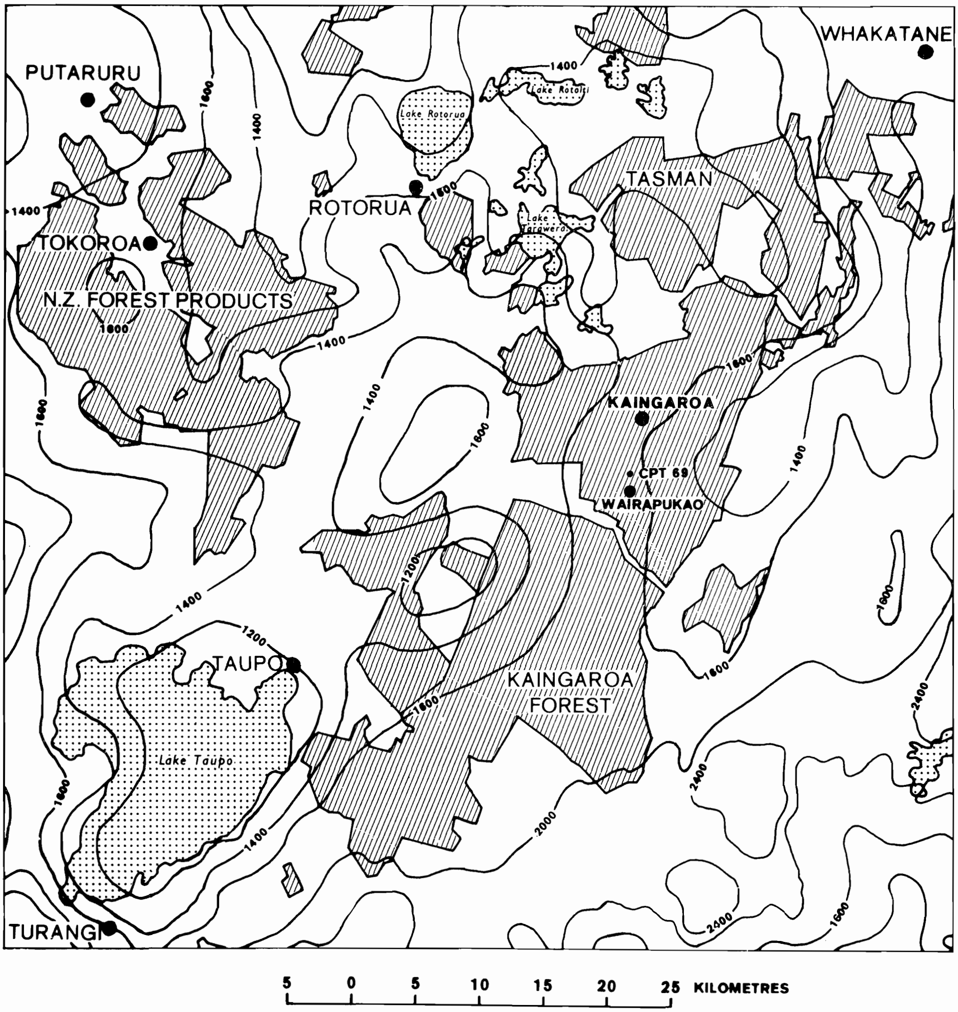


FIG. 2—Map of central pumice plateau showing rainfall isohyets (mm) for the standard period 1941-1970. Data from N.Z. Met. Serv. (unpubl.).

(1962-64), and for 65% in the second period (1967-73). The estimated regression lines for D_0 upon P_g for these two periods are given by the equations:

(1962-64) $Y = 0.38X - 246$ ($r^2 = 1.00$; $p = 0.05$) .... (1)

(1967-73) $Y = 0.38X - 410$ ($r^2 = 0.66$; $p = 0.05$) .... (2)

These simple regressions suggest that once the young trees are fully occupying the site, the annual yield of deep seepage is, on average, about 164 mm less than in the early establishment phase. They also predict that no deep seepage will occur if P_g is $\leq$648 mm and 1079 mm for the respective stages of stand development. As the former value is less than half the rainfall normal for the district (Anon, 1973), and the latter is only slightly more than three-quarters, it appears almost inevitable that deep seepage will occur in the early years after establishment, and highly probable that it will continue to occur annually under young well-established stands, on this and comparable sites. However, actual antecedent soil moisture conditions and seasonal rainfall distributions could affect the validity of this prediction in certain years.

During the study period not only did the total rainfall vary considerably from year to year, but the actual monthly totals often differed markedly from the long-term monthly normals (Anon, 1973). This in turn had its effect on the incidence and intensity of lysimeter discharge (Fig. 3). No two years were alike in seasonal distribution

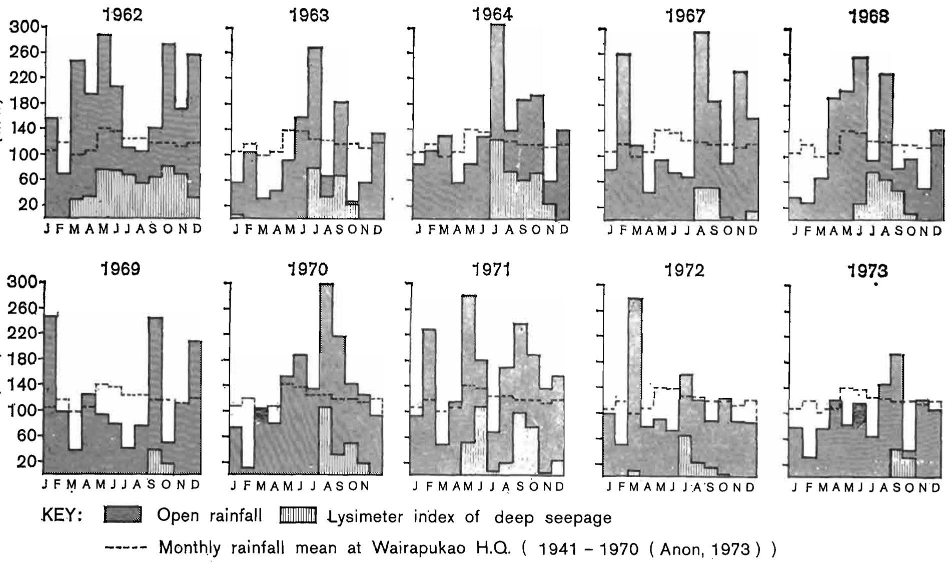
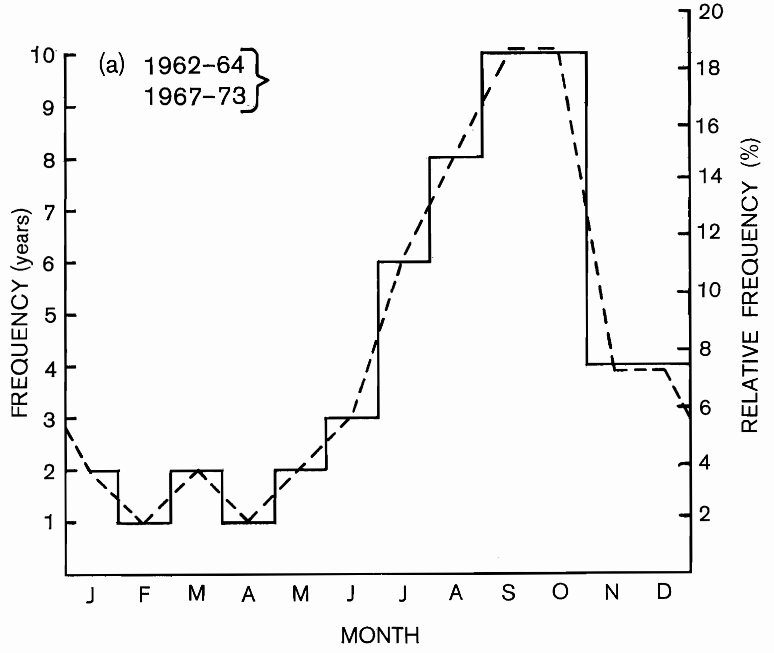


FIG. 3—Histograms for each of 10 years of observations showing gross rainfall recorded each month at the study site in relation to
(a) the long-term rainfall average for each month for nearby Wairapukao HQ, and
(b) the lysimeter index of deep seepage for each month.

of rainfall and this was reflected in the wide range of totals recorded for monthly deep-seepage flow. Figure 4 illustrates the seasonal incidence of deep seepage on the basis of number of observation years in which lysimeter discharge was recorded in individual months.

Daily rainfall and lysimeter discharge for each year of the study have been fully documented by Knight (1974). In the present shortened account a few examples have been selected to illustrate the considerable yearly variation observed during the study. The histograms in Fig. 5 depict daily rainfall and lysimeter discharge for the years 1971,1972, and 1973. In chronological order these years were: much wetter than average, slightly drier than average, and appreciably drier than average, as compared with the rainfall normal (1941-70) given for Wairapukao (Anon, 1973). In the following abstract



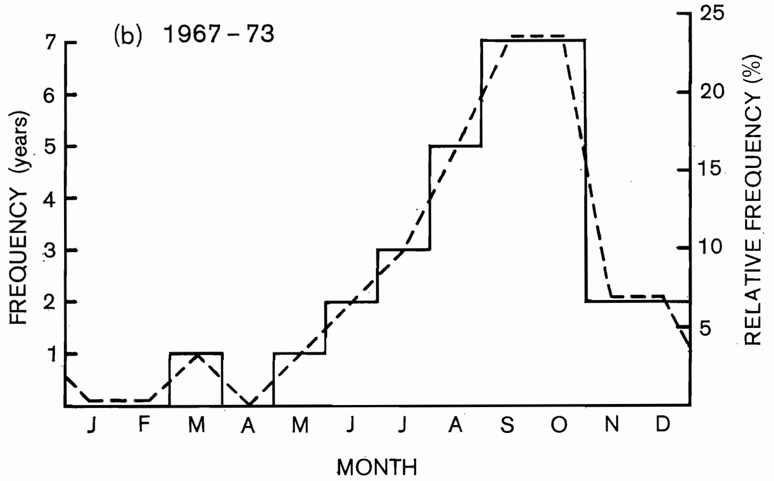


FIG. 4—Frequency histograms and polygons showing seasonal incidence of lysimeter discharge month by month for

(a) 10 years of observations,

(b) 7-year period since canopy closure.

of data, periods of lysimeter discharge (horizontal lines) are shown in relation to deviation from the monthly rainfall norm:

Year	J	F	M	A	M	J	J	A	S	O	N	D	12 months
	—	—	—	—	—	difference from norm (mm)				—	—	—	—
1971	—12	+111	—50	+11	+142	+43	—60	+32	+121	+72	+28	+40	+478
1972	—8	—69	+181	—28	—51	—67	+31	—8	—30	+6	—23	—32	—98
1973	—26	—85	—20	+16	—57	—21	—60	+29	+76	—72	+13	—11	—218

Gessel and Cole (1965) reported that the flow characteristics of water in the soil beneath a 35-year-old stand of Douglas fir (*Pseudotsuga menziesii* (Mirb.) Franco) were similar to the ascending, maximum, and recessional periods of a stream hydrograph. This observation also applies to the flow recorded in this present study. The histograms in Fig. 5 show that, once discharge of drainage water has commenced, rapid increases in the rate of flow generally follow within at least 48 hours of periods of intense rainfall. The peak flow is seldom sustained for longer than a day except when heavy rain persists for a number of days.

The largest flow recorded in any one 24-h period was equal to 16.3 mm, i.e., an average of 0.68 mm/h. Although flow was not normally measured on an hourly basis, spot checks showed flow rates of up to 0.74 mm/h during periods of peak discharge.

Based on data reported by Will and Stone (1967), the soil column above the base of the lysimeter has an estimated total moisture retention storage capacity of 1240 mm. This total, which refers only to the water retained for longer periods of time by capillary forces, does not include water detained in the soil mantle only briefly after a storm. Such temporary, or detention storage may well amount to an additional 200-400 mm, as Will and Stone (1967) found at a nearby site that at least 200 mm drained from a similar depth of soil in the 10-week period after saturation. As flow occurred in each year of the study it appears that the soil profile is fully recharged each year. When seasonal trends of precipitation and evaporation in the district are compared (Fig. 6) it is evident that a precipitation deficit is most likely over the November-March period, and an excess from April to October.

It follows that depletion of soil moisture can normally be expected over much of the November-March period and recharge during April-October. As can be seen in Fig. 4, flow from the lysimeter invariably occurred in September and October, and usually in August, i.e., the final 3 months of the "recharge season". Flow did not normally occur during January to April, i.e., the final 3 months of the "depletion season" and the first month of the "recharge season".

In the 7-year period after canopy closure an average of 66% of total flow occurred in the months of August-October and almost 90% June-October.

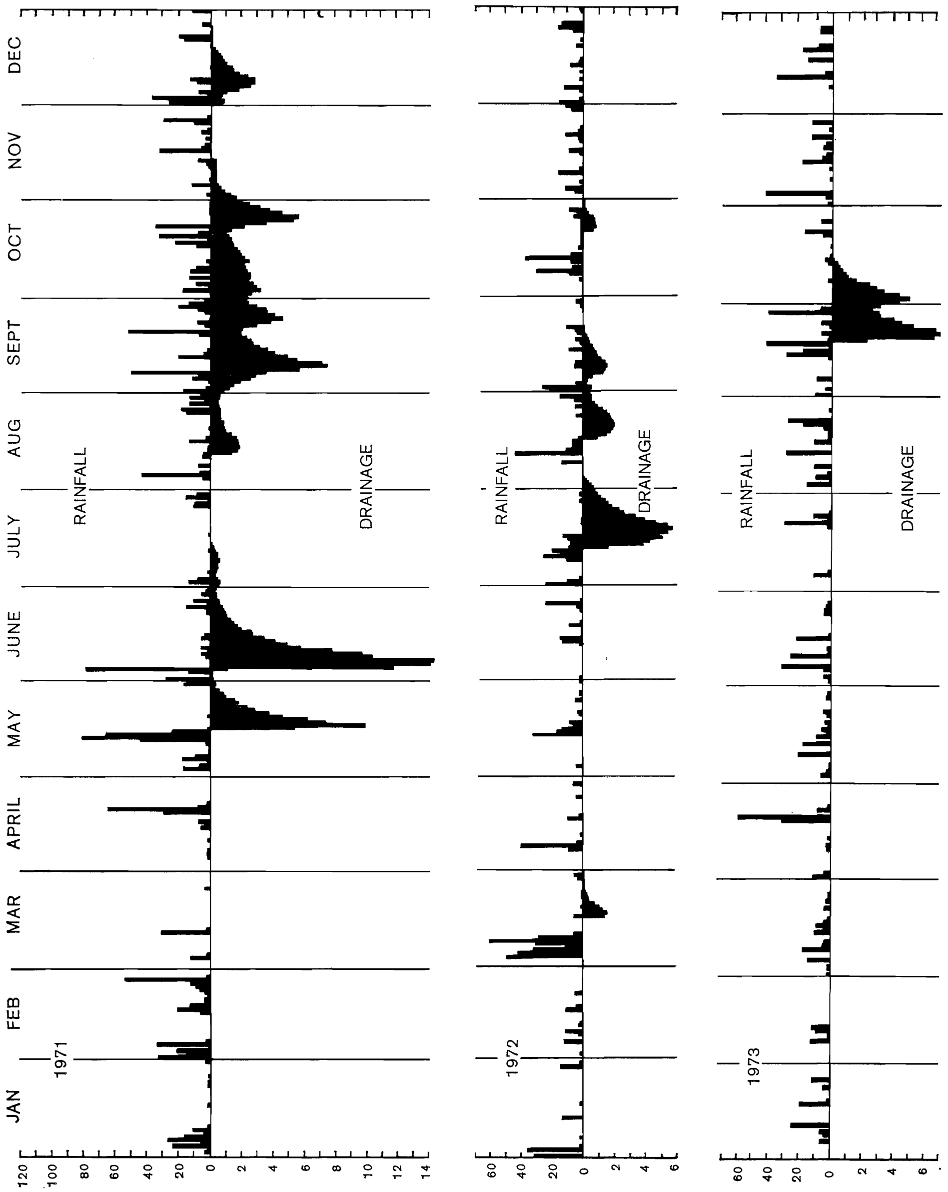


FIG. 5—Histograms showing daily lysimeter index of deep seepage (mm) in relation to gross daily rainfall (mm) for the years 1971-73.

Water Balance

As a more detailed treatment of the water balance aspect of the lysimeter study is intended for a later paper, the subject will be dealt with only briefly here in relation to the reliability of the lysimeter deep seepage index. It is generally recognised that lysimeters are far from perfect devices for measuring vertical water flow in soil columns, one reason being their innate susceptibility to boundary effects. The question arises, therefore, as to how much reliance can be placed on the lysimeter index of deep

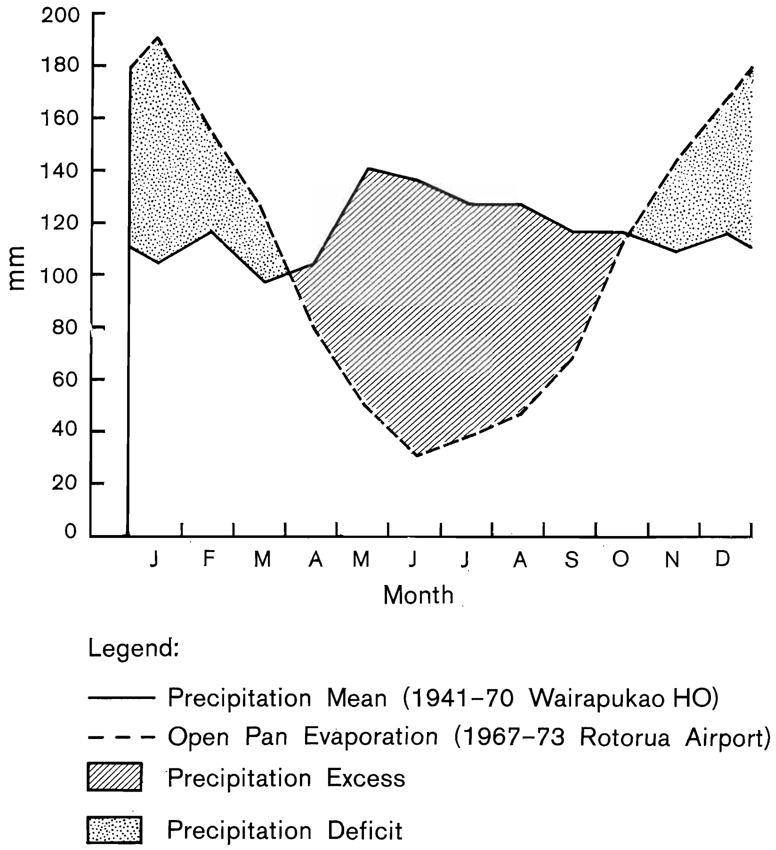


FIG. 6—Comparison of mean monthly precipitation and open pan evaporation data.

seepage. It must be admitted at the outset that some uncertainty exists as to whether the lysimeter with its low surround walls collects the entire volume of naturally occurring deep seepage. The uncertainty is engendered by the large differences recorded between gross precipitation (P_g), i.e., input, and observed deep seepage (D_o) (Table 1). It will be noted that the depth of water not accounted for by D_o in the observation period since canopy closure (i.e., $P_g - D_o$) averaged 1333 mm (s.d. ± 162) per year, ranging from 1118 to 1555 mm. On a weighted basis, D_o accounts for only 11.1% of P_g in this 7-year period. The strong correlation between ($P_g - D_o$) and P_g (see Fig. 7) suggests that the depth of water not accounted for by D_o increases rapidly with P_g.

Assuming no overland flow takes place at the site, and that D_o approximates closely to actual deep seepage (D_a), the water balance can be represented by the equation:

$$P_g - E_t - D_o - \Delta S = 0 \quad \text{..........} \quad (3)$$

where E_t = total evaporation plus transpiration

ΔS = change in stored moisture.

As regards the first assumption, it may be that some run-off occurred during intense rainstorms in the initial years of the study, when ground was still relatively bare.

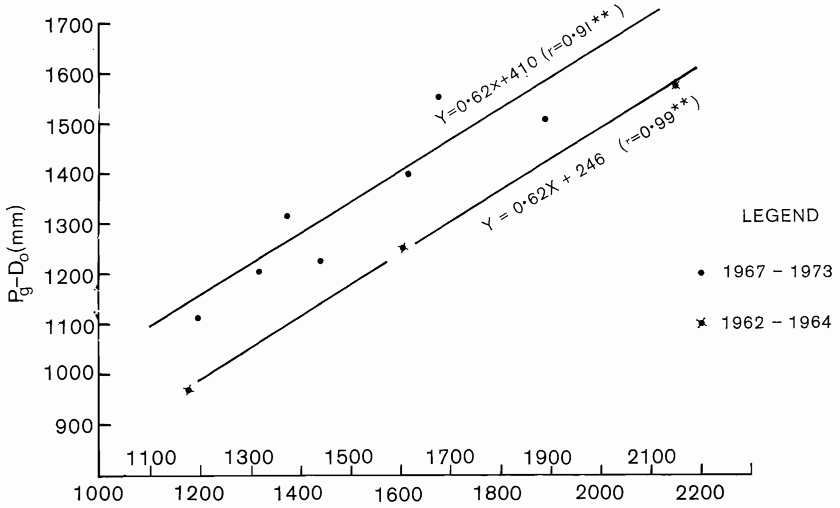


FIG. 7—Relationship between annual gross precipitation (mm) at the lysimeter site and the difference between P_g and the lysimeter index of drainage (D_0) for the two observation periods.

However, by the time the later period of observations began, the forest canopy and the accumulated litter layer largely precluded overland flow. As pointed out by Lull (1964), infiltration is maintained at a maximum by undisturbed forest canopy and floor; also, penetration and subsequent decay of tree roots in forest soils are responsible for their higher rates of infiltration as compared with cultivated and pasture lands.

If $D_o = D_a$, then $P_g — D_o$ should equal $E_t + \Delta S$ (see Equation 3). It would also follow from the strong positive correlation between $P_g — D_o$ and P_g ($r = 0.91$) that one or both of the terms $E_t + \Delta S$ must be very dependent on rainfall. The very large soil moisture retention capacity (*c.* 1240 mm) suggests that transpiration should be largely free from restriction imposed by soil moisture availability, and is therefore unlikely to depend on rainfall. But E_t can be considered as comprising the two components transpiration (T) and interception loss (I), where the latter term is taken to include evaporation from both the forest floor and the wetted aerial parts of the trees. Interception loss is commonly found to be rainfall dependent, usually amounting to about 0.2 to 0.3 P_g. By taking out interception loss from both sides of the linear equation for ($P_g — D_o$) on P_g ($Y = 0.62X + 410$) the following relationship can be derived:

$$P_g — D_o — I = 0.32\ P_g + 410$$

Then, if it is further assumed that the variability in $P_g — D_o$ is entirely due to differing water storage in the system at the end of each year, it follows:

$$P_g — D_o — I \simeq T \simeq 0.32\ P_g + 410$$

On this basis, mean transpiration ($\overline{T}$) is given by

$$\overline{T} \simeq 0.32\ \overline{P}_g + 410 \simeq 890\,\text{mm}$$

and the average depth of water evaporated annually would be of the order of 1340 mm, i.e., *c.* 90% of gross annual precipitation.

This amount, which is equivalent to 1.6 E_0 (where E_0 is the mean annual open-water evaporation (1967-70) reported by Finkelstein (1973) for Rotorua Aerodrome), appears high relative to other published data on consumptive use* of water by conifers (Sopper and Lull, 1967). However, it appears (D. S. Jackson, pers. comm.) that net annual radiation† in the region represents sufficient energy to evaporate at least 2000 mm of water per year. As pointed out by Will and Stone (*op. cit.*) the abundant and sustained moisture supply in this pumice soil is a factor in the "exceedingly high" dry matter production of *P. radiata* crops on these soils. When the uninterrupted moisture supply, the plentiful available radiant energy, and the year-long growing season are considered together, the tentative estimate for E_t, although high, does not seem altogether unreasonable.

Percolate Quality

The percolate discharged from the lysimeter was clear, colourless, and without odour. The electrical conductivity of the water was generally in the range 50-80 μS/cm and the pH was usually slightly acid. However, at the end of periods of flow when the flow rate amounted to less than 1 litre/day, the conductivity rose to as high as 500 μS/cm and the pH to 8.5.

The conductivity generally recorded for percolate indicates a low level of ionic material. The higher conductivity normally recorded in the terminal litre or so of percolate was probably caused by the longer residence time of the water in the soil. Because of the very small volumes normally involved, the higher concentrations of constituents recorded in the terminal flow make an almost insignificant contribution to the total amount of nutrients lost in a period of deep seepage. The concentration ranges and means for elements determined in the percolate are shown in Table 2 for individual years and for the separate observation periods.

When weighted average concentrations of inorganic drainage water constituents (calculated total weight in the percolate divided by the total volume discharged in a given period) for the first 3-year period of the study are compared with those for the 7-year period which followed canopy closure, it is evident that the concentrations of nitrogen, phosphorus, and calcium were appreciably lower during the latter period:

Period	Weighted average concentration (μg/ml)							
	N	P	K	Ca	Mg	Na	Cl	Si
1962-64	1.3	0.026	3.9	8.5	0.6	6.4	0.4	- -
1967-73	†	0.005	2.5	3.3	0.9	7.6	3.2	23.2

† none detected
- - not determined.

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* Use of water resulting in a large proportion of loss to the atmosphere by evapotranspiration.

† The difference between total upward and downward radiation fluxes, i.e., "the fundamental quantity of energy available at the earth's surface to drive the processes of evaporation, air and soil heat flux, as well as other smaller energy-consuming processes such as photosynthesis" (Rosenberg, 1974).

TABLE 2—Ranges and means of element concentrations in drainage water discharged from CPT 69 lysimeter (μg/ml)

Year	N	P	K	Mg	Ca	Na	Cl	Si
1962	0.08-0.95 (0.93)	<0.001-0.020 (0.005)	3.5-11.4 (4.5)	0.2-1.1 (0.5)	2.0-38.5 (9.0)	6.3-16.2 (7.4)	0.2-7.8 (0.6)	- -
1963	1.45-3.85 (2.04)	<0.001-0.078 (0.022)	2.2-4.9 (2.7)	0.3-0.8 (0.5)	3.2-37.0 (8.6)	7.5-20.0 (9.5)	0.2-0.9 (0.5)	- -
1964	0.96-1.76 (1.34)	0.047-0.070 (0.061)	2.8-5.6 (3.6)	0.5-1.0 (0.7)	4.2-10.8 (7.5)	1.5-8.4 (3.0)	<0.1-0.2 (0.1)	- -
1967	*	0.008-0.020 (0.011)	1.8-2.5 (1.9)	0.3-1.2 (0.6)	- -	- -	- -	- -
1968	*	0.001-0.005 (0.004)	2.4-4.3 (2.6)	0.7-1.0 (0.9)	2.5-5.2 (2.9)	6.2-9.8 (6.8)	0.6-2.0 (0.8)	22.0-23.1 (22.5)
1969	*	0.001-0.003 (0.002)	2.8-8.2 (3.1)	0.7-1.0 (0.9)	3.6-6.9 (3.0)	7.5-31.2 (9.1)	0.7-1.5 (1.4)	22.0-24.6 (23.7)
1970	*	0.001-0.002 (0.001)	1.4-6.0 (2.4)	0.6-1.3 (1.0)	2.6-10.6 (3.4)	6.9-13.6 (7.7)	1.8-4.0 (3.0)	
1971	*	0.002-0.013 (0.005)	1.8-39.1 (2.6)	0.6-1.6 (1.1)	1.3-75.0 (3.8)	5.1-46.8 (7.6)	3.3-5.3 (4.4)	21.8-27.1 (24.2)
1972	*	0.004-0.007 (0.006)	1.9-30.6 (2.3)	0.5-1.1 (0.9)	2.3-58.6 (3.2)	6.2-77.0 (7.2)	1.6-8.2 (3.8)	21.8-27.1 (24.2)
1973	*	0.003-0.004 (0.003)	2.2-13.1 (2.4)	0.9-1.3 (1.1)	3.4-9.0 (3.7)	6.8-77.8 (7.2)	4.5-9.9 (5.8)	16.3-21.4 (21.2)
Period range								
1962-64	0.08-3.85	<0.001-0.078	2.2-11.4	0.2-1.1	2.0-38.5	1.5-20.0	<0.1-7.8	
1967-73	*	0.001-0.020	1.4-30.6	0.3-1.6	1.3-75.0	5.1-77.8	0.6-9.9	21.2-24.3
Period mean and S.E.								
1962-64	1.44 ± 0.56	0.029 ± 0.029	3.6 ± 0.9	0.6 ± 0.1	8.4 ± 0.8	6.6 ± 3.3	0.4 ± 0.3	
1967-73	*	0.005 ± 0.003	2.5 ± 0.4	0.9 ± 0.2	3.3 ± 0.4	7.6 ± 0.8	3.2 ± 1.9	23.2 ± 1.3

* None detected. Bracketed values are weighted means. - - No data.

As the topsoil contains the highest exchangeable-calcium concentration and nearly all of the readily-available nitrogen and phosphorus of the profile (Will and Knight, 1968; Knight and Will, 1970), it seems likely that the reduction in concentrations of these nutrients in the drainage water resulted from fuller exploitation of this part of the profile by fine feeding roots.

Another factor which may have been partly responsible for the initially higher concentrations was the soil disturbance which was unavoidable during replacement of the soil layers. In a survey and discussion of lysimeters, Kohnke *et al.* (1940) note that the nitrate content of percolate from filled-in lysimeters is often "rather high" initially, but later decreases to a very low level. This they attribute to temporarily improved conditions for nitrification, i.e., better aeration and porosity brought about by stirring during replacement of the soil; once the soil has settled down and the spaces have closed up, the rate of nitrification falls off.

A possible explanation of the higher calcium concentrations recorded initially may be that the efforts to seal off the concrete base were not entirely successful, though this is only conjecture. Annual weighted averages for the first 3 years were successively 9.0, 8.6, and 7.5 μg/ml, and after canopy closure ranged from 2.9 to 3.8 μg/ml, suggesting a progressive reduction in concentration until a steady state was eventually reached.

Reasons for the increase in chloride concentration in the percolate from 1969 onwards are not clear; the increase might be attributable to the particular stage of litter decomposition, or possibly to the modified method of chloride analysis used (see Appendix). The data on rainfall chloride content reported by Knight (1970) suggest that, on an annual basis, the rainfall input is likely to exceed leaching losses by a substantial margin, regardless of the apparent increase.

In the period of observations after canopy closure, concentrations of both nitrate and ammonium forms of nitrogen in the percolate were consistently below the threshold of detection for the methods used. Phosphorus, as dissolved orthophosphate, ranged from 0.001 to 0.020 μg/ml with a weighted average of 0.005 μg/ml. This is consistent with other published results which generally indicate that forest drainage is typically low in nitrogen and phosphorus (Cooper, 1969; Ryden *et al.,* 1973).

Dissolved silica is a major constituent of the percolate and is presumably derived mainly from active weathering of the pumice ash soil, as precipitation is usually almost free of silicon (0.1 to 1.0 μg/ml — Allan *et al.,* 1974). Kohnke *et al.* (1940) have noted that low concentrations of electrolytes in the soil solution seem to encourage the percolation of silica because, under such conditions, the inorganic soil colloids become easily peptized and comparatively mobile. The general order of cation abundance was Na>Ca>K>Mg. Losses of the cations sodium, potassium, calcium, and magnesium were relatively large compared with those of phosphorus.

Cation and silicon concentrations recorded from week to week in the percolate samples generally ranged within narrow limits despite considerable fluctuations in the net volume of water discharged. When discharge had practically ceased, i.e., less than about 1 litre/week, concentrations of Na^+, K^+, and Ca^{++} in the percolate tended to rise steeply. Such terminal increases in the concentrations of these cations account for the relatively wide ranges for these elements which sometimes appear in Table 2. Over the main period of discharge, however, the concentrations were generally close to the values shown for weighted means in the same Table. Leaching losses recorded in any one year were therefore almost directly proportional to the volume of percolate discharged (Fig. 8).

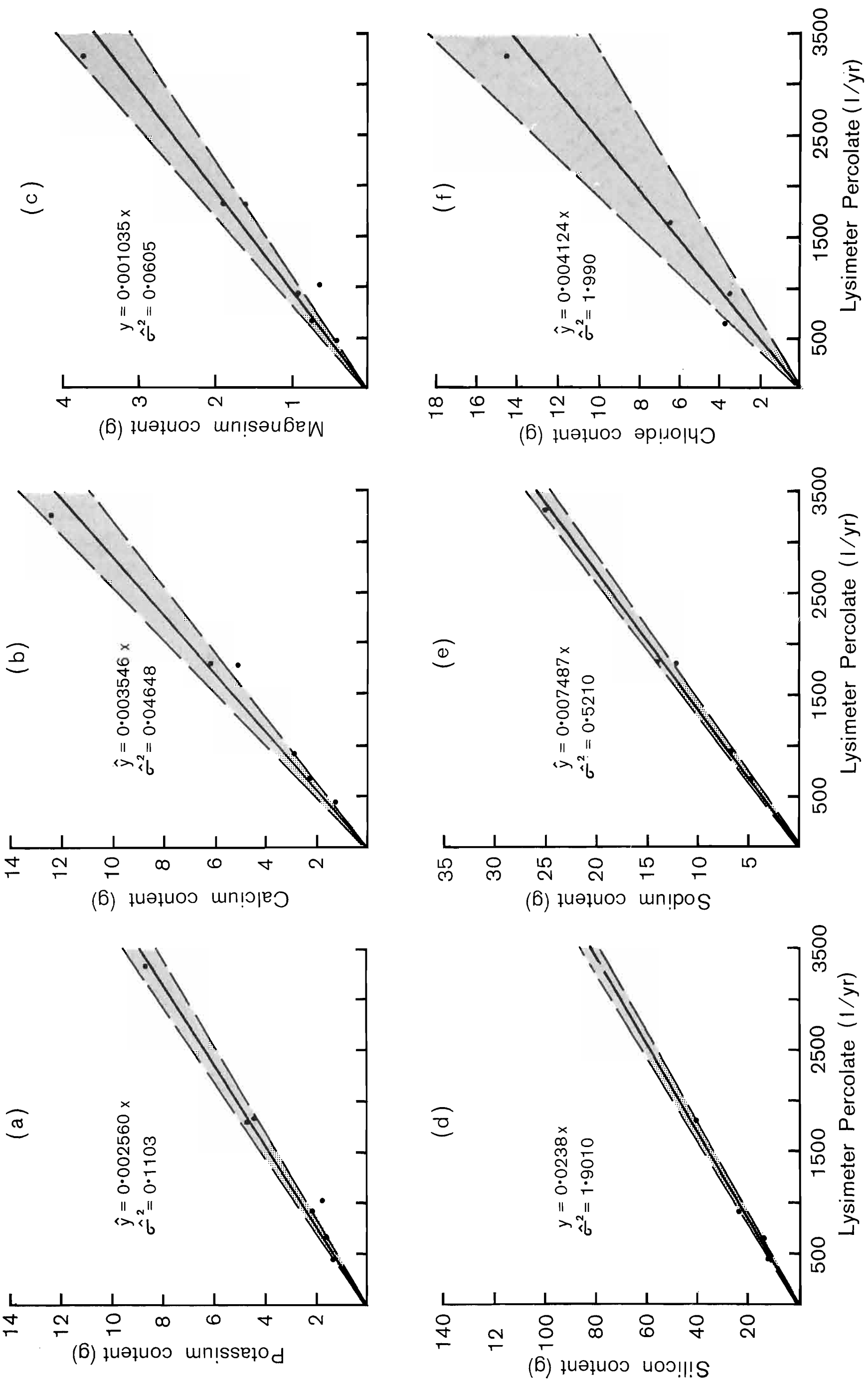

FIG. 8—Relationship between total volume of percolate (litres) discharged annually by the Cpt 69 lysimeter and total percolate content (grams) of (A) Potassium, (B) Calcium, (C) Magnesium, (D) Silicon, (E) Sodium, (F) Chloride. The 95% confidence intervals are also shown on each graph.

According to Jordan and Kline (1972), "ecosystem drainage water in which the element concentration does not vary with volume indicates that the plants growing in the ecosystem do not suffer from a lack of these elements". A small response obtained in a multi-element fertiliser trial in the same compartment has been attributed entirely to applied nitrogen (Ballard, 1971). This, and the fact that no dissolved inorganic nitrogen was detected in the percolate, tend to support the above contention.

Leaching Losses of Nutrient and Mineral Elements

When the study was planned over a decade ago, various considerations such as cost and workload precluded any replication of the lysimeter facilities. It has not been established therefore, that the results obtained are representative of more than the immediate study site. However, the soil mantle, which has been built up by deposition of successive volcanic ash showers, is similar in both profile (Pullar, 1968) and moisture retention properties (Will and Stone, 1967) over a wide area of the 150 000-ha forest which covers the Kaingaroa Plains. The results of this study should therefore provide at least a broad indication of the magnitude of leaching losses under similar young established stands in this forest area.

Estimates of annual leaching losses based on the data obtained from the lysimeter during the two measurement periods are given in Table 3.

The results obtained are consistent with others which indicate that leaching losses of nitrogen* and phosphorus are generally very small under undisturbed forest ecosystems. Thus Cole *et al.* (1967) reported annual leaching losses under 36-year-old Douglas fir of 0.2 and 0.6 kg/ha/yr for nitrogen and phosphorus respectively.

Fredriksen (1972) has noted that a Douglas fir forest system in western Oregon "retains nitrogen very effectively" and suggested that "this retention property may be general for Douglas fir forests in that region". He observed that "nitrate-N outflow is regulated to much less than input in precipitation (0.004 kg/ha/yr compared with an input of 0.06 and 0.20 kg/ha in two separate years)", and also found that ammonium- and nitrite-N were not present in the streamflow in measurable quantities. The streamflow load of orthophosphate, which he considered was derived from mineral weathering, remained fairly constant throughout the year ranging from 0.01 to 0.02 μg/ml of P; total P leaving the watershed in streamflow was estimated at 0.52 kg/ha/yr.

Cooper (1969) and Ryden *et al.* (1973) quote data from various sources which suggest that amounts of annual losses of P from stable temperate forest watersheds are generally comparable over a wide geographic area. Figures quoted by these authors for P losses in streams in such situations range from 0.02 to 0.68 kg/ha/yr, and in several instances amount to rather less than 0.1 kg/ha/yr.

The annual losses of P presented in Table 3 refer to dissolved inorganic phosphate only, as no other forms were routinely determined. It should be noted that the total P data quoted by Ryden *et al.* (1973) embrace all forms of P in streamflow and could be expected therefore to include any P contained in suspended particulate matter.

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* The lysimeter is currently being used to study the movement of applied N through the soil; an experiment in which urea tagged with 5% ^{15}N was applied to the forest floor in the lysimeter area at the rate of 150 kg/ha is in progress at the time of writing.

TABLE 3—Summary of annual leaching losses (kg/ha) extrapolated from lysimeter data for the periods 1962-64 and 1967-73

Year	"Open" rainfall (mm)	Drainage (mm)	Extrapolated Loss (kg/ha)							
			N	P	K	Mg	Ca	Na	Si	Cl
1962	2150	573	5.4	0.026	25.8	3.1	51.8	42.2	- -	3.2
1963	1179	206	4.2	0.045	5.6	1.1	17.6	19.6	- -	1.0
1964	1606	354	4.7	0.217	12.6	2.5	26.5	10.5	- -	0.4
Total	4935	1143	14.3	0.288	44.0	6.7	68.7	72.3	- -	4.6
Mean	1645	378	4.8	0.096	14.7	2.2	34.4	24.1	- -	1.5
	(±487)	(±185)	(±0.6)	(±0.105)	(±10.3)	(±1.01)	(±23.7)	(±16.3)	- -	(±1.5)
1967	1673	118	*	0.013	2.3	0.8	(4.2)	(8.8)	(28.0)	(4.8)
1968	1440	211	*	0.008	5.5	1.8	6.1	14.3	47.5	1.8
1969	1370	54	*	0.001	1.7	0.5	1.6	4.9	12.9	0.8
1970	1616	214	*	0.002	5.2	2.2	7.4	16.4	(50.9)	6.5
1971	1891	385	*	0.019	10.2	4.3	14.6	29.4	93.2	16.9
1972	1315	110	*	0.006	2.5	1.0	3.5	7.9	26.6	4.1
1973	1195	77	*	0.003	1.8	0.9	2.8	5.6	15.3	4.4
Total	10500	1169	*	0.052	29.2	11.5	40.2	87.3	275.4	39.3
Mean	1500	167	*	0.007	4.2	1.6	5.7	12.5	39.3	5.6
	(±239)	(±114)		(±0.007)	(±3.1)	(±1.3)	(±4.4)	(±8.6)	(±27.8)	(±5.3)

* None detected

- - Not determined

Values shown in brackets for 1967 and 1970 are estimates for missing data calculated from regression equations given in Fig. 7. Values for s.d. in row below mean.

Whereas appreciable amounts of suspended material can enter streamflow during periods of high flow, none was present in the lysimeter percolate. This may account, in part at least, for the relatively small average loss of P per year in this study as compared with losses reported in the various watershed studies referred to by Ryden *et al.* The low orthophosphate-P concentration found in the lysimeter percolate (average 0.005 μg/ml for the 1967-73 period) supports these authors' statement that "the 'chemical sieving' action of the soil plays a major role in maintaining the consistently low dissolved inorganic P concentration in forest streams".

As reported in several of the watershed studies referred to above, leaching losses of the cations Na^+, K^+, Ca^{2+}, and Mg^{2+} were large compared with those of N and P. As far as can be judged from the limited data available on nutrient input at the site (Knight, 1970), annual leaching losses of K, and probably Mg, are likely to be offset by the quantities added by precipitation, while those of Ca could exceed the rainfall input in years when appreciable deep seepage takes place. Losses of silicon as dissolved silica are substantial; similar large losses reported in other studies, e.g., Rothacher *et al.* (1967) and Fredriksen (1972), have been attributed largely to mineral decomposition. Kohnke *et al.* (1940), in a survey of lysimeters, noted that silica is lost in great quantities from most soils.

The generalisations which Cooper (1969) makes regarding nutrient output from managed forest could equally well be used to describe the results of the present study.

(1) "Forest drainage ordinarily carries a minimal concentration of nutrient elements."
(2) "Water draining from undisturbed forests sets a base-line for water quality."
(3) "Nitrogen and phosphorus are typically low in drainage from forest ecosystems."
(4) "Forest cover regulates nutrient output both by storing nutrients in standing vegetation and by influencing the flow of water through the soil profile."

CONCLUSIONS

This study, conducted over more than a decade, at a site broadly representative of wide areas of pine plantations located on yellow-brown pumice soils in the volcanic plateau region, has provided information previously lacking as to:

(a) when deep seepage is most likely to occur;
(b) the extent to which deep seepage is influenced by annual and seasonal variations in rainfall;
(c) the chemical quality of deep seepage water; and
(d) the amounts of nutrients lost annually from the forest system in deep seepage.

The main conclusions, relating to well-established young *P. radiata* stands (up to 11 years old) growing on comparable pumice soils in this region, are as follows:

(1) Deep seepage is strongly seasonal as a result of an annual soil moisture cycle in which an extended summer period of soil moisture depletion is followed by a winter period of recharge. The moisture flux in spring and autumn, which is governed by prevailing weather conditions, is less predictable.
(2) Deep seepage is most likely to occur June-October, and especially in the last 3 months of this period after autumn and winter rains have recharged the soil mantle to field capacity. Deep seepage does not normally occur from January to April inclusive; throughout this period, the forest tends to withdraw moisture from the soil faster than it can be replenished by rainfall.

(3) Once deep seepage has commenced, it may last for weeks or months depending on the subsequent pattern of rainfall. A succession of unusually wet months with frequent heavy rainstorms can be expected to result in an extended period of deep seepage. The rate of deep seepage is governed by the intensity of rainfall. Large increases in the rate of deep seepage generally follow within 1-2 days of a heavy rainstorm. Owing to delayed drainage, deep seepage characteristically continues for a week or more into a relatively rain-free period. Several distinct periods of deep seepage may occur in a single year.

(4) The amount of annual deep seepage is positively correlated with gross annual rainfall. At the site studied, differences in gross annual rainfall 1967-73 account for 65% of the variation in annual lysimeter deep seepage without correction for water stored in the soil. The lysimeter index has ranged from 54 to 385 mm per year, averaging 167 mm over the 7-year period since canopy closure. This amounts to an average of only about 11% of the gross rainfall. A large part at least of the observed difference can be accounted for, however, by interception and evapotranspiration processes.

(5) The limited data available from the study suggest that once the trees are fully occupying the site, the annual yield of deep seepage may on average be about 164 mm less than in the early establishment phase.

(6) Water leaving the tree rooting zone of this pumice-based pine forest is, under natural conditions, near neutral in pH and very low in chemical content with conductivity of between 50 and 80 μS/cm at 20°C. Inorganic nitrogen in either ammonium or nitrate form is not present in readily detectable concentrations, and phosphorus in dissolved orthophosphate form occurs only at concentrations of about 0.005 μg/ml P.

The strong retention of ammonium-N and orthophosphate-P against leaching, is an important factor in the natural capacity of these soils to sustain high productivity in successive tree crops. Average concentrations of other major nutrient and mineral elements (μg/ml) are silicon 23.2, sodium 7.6, calcium 3.3, chlorine 3.2, potassium 2.5, and magnesium 0.9.

As concentrations of these elements remain relatively constant despite wide fluctuations in the rate of deep seepage, annual losses are almost directly proportional to the amount of deep seepage. Average losses per year are tentatively estimated as follows:

			(kg/ha)				
N	P	K	Mg	Ca	Na	Si	Cl
†	0.01	4.2	1.6	5.7	12.5	39.0	5.6

† none detected

Comparison of these estimates with the limited data available on annual nutrient input in gross precipitation at the site, suggests that a net loss is likely only for silicon and possibly calcium.

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Appendix — Chemical analysis of water samples

As many of the methods used to analyse samples during the 1962-64 period were superseded in the 1967-73 period by methods which were either more convenient or more sensitive, the methods for both periods are dealt with separately below.

1962-64

Nitrogen: By distillation with magnesium oxide and Devarda's alloy; any ammonia produced was collected in a 4% boric acid solution and titrated against 0.02 N HCl.

Phosphorus: After evaporation to dryness, soluble silica in the sample was rendered insoluble by baking. Phosphorus was determined in an acid extract of the residue using the molybdo-vanadate yellow colorimetric procedure.

Chloride: By titration against standard mercuric nitrate after concentration by evaporation.

Potassium and sodium: By emission flame photometry after concentration by evaporation.

Calcium and magnesium: By atomic absorption spectrophotometry after concentration by evaporation.

1967-73

Ammonium-nitrogen:

1968 samples — colorimetric method using indophenol (Anon, 1968) except that distillation was employed.

1969 samples — the indophenol blue colorimetric method described by Rommers and Visser (1969).

1970-73 samples — an improved indophenol method described by Harwood and Kühn (1970).

Chloride:

1968 samples — colorimetric method using mercuric thiocyanate (Vogel, 1964).

1969-73 samples — colorimetric method using mercuric thiocyanate (Anon, 1968).

Calcium, magnesium, potassium and sodium: These cations were determined by atomic absorption spectrophotometry. No pre-concentration of the percolate samples was found necessary. Precautions were taken to overcome possible enhancement or suppression. For determination of calcium the solutions to be flamed were prepared so as to contain 1500 μg/ml strontium as strontium chloride in order to counteract possible interference from aluminium, phosphate, or sulphate (David, 1960). Where it was necessary initially to use magnesium standards prepared from magnesium sulphate, lanthanum chloride (10 000 μg/ml lanthanum) was used (Fishman, 1966) in place of strontium to avoid precipitation of insoluble strontium sulphate. The levels of aluminium, phosphate, and sulphate subsequently found in the percolate are such that the use of suppressants is probably unnecessary. Calcium standards were made up to contain Na and K in concentrations comparable to the percolate samples to compensate for possible enhancement effects due to these elements. Potassium was determined after the addition of 200 μg sodium/ml (as sodium chloride) to both standards and samples to suppress potassium ionization in the flame (Fishman, 1966).

Phosphate: The 1968 samples were concentrated as in previous years, but phosphate was subsequently determined by the molybdenum blue method as described by Murphy and Riley (1962). In 1969, the modified molybdenum blue method described by Edwards **et al.** (1965) was used with extraction into isopropyl alcohol. From 1970-73 phosphate was determined colorimetrically as phosphomolybdate blue after extraction of the blue complex in isobutyl methyl ketone, using a New Zealand DSIR Chem. Div. procedure (Anon, 1970).

Silicate: The colorimetric method (Anon, 1966) in which the silicomolybdic acid, formed when the silicate reacts with molybdate in an acid medium, is reduced to molybdenum blue with a sodium sulphite/1-amino-2-naphthol-4-sulphuric acid mixture.

Nitrate:

1968 samples — the colorimetric phenol disulphonic acid method described by Chapman and Pratt (1961).

1969-73 samples — ultra violet spectroscopy (Cawse, 1967).

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