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A WATER BALANCE ASSESSMENT OF THE NEW ZEALAND RAINFALL

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ABSTRACT

A simple water balance analysis of New Zealand daily rainfall data provides an approximation to the distribution of water surpluses and deficiencies with respect to the average seasonal water need.

A simple water balance analysis of daily rainfall data from representative stations can provide a broad-scale climatological view of the availability of water supply derived from rainfall, firstly as stored soil moisture available to vegetation, and secondly as the surplus ultimately available for streamflow (see e.g., Gabites, 1956).

In this study, as a first approximation, water demand for vegetation was taken as the average rate of potential evapotranspiration for the month in question, as given by Thornthwaite's formula (*PE*). If the available water (soil moisture plus rainfall) over a period was insufficient to meet this demand, the amount by which it fell short (as calculated) was taken as a measure of water deficiency or irrigation requirement (*DE*). Such periods when soil moisture is exhausted may then be termed days of 'agricultural drought' (Rickard, 1960) or 'days of soil dryness'. An arbitrary limit was chosen for soil moisture capacity (*S*), and 'actual' evapotranspiration (*AE*) was considered to continue at the potential rate until the available soil moisture was used up. Each day's rainfall (*RR*) was allocated towards the day's water need (*PE*). Any remainder replaced soil moisture previously withdrawn from storage (*DS*), and then provided a surplus for 'runoff' (*RO*).

The 'actual' evapotranspiration (*AE*), surplus (*RO*), water deficiency (*DE*), number of 'days of soil dryness' (*ND*) and num-

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ber of days with water surplus (NR) are given by the following relations:

$$
\begin{aligned}
AE &= RR+S-DS && \text{if } (RR+S-DS) \leqslant PE \\
&= PE && \text{if } (RR+S-DS) > PE \\
RO &= RR-PE-DS && \text{if } (RR-PE-DS) > 0 \\
&= 0 && \text{if } (RR-PE-DS) \leqslant 0 \\
DE &= PE-AE && \\
ND &= \text{No. of days with } DE > 0 && \\
NR &= \text{No. of days with } RO > 0 &&
\end{aligned}
$$

Writing DS_n for the current value and DS_{n+1} for the new value of the amount of soil moisture withdrawn from storage for the next day's calculations, then

$$
\begin{aligned}
DS_{n+1} &= DS_n+AE-RR && \text{if } 0 \leqslant (DS_n+AE-RR) \leqslant S \\
&= 0 && \text{if } (DS_n+AE-RR) < 0 \\
&= S && \text{if } (DS_n+AE-RR) > S
\end{aligned}
$$

The balance was carried forward from day to day so long as the series of daily rainfall values was complete, commencing either with a day when soil moisture was fully withdrawn ($DS=S$) after a long dry spell, or with a day when soil moisture withdrawal was nil ($DS=0$) after a wet period.

In a previous water balance study monthly rainfall data were used to assess the broad-scale features of the water balance over New Zealand, and data from some 200 climatological and rainfall stations were used (Coulter, 1966). In the present analysis, daily rainfall data from about 180 climatological stations (of these about 120 had at least 20 years of data) provided a generalized representation of the water balance over most of the country. A value of 75 mm was adopted for S. For each station, for each month of the sequence of daily rainfalls, the number of days of runoff and its total amount, and the number of days of evapotranspiration deficit ('days of dryness') and the total deficit for the month were calculated and tabulated. The accumulated runoff for the calendar year, and the total deficit in the 'growing' season year (July–June) are also tabulated and, in a separate summary table, averages and frequency data for monthly and annual totals. Examples of the latter are given in Table 1, and some of the results are illustrated in the figures.

Fig. 1 shows average annual evapotranspiration deficit (DE), or nominal irrigation need, ranging from zero in the west of the South Island and in high rainfall areas in the North Island to nearly 200 mm in the driest parts of the North Island and to 300 mm near Alexandra in Central Otago.

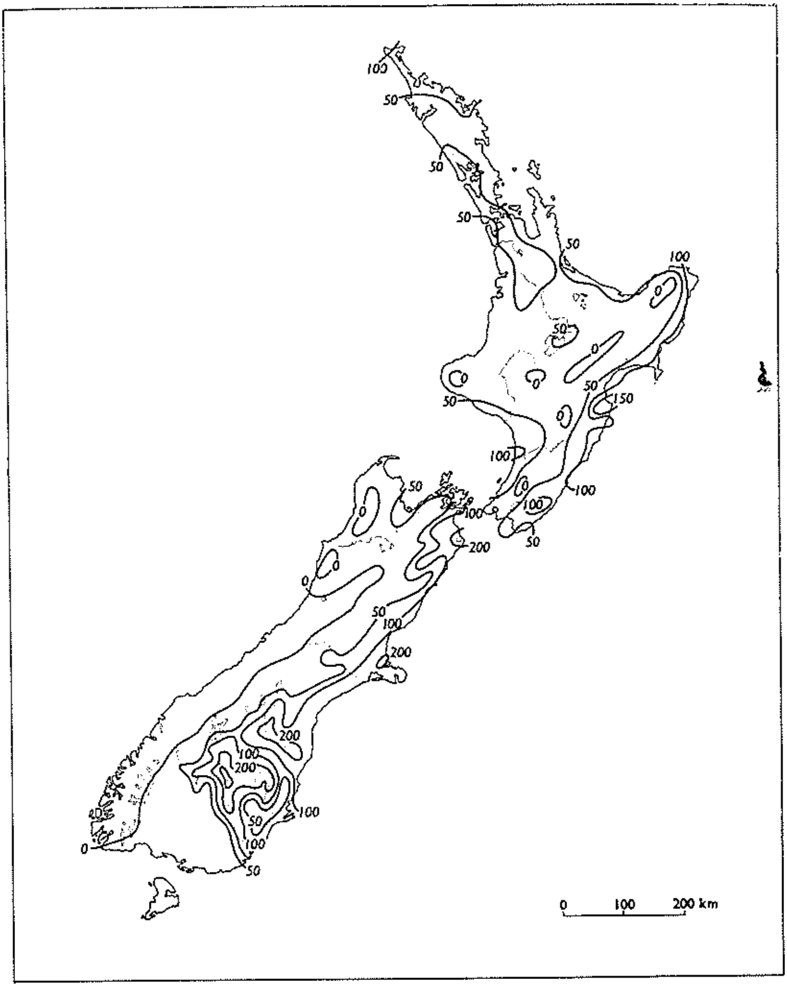

FIG. 1 — Average annual water deficit (DE) in mm. (Deficiency of rainfall plus available soil moisture with respect to average Thornthwaite potential evapotranspiration PE, for soil moisture capacity S of 75 mm, based on a daily water balance.)

TABLE 1 — Daily water balance summary, for $S=75$ mm; average potential evapotranspiration (*PE*), rainfall (*RR*), evapotranspiration deficit (*DE*), water surplus (*RO*), number of days with deficit (*ND*), number of days with surplus (*NR*). Blenheim 1941–72.

	Jan	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*	*Year*
Averages													
PE (mm):	103	87	75	51	33	20	19	27	40	59	76	97	687
RR (mm):	52	41	50	52	70	60	65	64	53	57	49	47	646
DE (mm):	56	46	28	12	3	0	0	0	0	0	9	37	191
RO (mm):	2	1	1	5	19	26	38	37	20	17	5	3	174
ND (days):	19	16	13	8	3	1	0	0	0	0	4	13	77
NR (days):	0	0	0	0	2	3	5	5	2	2	1	0	30
Frequency of months/years with water deficit ($DE>0$)													
Frequency (%):	94	94	88	72	35	6	0	0	0	6	39	87	100
Frequency of months/years with water surplus ($RO>0$)													
Frequency (%):	15	6	6	9	45	61	87	87	74	32	16	10	97

Frequency distribution of annual (July–June) totals of days with deficit (*ND*)

ND ⩾	10	20	30	40	50	60	80	100
Frequency (%):	97	93	93	93	90	80	57	20

Frequency distribution of annual (July–June) totals of evapotranspiration deficit (*DE*)

DE (mm) ⩾	0.1	25	50	100	150
Frequency (%):	75	50	44	13	0

Fig. 2 shows average annual water surplus (*RO*), ranging from just above zero in parts of Central Otago to more than 6400 mm in the Southern Alps. The North Island values are more uniform, falling to less than 400 mm in the Manawatu, Wairarapa and Hawke's Bay.

Annual values of calculated 'actual' evapotranspiration (*AE*) are equal to *PE* (600–650 mm approximately) in the zero-deficit, high-rainfall areas, and fall to less than 400 mm in the driest areas in the South Island. In the dry areas, where deficits occur in virtually every year, the calculated value of *AE* is to a large extent independent of the precise value adopted for *PE*.

In July, water surplus (*RO*) essentially parallels precipitation, while water deficiency (*DE*) is zero in almost all places. Average January surplus (*RO*) is small (less than 10 mm) in an appreciable area in both islands. In January, *DE* averages more than 100 mm in extensive areas, mostly in the east of the South Island.

Most of the South Island, except Westland and Buller, and much of the North Island have deficits ($DE>0$) at some time in 50 to 100 percent of years, with deficits of 100 mm or more in parts

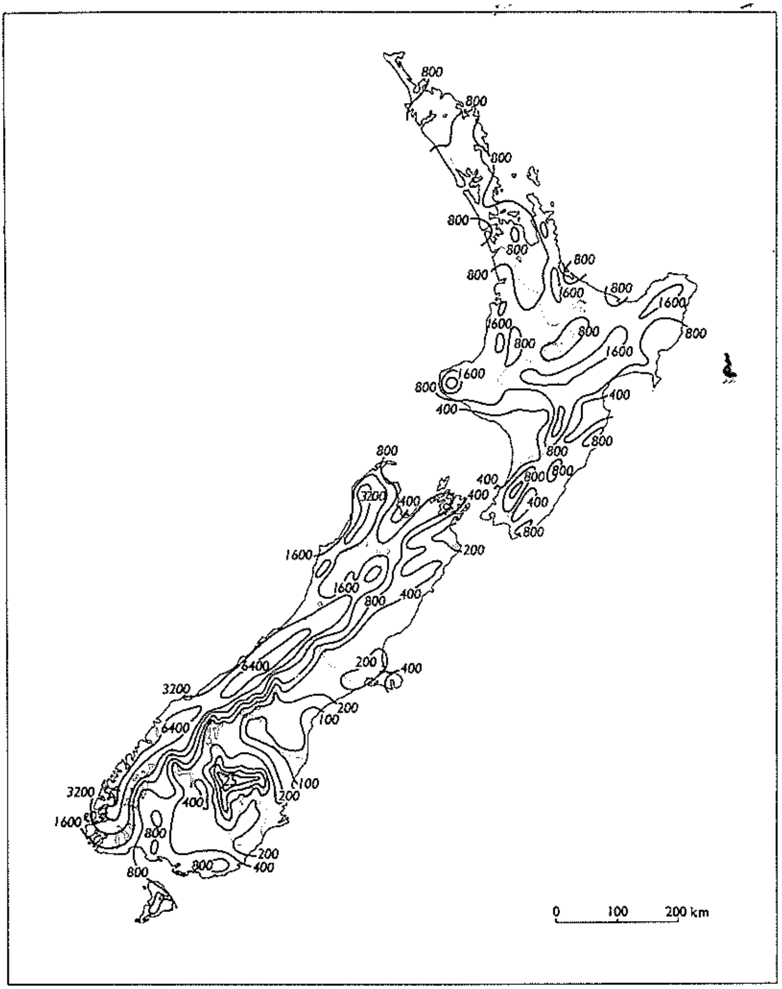

FIG. 2 — Average annual water surplus (*RO*) in mm. (Surplus of rainfall with respect to calculated 'actual' evapotranspiration *AE* plus soil moisture recharge, from daily water balance with $S=75$ mm.)

of Canterbury, Otago, Marlborough and in eastern areas of the North Island in more than 50 percent of years.

Table 1, a sample station summary table, gives an indication of the frequency distribution of annual deficits. Table 2 illustrates the frequency distribution of monthly *RO* values and shows that the variability in *RO* is considerable. In fact, it is appreciably greater than the corresponding variability of rainfall values, especially in the low- and medium-rainfall areas.

TABLE 2 — Percentiles of water surplus (*RO*) (calculated from daily water balance) in mm.

Percentile	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*	*Year*
Waipoua Forest 1940–72													
10	0	0	0	0	8	27	33	57	7	0	0	0	756
20	0	0	0	0	26	62	75	82	30	16	4	0	814
50	0	0	0	44	105	167	150	150	97	86	47	12	963
80	31	79	57	110	209	204	182	215	159	136	82	53	1164
90	64	136	87	174	217	213	214	254	181	154	125	79	1308
Albert Park (Auckland) 1940–72													
10	0	0	0	0	2	30	45	46	2	0	0	0	345
20	0	0	0	0	15	52	65	56	12	8	0	0	426
50	0	0	0	17	63	101	110	94	58	57	12	0	618
80	2	49	28	80	126	138	161	164	81	95	41	24	770
90	29	82	42	132	146	149	170	189	117	121	81	27	809
Chateau Tongariro 1940–72													
10	39	14	1	48	82	140	130	93	89	90	85	82	1897
20	59	39	25	77	107	165	163	158	121	134	121	114	2082
50	98	117	102	172	206	283	240	214	197	229	193	187	2415
80	155	205	205	254	335	345	299	313	290	334	286	263	2649
90	215	289	244	284	414	432	392	357	383	400	332	280	2771
Nelson Aerodrome 1941–70													
10	0	0	0	0	0	2	16	10	0	0	0	0	275
20	0	0	0	0	9	3	22	17	3	0	0	0	283
50	0	0	0	1	61	60	68	66	35	20	0	0	378
80	13	10	33	57	110	91	106	111	68	58	49	20	498
90	34	33	75	82	142	112	126	142	96	75	77	33	652
Christchurch 1941–72													
10	0	0	0	0	0	0	1	0	0	0	0	0	36
20	0	0	0	0	0	0	9	5	0	0	0	0	59
50	0	0	0	0	0	15	42	18	5	0	0	0	167
80	0	0	0	4	57	43	63	55	28	11	0	0	260
90	0	0	22	17	120	64	75	78	51	35	15	7	349
Invercargill 1940–72													
10	0	0	0	0	4	24	20	9	8	0	0	0	268
20	0	0	0	13	24	33	28	17	15	1	0	0	324
50	0	0	2	38	52	83	45	33	30	24	14	6	413
80	16	7	54	65	89	135	68	65	62	66	38	30	503
90	50	17	95	126	123	157	80	78	86	74	62	45	580

In all seasons in high-rainfall areas and in most places in winter, monthly rainfall statistics (e.g. N.Z. Met. Service, 1973) give an adequate representation of the frequency distribution of runoff (by subtracting *PE*, which is usually comparatively small, from the rainfall values).

Table 3 illustrates the annual trend of *RO* and *DE* (frequency and amount) for a few representative stations.

TABLE 3 — Average evapotranspiration deficit (*DE*), average water surplus (*RO*), percentage of years with deficit (% *DE*), and percentage of years with surplus (% *RO*).

	Jan	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*	*Year*
Albert Park (Auckland) 1920–72													
DE (mm):	24	23	17	5	0	0	0	0	0	0	0	5	74
RO (mm):	10	28	13	37	71	103	111	94	56	48	24	11	606
% DE:	69	67	50	38	4	0	0	0	0	0	4	37	88
% RO:	23	40	38	58	88	100	100	100	94	90	67	44	100
Taumarunui 1920–72													
DE (mm):	8	15	7	3	0	0	0	0	0	0	0	0	33
RO (mm):	19	22	17	35	94	123	104	101	83	82	63	44	787
% DE:	24	48	39	25	0	0	0	0	0	0	0	6	61
% RO:	41	42	45	65	96	100	100	100	96	90	92	63	100
Gisborne Aerodrome 1937–72													
DE (mm):	40	29	15	7	1	0	0	0	0	0	4	29	125
RO (mm):	8	9	16	31	61	70	93	88	41	25	12	7	461
% DE:	86	63	60	34	9	0	0	0	0	0	34	69	100
% RO:	20	23	34	54	76	85	94	100	91	60	29	14	100
Christchurch 1920–72													
DE (mm):	43	42	30	14	2	0	0	0	0	0	11	34	176
RO (mm):	1	2	4	7	25	24	40	32	17	6	4	3	165
% DE:	87	94	88	72	29	6	0	0	0	6	46	75	98
% RO:	8	6	10	15	40	67	92	90	56	33	17	12	100
Alexandra 1940–72													
DE (mm):	65	57	38	17	5	0	0	0	5	21	47	67	322
RO (mm):	0	0	0	0	0	1	1	1	1	0	0	0	4
% DE:	100	98	93	91	65	16	2	9	35	74	95	98	100
% RO:	0	2	2	0	0	7	14	7	5	0	0	0	19
Invercargill Aerodrome 1940–72													
DE (mm):	2	3	3	0	0	0	0	0	0	0	0	0	8
RO (mm):	12	5	24	48	59	86	48	41	39	34	24	16	436
% DE:	13	30	23	3	0	0	0	0	0	0	0	0	41
% RO:	47	33	53	87	90	100	100	97	94	81	70	57	100

DISCUSSION

This water balance model was designed for application in a broad-scale climatological survey, and is of necessity highly simplified. It ignores variations from day to day (and from year to year in the monthly mean values) of potential evapotranspiration. These are, however, much smaller as a source of variability than the fluctuations in rainfall. Nevertheless, some refinement could be made by allowing for them. The variability of tank evaporation is relevant to this and has been discussed by Finkelstein (1973). Similarly, the Thornthwaite formula gives only a crude approximation to the true *PE*. Estimates calculated by the Penman formula, and estimates based on tank evaporation, suggest that Thornthwaite *PE* values are appreciably too low in the drier areas of New Zealand during dry periods.

The use of a constant rate of evaporation regardless of soil moisture status up to a fixed limit, and the assignment of the fixed value of 75 mm for the limiting soil moisture capacity restrict the validity of the results to areas where these approximations are likely to be realized.

Detailed water balance studies of specific localities can, of course, make use of more realistic models.

The work was carried out primarily to provide a moisture-stress/drought index for application in regard to pasture production for between-year and between-district comparisons. It appears to be reasonably successful in this (e.g. Maunder, 1973). Tabulations for any individual stations of particular interest are available from the Meteorological Service, Wellington. They can be provided for any specified value of *S*, and the values adopted for average *PE* can be adjusted if desired. The maps do not purport to show accurate or detailed values of the various elements, but rather the generalized features of their geographical distribution. They should not be used to obtain numerical values for individual applications. As has been pointed out in a similar context (Smith, 1967), the appropriate calculations for any particular circumstances can usually be carried out with pertinent rainfall data and with appropriate values for effective soil moisture capacity and potential evapotranspiration.

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