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SURVEY OF NEW ZEALAND TANK EVAPORATION

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ABSTRACT

The increased length of tank evaporation records in New Zealand and the extended network of stations has warranted an updating of a previous 1961 survey of open-water evaporation. It is found that a modified form of Penman's equation can be used to calculate average monthly open-water evaporation from simpler meteorological parameters.

Maps showing the variation over New Zealand of annual open-water evaporation as well as that for selected months are presented.

The annual averages are mainly in the range 650–850 mm in the North Island and 700–950 mm in the South Island, where five stations have values exceeding 1000 mm.

INTRODUCTION

A method of evaporation measurement which has been widely used for many years is that using tank evaporimeters. In New Zealand the first measurements of this kind were made over 50 years ago, and a considerable number of stations have now been operating for more than 20 years. A summary and an interpretation of these measurements was first given by Finkelstein (1961), but with recent increases in the network a new survey is needed.

Tank evaporimeters, or evaporation pans as they are sometimes called, are designed primarily to provide an estimate of what is variously called 'open-water evaporation', 'free-water evaporation', or 'reservoir evaporation', by the use of suitable reduction factors. Over a year this estimate is also usually coincident with lake evaporation. It has been shown by Penman (1948) that in south-east England the ratio of the potential evapotranspiration or water need to the open-water evaporation is constant at any one time of the year; this was also shown by Finkelstein (1961) for the

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Canterbury Plains in New Zealand. It follows that the tank evaporation suitably adjusted may be used as an estimate of the potential evaporation.

THE TANKS AND THEIR REDUCTION FACTORS

Before 1957 nearly all measurements were made with the standard New Zealand sunken-pan evaporimeter. Since then all new installations have been of the raised pan, identical with the U.S. Weather Bureau Class A pan.

For consistent measurements of evaporation, it is important to maintain the water level at a fixed distance below the rim of the tank. Before 1956 this was not the normal practice.

A comparison of the two types of evaporimeter was carried out at Winchmore, near Ashburton, over a period of 10 years. It showed that for the months October to March the overall ratio of the evaporation from the raised pan to that from the sunken pan was 1.24. The standard deviation of the monthly ratios over the 63 months was 0.15, and the extreme values were 1.00 and 1.61. In spite of the comparatively high variability of this ratio it was noted that: (a) there was no obvious correlation with weather data, and (b) there was very little variation in the average ratios between different months of the year.

A similar comparison is now being made at Invercargill, and the result so far – over a period of 2 years – gives a somewhat higher ratio.

From the Lake Hefner studies, Kohler (1952) gave 0.69 as the reduction factor to be used for estimating open-water evaporation from raised pan measurements. No experiments have ever been carried out to determine directly the reduction factor of the New Zealand sunken-pan evaporimeter. However, using the ratio of 1.24 between the pans gives a reduction factor for the sunken pan of 0.86 – higher than the 0.79 originally proposed (Finkelstein, 1961).

The figure of 0.69 for the reduction factor of the raised-pan evaporimeter refers to an unpainted galvanized iron surface. Corrosion of the tanks has been quite a serious problem. A few observers have (incorrectly) painted their tanks outside, and the Meteorological Service is now installing tanks of stainless steel instead of galvanized iron.

Nordenson and Baker (1962) compared stainless-steel and standard Class A pans and found that the stainless-steel pan gave 6 percent less evaporation. Quintela *et al.* (1970) found a figure

TABLE 1 — Average monthly and annual open-water evaporation in millimetres. Latitude (S), longitude (E) and altitude (in metres) are given in that order, then period of record and type of tank: S=sunken pan; S′=electricity type; R=raised pan; RP=raised pan, non-standard owing to painting (adjustment made).

Jan	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*	*Year*
Puketurua 35° 40′, 174° 05′, 101 m, 1966–70 R												
119	91	76	53	33	23	23	43	51	79	94	112	797
Leigh 36° 16′, 174° 48′, 27 m, 1967–70 R												
132	109	102	69	46	33	36	48	53	84	107	122	941
Otara, Auckland 36° 57′, 174° 52′, 12 m, 1958–70 R												
122	94	79	53	30	20	23	30	48	76	99	124	798
Mangere, Auckland 36° 58′, 174° 47′, 1959–70 R												
124	99	81	51	30	23	25	30	51	74	97	114	799
Ngatea 37° 16′, 175° 31′, 2 m, 1966–70 R												
112	89	74	46	25	15	20	28	43	66	89	109	716
Ruakura, Hamilton 37° 47′, 175° 19′, 40 m, 1956–69 S												
108	86	74	50	30	20	20	27	42	64	83	100	714
Rukuhia, Hamilton 37° 50′, 175° 18′, 66 m, 1956–70 S												
113	97	78	53	36	25	25	36	47	65	86	108	769
Rotorua Aerodrome 38° 07′, 176° 19′, 287 m, 1967–70 R												
130	109	91	58	36	20	28	30	48	81	102	99	832
Wairakei 38° 37′, 176° 07′, 402 m, 1964–70 R												
99	81	69	46	23	13	15	20	38	66	84	97	651
Otutira 38° 38′, 175° 49′, 579 m, 1967–70 R												
117	89	74	36	25	18	20	28	41	66	89	94	697
Taupo 38° 41′, 176° 04′, 376 m, 1956–70 S												
124	100	75	50	32	25	22	27	45	68	93	111	772
Waerenga-o-kuri 38° 41′, 177° 48′, 314 m, 1961–70 S												
97	94	81	53	42	31	27	36	56	81	100	94	792
Onepoto, L. Waikaremoana 38° 48′, 177° 07′, 643 m, 1956–70 S′												
91	68	58	40	30	22	22	25	33	50	75	81	595
Makahu Saddle 39° 17′, 176° 24′, 974 m, 1968–72 R												
82	63	74	39	33	23	30	25	49	66	72	70	626
Havelock North 39° 40′, 176° 53′, 9 m, 1962–70 R												
117	86	74	43	25	18	20	25	41	81	91	104	725
Palmerston North 40° 23′, 173° 37′, 34 m, 1956–70 S												
118	103	83	50	33	22	22	30	45	63	88	108	765
Levin 40° 39′, 175° 16′, 46 m, 1961–70 RP												
110	84	70	40	26	19	16	26	43	62	81	100	677
Taita, Lower Hutt 41° 11′, 174° 58′, 65 m, 1957–70 S												
122	97	78	50	30	22	20	27	42	67	83	103	741
Makara Radio 41° 15′, 174° 42′, 279 m, 1967–70 R												
109	94	74	53	36	30	30	36	61	74	94	99	790
Kelburn, Wellington 41° 17′, 174° 46′, 127 m, 1957–70 S												
128	108	86	58	41	27	25	36	47	67	88	113	824
Riwaka, Motueka 41° 06′, 172° 58′, 8 m, 1958–70 RP												
121	94	70	46	24	16	16	24	43	75	99	119	747

TABLE 1 (*continued*)

Jan	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*	*Year*
Appleby, Nelson 41° 17′, 173° 06′, 17 m, 1956–70 S												
127	106	75	50	32	25	22	27	45	69	94	113	785
Moutere Hills 41° 22′, 173° 04′, 137 m, 1960–70 R												
145	127	104	76	51	41	41	51	63	99	119	140	1057
Wither Hills, Blenheim 41° 33′, 173° 58′, 31 m, 1958–70 RP												
157	120	89	55	31	21	21	31	53	83	120	139	920
Lake Grassmere 41° 44′, 174° 09′, 2 m, 1964–70 S												
179	149	120	83	50	40	38	52	77	125	159	174	1246
Molesworth 42° 05′, 173° 16′, 894 m, 1965–70 R												
127	112	81	53	20	20	13	23	43	86	99	119	796
Craigieburn Forest 43° 09′, 171° 43′, 915 m, 164–70 R												
81	71	53	30	15	8	8	20	30	53	61	81	511
Harper River 43° 13′, 171° 26′, 533 m, 1955–66 S′												
126	98	71	40	22	9	8	16	39	70	91	119	709
Darfield 43° 29′, 172° 08′, 195 m, 1952–70 R												
94	71	48	30	15	10	10	20	33	58	76	86	551
Christchurch Airport 43° 29′, 172° 32′, 30 m, 1964–70 R												
140	122	76	56	25	15	15	33	63	99	124	142	910
Bromley, Christchurch 43° 32′, 172° 43′, 9 m, 1962–70 R												
127	94	69	43	23	15	15	28	48	86	104	122	774
Rudstone, Methven 43° 33′, 171° 41′, 371 m, 1937–53 R												
116	98	83	52	43	29	29	43	60	90	103	113	856
Highbank, Methven 43° 36′, 171° 44′, 336 m, 1953–70 R												
130	105	86	63	39	29	29	44	64	97	115	122	923
Lincoln 43° 39′, 172° 28′, 11 m, 1964–70 R												
140	117	86	51	30	20	20	33	58	97	117	135	904
Winchmore 43° 48′, 171° 48′, 160 m, 1956–70 S												
133	106	78	42	39	22	21	33	50	84	108	123	839
Mt John 43° 59′, 170° 28′, 1027 m, 1956–71 R												
165	150	99	74	(41	22	19	34)	93	127	142	165	1131
Tara Hills, Omarama 44° 32′, 169° 56′, 488 m, 1956–70 S												
179	155	99	59	28	11	8	28	57	107	139	163	1036
Alexandra 45° 15′, 169° 23′, 141 m, 1963–70 RP												
126	105	71	40	13	8	5	19	44	83	107	139	760
Manorburn Dam 45° 22′, 169° 36′, 746 m, 1961–67 S												
119	100	64	46	25	*	*	16	36	81	88	117	—
Taieri 45° 51′, 170° 22′, 24 m, 1960–70 R												
104	86	63	38	20	13	13	25	36	76	81	104	659
Mahinerangi Dam 45° 53′, 169° 58′, 396 m, 1953–70 S												
81	66	50	31	20	10	8	14	32	56	66	83	517
Invercargill Aerodrome 46° 25′, 168° 20′, 0 m, 1953–70 S												
100	83	62	47	25	20	15	22	39	67	83	103	741

Notes: (1) Mt John: May–August averages estimated.

(2) Manorburn Dam: no observations June and July because of pan freezing over.

of 7 percent for this reduction, and the same for the reduction due to painting the tank white. Here, 0.73 is adopted as the reduction factor of the stainless-steel tank, and also the reduction factor of a tank painted white. It has been assumed that the effect of painting a tank grey is less but still appreciable – about 2 percent.

ERRORS

By far the most serious and persistent error in tank evaporation measurements arises from the fact that the tank does not generally catch the same amount of rain as the raingauge (Finkelstein, 1961).

An examination of daily figures for two typical raised-pan stations (Otara and Lincoln) showed that over a period of several months the raised pan catches more rain than the raingauge about as often as it catches less.

The error due to spray being blown out of the tank has been investigated for Mt John, a very exposed mountain station which quite often has mean wind speeds exceeding 80 km/h, and some adjustments have been made to the recorded daily values and monthly totals. It seems likely that a few other stations are occasionally affected, especially those in the more exposed areas around Cook Strait, such as Makara, Lake Grassmere and Kelburn.

RESULTS

The average values of tank evaporation have all been converted to open-water evaporation and are shown in Table 1. Monthly and annual values for three stations (Tauranga, Napier and Hokitika), estimated from weather data by the method indicated below, are shown in Table 2. In addition, long-period annual averages estimated from 10 short records by comparison with surrounding stations are shown in Table 3. All these values have been used in drawing the maps of open-water evaporation for the year and for the months January, April and October (Figs. 1 to 4).

TABLE 2 — Monthly and annual evaporation values (in millimetres) estimated from climatological data. Latitude (S), longitude (E) and altitude (in metres) are given in that order for each station.

Jan	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*	*Year*
Tauranga Aerodrome 37° 40′, 176° 12′, 4 m												
140	112	93	62	38	25	29	40	59	84	107	128	917
Napier 39° 30′, 176° 55′, 2 m												
143	103	85	56	34	25	26	38	56	90	116	131	903
Hokitika South 42° 43′, 170° 57′, 4 m												
93	67	58	34	21	14	21	26	42	61	76	93	606

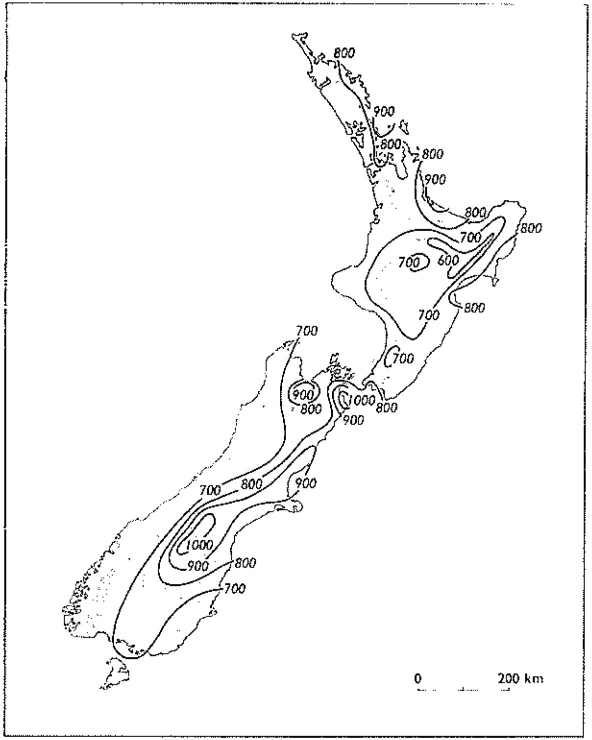

FIG. 1 — Average annual open-water evaporation (in millimetres).

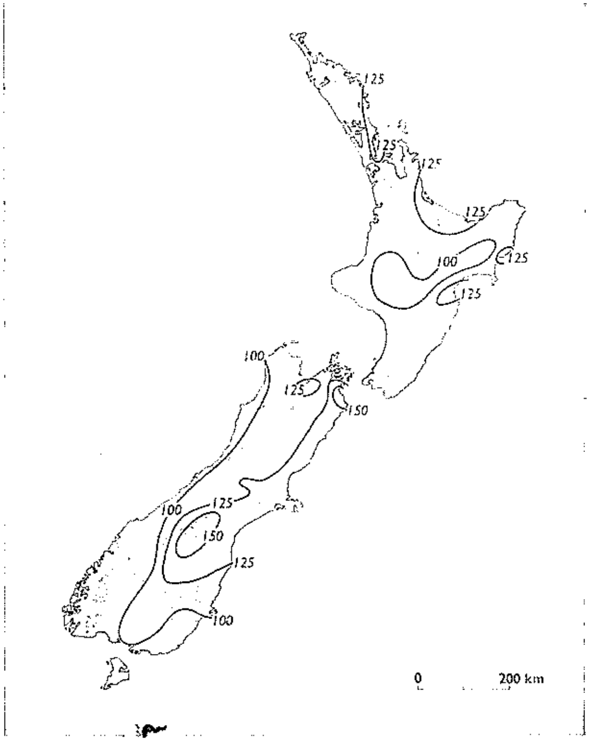

FIG. 2 — Average open-water evaporation (in millimetres) for January

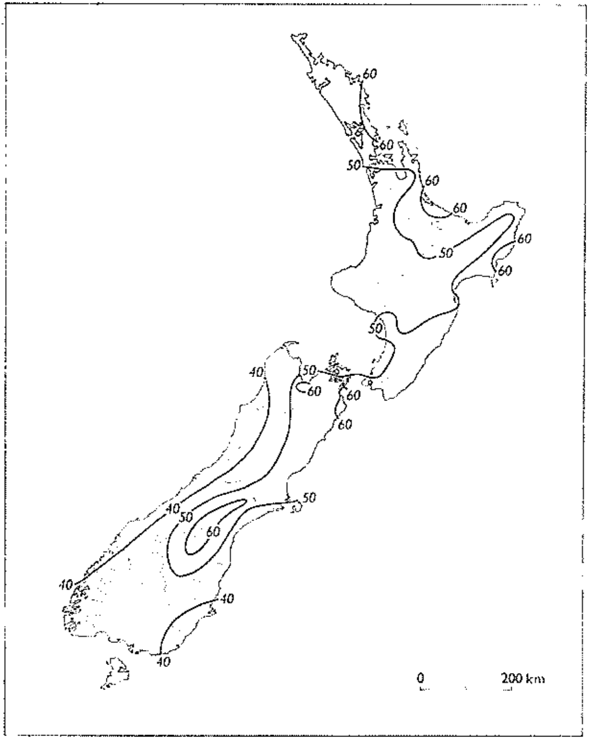

FIG. 3 — Average open-water evaporation (in millimetres) for April.

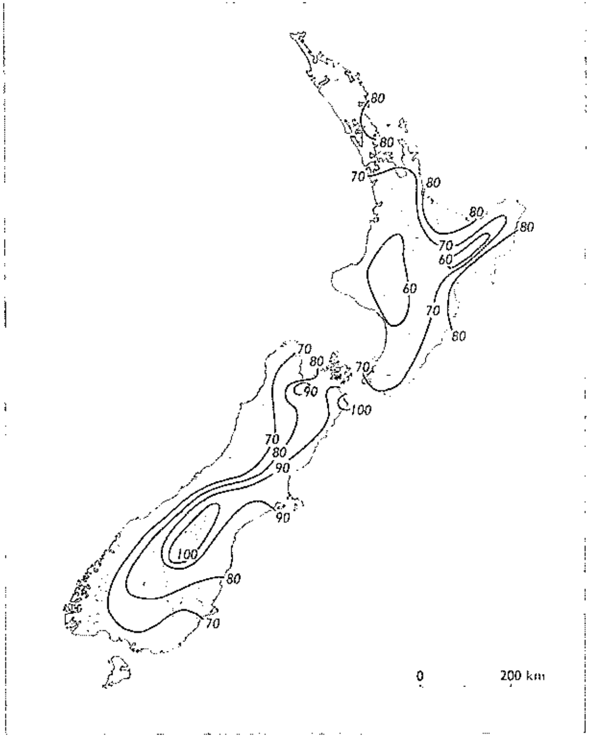

FIG 4 — Average open-water evaporation (in millimetres) for October.

TABLE 3 — Long-period annual average evaporation estimated approximately from short records. All stations have raised pans. SS=stainless-steel pan (adjustment made).

Station	*Lat.(S)*	*Long. (E)*	*Alt. (m)*	*Type*	*Av. evap. (mm)*
Punakitere	35° 26′	173° 40′	180	SS	770
Whau Valley	35° 42′	174° 18′	152	SS	520
Pukekohe	37° 12′	174° 52′	82	SS	790
Purukohukohu	38° 26′	176° 13′	631	SS	510
Manutuke	38° 41′	177° 53′	31	SS	850
Omata	39° 05′	174° 00′	61		760
Gladstone	41° 08′	175° 38′	117	SS	760
Vernon Lagoons	41° 32′	174° 02′	2	SS	1030
Lake Pukaki	44° 11′	170° 28′	11		910
Adair	44° 26′	171° 10′	85		850

EVAPORATION AND WEATHER DATA

Evaporation is dependent on other meteorological parameters. and overseas investigations have shown a positive correlation with radiation and with wind speed and a negative correlation with relative humidity. A marked positive correlation is found with the saturation deficit, defined as the saturation vapour pressure at the existing temperature minus the actual vapour pressure.

Penman (1948) proposed the relation shown between the English tank evaporimeter (a 6 ft, 183 cm, square sunken pan) and other meteorological parameters:

$$E_0 = \frac{\Delta H + \gamma E_a}{\Delta + \gamma}$$

where E_0 is the calculated tank evaporation;
H the net radiation;
E_a a function of the saturation deficit and wind speed;
Δ the increase in saturation vapour pressure with temperature;
γ the constant of the wet-bulb equation.

With the units used by Penman originally, that is, millimetres and (for radiation) 'equivalent millimetres', the value of γ was 0.27.

Kohler (1952) showed that the evaporation data for different types of tanks fitted Penman's equation provided that different values of γ were used for the different tanks. He multiplied γ by a factor k which was different for different tanks.

Finkelstein (1961) showed similarly that New Zealand sunken-pan data fitted the same equation with $k = 2.2$.

In the present investigation, less than half the stations had monthly data suitable for checking the Penman relation. The following 10 sunken-pan stations were selected: Rukuhia, Taupo. Palmerston North, Kelburn, Appleby, Lake Grassmere, Lincoln (old site 1956–63), Winchmore, Tara Hills, and Invercargill; and the following eight raised-pan stations: Otara, Rotorua Aerodrome, Makara Radio, Wither Hills, Highbank, Lincoln, Mt John, and Alexandra. This selection includes nearly all the stations with highest evaporations (the exception being Moutere Hills) but none of the stations with lowest evaporations.

Details of calculation of only two elements in Penman's equation are shown:

(a) H, the net radiation. This consists of the direct radiation corrected for reflection minus the long-wave outgoing radiation. The direct radiation was calculated by the method of de Lisle (1966), and 5 percent reflection was assumed. The outgoing long-wave radiation was calculated by the method of Penman (1948).

(b) E_a, the term containing wind and saturation deficit. The later form of this term proposed by Penman (1956) was used, namely

$$E_a = 0.35\ (0.5 + 9.8 \times 10^{-3} u_2)\ (e_s - e_d)$$

where u_2 is the wind speed in miles per day at 2 metres, and $e_s - e_d$ is the saturation deficit in mm. This was modified to suit New Zealand conditions, especially the different height (6 m) at which most New Zealand wind speeds are measured. For details regarding u_2 and $e_s - e_d$ see Finkelstein (1961).

In comparing the calculated with the observed evaporation it was soon evident, as previously found (Finkelstein, 1961), that γ needed to be multiplied by a factor K. The best fit for each type of tank was given by $K = 2.5$.

For comparisons of total evaporation, only the period September to April was used, and the figures were all converted to open-water values. Using the September–April totals, it was found that

$$E = A \left(\frac{\Delta H + K\gamma E_a}{\Delta + K\gamma} \right)$$

where the value of A is 0.94 for each type of tank. The coefficients of variation and the ranges of values of A between the different stations were: sunken pan 8 percent, range 0.21; raised pan 5 percent, range 0.13. The correlation coefficients between calculated and observed values in January and October were: sunken pan, 0.96 in January and 0.93 in October; raised pan, 0.93 in January and 0.95 in October.

Monthly averages for Tauranga, Napier and Hokitika have been estimated by this formula.

THE PATTERN OF EVAPORATION OVER NEW ZEALAND AND THE SEASONAL VARIATION

The relationship established between evaporation and weather data now allows us to interpret both the seasonal variation of evaporation and the spatial pattern.

Penman's equation as modified above consists of two terms:

$$\left(\frac{A\Delta}{\Delta+K\gamma}\right) H \qquad \text{Radiation term}$$

and

$$\left(\frac{\Delta K\gamma}{\Delta+K\gamma}\right) E_a \qquad \text{Wind and saturation deficit term}$$

The ratio of these two is $\frac{\Delta H}{K\gamma E_a}$ or $\frac{\Delta}{K\gamma} \times \frac{H}{E_a}$

Note that Δ is somewhat less than $K\gamma$ at all times of the year. Apart from slight variations due to changes in Δ with temperature, the seasonal variation is controlled by the variations in H and E_a. Typical values for these in equivalent mm per day are as follows:

H in December–January: mainly 6, but 7 for stations with high sunshine.

H in June–July: 1 in the north, 0 in the south.

E_a in December–January: 2 to 3 at many stations, but about 6–7 at some high-evaporation stations such as Moutere Hills, Lake Grassmere, and Mt John.

E_a in June–July: about one-third of its value in December–January. The reduction is mainly due to the decrease in saturation deficit, as wind speeds are not greatly affected.

The seasonal variation of evaporation is very marked, because of the large variation in net radiation. The maximum is in December–January, and the minimum in June–July.

While the seasonal variation is determined largely by radiation, the spatial pattern is dependent mainly on relative humidity variations, though sunshine and wind speeds are also of some importance.

Relative humidity (and therefore saturation deficit) does not vary greatly over the North Island, but it is higher there than over the South Island. The mean and extreme saturation deficits with the standard deviations for 22 of the stations in the North Island

and 21 in the South Island for which actual or estimated evaporations are quoted, over the main evaporation period September to April, are shown in Table 4.

TABLE 4 — Saturation deficits for 22 stations in the North Island and 21 stations in the South Island, over the period September to April, in millibars.

	Average	*Std dev.*	*Highest*	*Lowest*
Nth Island:	3.3	0.6	5.2 (Napier)	1.7 (Makara Radio)
Sth Island:	4.4	1.0	6.2 (Alexandra)	1.7 (Hokitika)

Largely as a result of the above variations, evaporation is both less variable in the North Island than in the South Island and also lower. Average annual values are mainly 650–850 mm over the North Island but mainly 700–950 mm over the South Island.

In the South Island, the area of maximum evaporation is east of the ranges and well north of Dunedin. This coincides largely with the area having lower relative humidity, but sunshine is also a factor. In the North Island, the highest values – at Leigh, Tauranga and Napier – are all on the east coast.

All the stations with highest evaporation are in the South Island, because it is only there that the necessary combination of high saturation deficit with high wind speeds is found; at these stations sunshine is also high. The mean values of saturation deficit, wind-run, sunshine, and open-water evaporation for the four stations with highest evaporation are shown in Table 5 for the period September to April.

TABLE 5 — Climatological data for the four stations with the highest evaporation, mean values over the period September to April.

Station	*Sat. deficit (mbar)*	*Wind-run (km/d)*	*Sunshine (h)*	*Open-water evap. (mm)*
Lake Grassmere	5.3	556	1603	1066
Mt John	5.4	434	1834	1015
Moutere Hills	4.8	337	1758 (Nelson)	873
Tara Hills	5.6	273	1587	961

The lowest annual evaporations are similar in the two islands, mainly about 500 mm. However, one station with low evaporation, Darfield in North Canterbury, has a low value because of its poor exposure. There are many trees close to this station, greatly reducing both wind speed and sunshine.

Variations in wind speed have some curious effects. Local variations may cause considerable differences between stations quite close to each other, as for example Highbank and Rudstone, or Christchurch Airport and Bromley. On the other hand, in spite of Alexandra being much less humid and much more sunny than Invercargill, its annual open-water evaporation is only 19 mm greater than that of Invercargill because of much lower wind speeds. In drawing the lines of equal open-water evaporation on Figs. 1 to 4, it has been necessary to ignore both under-exposed and over-exposed stations.

The spatial pattern of evaporation through the main 'evaporation season' remains similar to that of the annual values. In January evaporations are mainly in the range 100–150 mm, in April 45–60 mm, and in October 60–90 mm.

VARIABILITY OF MONTHLY VALUES

For most stations, routine calculations of standard deviation would be unsatisfactory because of the errors which occur in monthly totals on days of considerable rain.

A careful examination of selected months for Otara (March, September, October) and Lincoln (September, October, December) after adjustment of totals showed that the average coefficient of variation of monthly evaporation in these months for both stations was 12 percent. The corresponding coefficient of variation for rainfall in the same months was 58 percent for Otara and 64 percent for Lincoln. Thus, at these stations the coefficient of variation of monthly evaporation was only about one-fifth of the value for rainfall.

The low variability of evaporation is a useful property, allowing satisfactory averages to be computed over a comparatively short period.

CONCLUSIONS

1. The recommended reduction factors to open water for the tanks are 0.69 for the standard galvanized-iron raised-pan evaporimeter and 0.86 for the standard New Zealand sunken-pan evaporimeter.

2. Tank evaporimeter measurements may be faulty on days with rain.

3. The average monthly open-water values fit a modified form of Penman's equation.

4. Evaporation shows a marked seasonal variation, with maxima in December–January and minima in June–July.

5. Annual open-water evaporation is mainly in the range 650–850 mm in the North Island and 700–950 mm in the South Island.

6. The highest values are found at very exposed windy sites with low relative humidity. Five stations have annual open-water evaporations exceeding 1000 mm.

7. For two representative stations the coefficient of variation of monthly evaporation was 12 percent, about one-fifth of that of rainfall.

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