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A Comparison of Some Methods for Estimation of Potential Evaporation

K. J. Kristensen
Hydrotechnical Laboratory,
Royal Veterinary and Agricultural University, Copenhagen

In most of the important agricultural regions of the world, evaporation in the growing season exceeds the precipitation, and also often the sum of precipitation and plant available water in the root zone. This causes a need of supplemental irrigation for effective agricultural use. Information about the greatest possible water consumption in given periods, therefore, is important for the water policy of a given region.

Several methods for estimation of the maximum (potential) evaporation have been suggested, and many methods have been compared earlier (W.M.O. 1966, Heldal 1969, Kristensen 1971, Iruthayaraj and Marachan 1978).

In Denmark a screened sunk iron pan has been used as a standard since 1956 (Aslyng and Hansen 1960). This standard pan and other methods for estimating potential evaporation have been compared during a 15-year period. The results are reported and discussed.

Materials and Methods

The measurements reported were carried out at the Climate and Water Balance Station of the Royal Veterinary and Agricultural University, Denmark. The station is situated about 20 km west of Copenhagen at 55^0 40′ North, 12^0 18′ East. The installations are placed in or above a level area covered by short grass. The area was irrigated whenever needed in order to avoid or reduce oasis effect caused by insufficient evaporation from areas surrounding the climate station.

The location of the different instruments is shown in Fig. 1. The methods

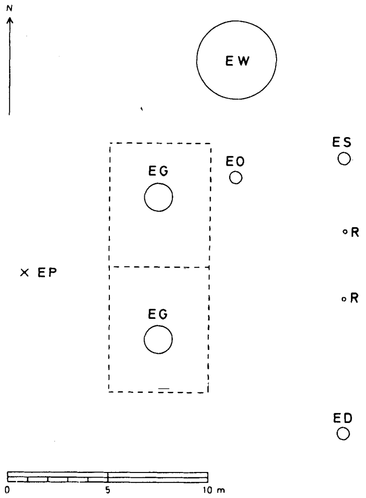

Fig. 1. Sketch of the experimental site. Symbols are explained in the text.

compared are:

EP = Calculated according to Penman's method.
EG = Measured from weighable, grass-covered evapotranspirometers.
EW = Measured from a 12 m^2 free water surface.
ES, EO, and ED = Measured from 0.315 m^2 sunk iron pan. The pans were differently equipped as described below.

The Penman method (Penman 1948) has been described and used frequently. In the present investigation daily values of net radiation, soil heat flux, air humidity, and wind speed were used. The net radiation was measured 1 m above and soil heat flux 5 cm below the grass-covered soil surface by instruments described elsewhere (Aslyng 1965, Jensen and Aslyng 1966, Mogensen 1970). Wind speed and air humidity were measured 2 m above the soil surface. The daily values are sum or average of integrated 10-minutes observations, recorded by a data logger on punch tape.

The weighable evapotranspirometers (EG in Fig. 1) consists of two grass-covered iron tanks, mounted so that their change in weight can be recorded. Each tank is 2 m^2 in area and 1 m deep. The area is on a level with the surrounding area. Construction details and method of operation are described elsewhere (Aslyng and Kristensen 1961). In order to achieve potential evapotranspiration, the evapotranspirometers were not allowed more than 30 mm soil water deficit before irrigated. The grass carried by the tanks and a small area surrounding it was cut at about 2 weeks intervals, alternating, so that one of the areas carried a vegetation that had grown for about one week or more after cutting. This was in order to ensure sufficient leaf density to meet the requirement for potential evapotranspiration (Kristensen 1974).

The 12 m^2 free water surface (EW in Fig. 1) consists of a 1 m deep sunk concrete tank. The tank is inside lined with black fiberglass-reinforced plastic in order to prevent leaching and to achieve an optically bottomless tank. The water level in the tank was kept constant by float-operated magnetic valves. The amount of water added or removed in order to keep the constant water level was recorded. The evaporation then is calculated as the sum of water supplied plus rainfall minus water removed.

The evaporimeters used (ES, EO, and ED in Fig. 1) are the type HL 315 described earlier by Aslyng and Hansen (1960). The area is 0.315 m^2 and the depth 1 m. In the present investigation three differently equipped evaporimeters were compared.

ES = Standard evaporimeter with a dense screen (60% opening area) without sand.
ED = Screen as for ES. Filled with sand to about 8 cm under standard water level.
EO = Sand as for ED. Screen with 91% opening area.

A sketch of an evaporimeter with the three different equipments indicated is shown in Fig. 2.

During the measuring period the water level in the evaporimeters was regulated three times a week by addition or removal of water, until the standard level, indicated by a pointer (P in Fig. 2), was reached. Evaporated water then is rainfall in the period plus added water minus removed water. Addition or removal of water was in 1 mm increments.

For the evaporimeters with dense screen, the evaporation such measured (ES' and ED') should be multiplied by empirical factors. The factors used in this presentation are those suggested by Aslyng and Stendal (1965). They are for April and September 1.2, for May, June, and August 1.3, for July 1.4, for October 1.0, and for November 0.7.

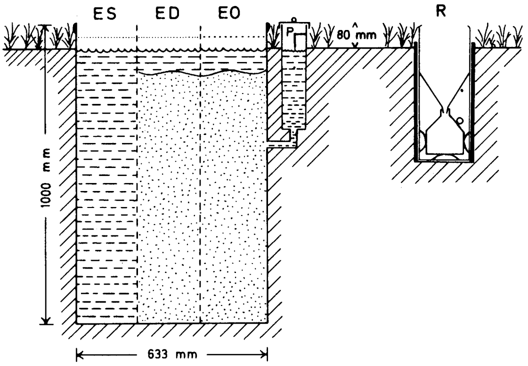

Fig. 2. Sketch of HL 315 evaporimeter. Rainfall is measured by a nearby standard Hellmann raingauge (R), having its orifice at the same height above ground level as the evaporimeter. The instruments are surrounded by short mown grass. The differences between the three evaporimeters compared are shown.

The methods EW, ES, ED, and EO were not in operation during the winter period due to frost hazard. EP and EG were maintained continuously all the year. EG, however, could not be measured during periods with snowdrift. For Danish conditions such periods are rather few and short, and the evaporation taking place during such periods is quite small. Omission of these periods therefore do not significantly influence the results obtained by EG.

Results and discussion

The evaporation measured by the different methods is reported in mm per month and for the growing period in Table 1. EP and EG were measured during the winter period, and therefore also reported for the whole year. In a few winter months the measurements had failed. Averaged values (given in brackets) are used here.

The evaporation reported for ES and ED are the values obtained when the direct measured evaporation loss (ES' and ED') was multiplied by the factors mentioned earlier. EW was not measured in 1971 due to reparation of the tank, and ED was terminated in 1977. As an average EP exceeds EG by about 55 mm or 14 per cent in the growing season and by about 95 mm or 20 per cent for the whole year. Differences between EP and EG are relatively greatest in the spring months. The main reason for this is most likely insufficient vegetation density in the early part of the growing season. For the summer months (June-August) EP exceeds EG by only about 10 per cent. Multiplying EP by 0.9 then brings the two methods to the same level in periods with the greatest evapotranspiration intensities.

The weekly evaporations, averaged for all the years involved, are shown in Fig. 3 for 0.9 EP, EG, EW, EO, and ES. The results are smoothened, however, by using three weeks running averages. As seen, 0.9 EP still exceeds EG until late May. Also the evaporimeters exceeds EG in that period, and actually agrees quite well with 0.9 EP. This suggests that EG is not potential in the first part of the growing season.

For the period May-September, the calculated evaporation (EP) exceeds the evaporation from a free water surface (EW) by about 15 mm or 3 per cent. The evaporation EW may correspond rather well to the evaporation from a lake. The Penman standard method, as used here, then gives a reasonably good estimate of lake evaporation, even when the net radiation, as in the present case, is measured over grass, providing the grass is not lacking water.

The evaporation from water tends to exceed EG and 0.9 EP in the autumn (Fig. 3). This is partly due to a greater heat accumulation in the water than in the soil, and partly due to thermal convection. By this convection energy from deeper layers is transported to the surface and used for evaporation. Energy from a greater area than the evaporimeter, consequently, may be available during

Table 1 – Evaporation in mm calculated from climate and measured by different methods

Penman's method (EP)

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	May-Sept.	Total
1964	(7)	(9)	(26)	48	97	93	98	76	56	13	(9)	(6)	420	538
1965	7	7	26	44	91	110	83	84	45	24	7	5	413	533
1966	1	7	28	41	93	101	98	71	55	20	6	7	418	528
1967	1	14	18	59	89	103	105	83	45	26	10	6	425	562
1968	4	5	29	74	81	116	93	86	49	21	13	7	425	578
1969	9	9	31	56	67	104	103	96	63	31	13	9	433	591
1970	9	7	17	40	99	126	88	82	46	19	5	6	441	544
1971	6	14	26	65	102	90	113	86	47	32	17	11	438	609
1972	14	7	30	55	81	93	95	86	45	21	7	3	400	537
1973	4	10	28	57	84	123	114	99	57	22	13	5	477	616
1974	13	14	40	85	101	114	112	79	43	15	4	2	449	622
1975	8	4	25	60	100	118	106	103	59	26	7	8	486	624
1976	4	9	26	63	96	116	123	111	47	24	2	0	493	621
1977	3	7	19	44	104	107	103	78	60	18	12	13	452	568
1978	11	10	31	64	125	109	91	95	46	22	11	7	466	622
AVER.	7	9	26	57	94	108	102	88	51	22	9	6	443	579

Evapotranspirometers (EG)

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	May-Sept.	Total
1964	3	3	14	41	82	87	71	78	44	16	7	2	362	448
1965	(6)	6	15	30	66	82	65	72	48	22	(9)	(5)	333	426
1966	(6)	7	16	17	75	93	82	62	44	16	6	7	356	431
1967	6	12	23	40	66	84	86	69	40	26	14	7	345	473
1968	5	4	19	52	67	105	81	82	47	22	9	5	382	498
1969	5	5	12	32	62	108	97	93	54	25	11	10	414	514
1970	6	1	1	14	84	128	73	74	40	12	10	4	399	447
1971	4	9	12	34	86	77	102	92	43	28	9	8	400	504
1972	12	7	17	36	61	76	86	76	41	19	7	5	340	443
1973	2	6	21	38	74	103	101	94	46	19	9	2	418	515
1974	4	7	25	63	91	101	85	68	35	11	7	3	380	500
1975	8	5	18	38	85	109	93	98	53	19	7	6	438	539
1976	5	5	15	31	78	109	125	111	47	18	7	5	470	556
1977	5	6	15	26	85	95	99	69	53	14	9	6	401	482
1978	5	2	13	45	95	94	79	82	34	16	9	6	384	480
AVER.	6	6	15	36	77	97	88	81	45	19	9	5	388	484

12 m^2 open water (EW)

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	May-Sept.	Total
1964				53	88	100	84	86	51	20	20		409	
1965				32	92	100	72	77	49	26	–		390	
1966				–	85	98	102	75	56	24	8		416	
1967				51	82	103	94	83	54	32	13		416	
1968				55	77	124	95	86	59	34	22		441	
1969				–	75	110	105	113	71	30	28		474	
1970				–	101	127	90	89	62	27	26		469	
1971				–	–	–	–	–	–	–	–		–	
1972				57	84	88	81	93	54	31	–		400	
1973				22	69	97	108	95	61	23	–		430	
1974				67	88	99	98	78	49	29	8		412	
1975				42	95	107	101	88	57	27	13		448	
1976				52	82	80	115	99	51	22	–		427	
1977				24	83	94	99	74	63	23	–		413	
1978				62	103	102	93	108	64	19	12		470	
AVER.				47	86	102	96	88	58	26	16		430	

HL 315 – open screen with sand (EO)

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	May-Sept.	Total
1964				49	93	99	86	93	60	30	15		431	
1965				42	86	95	69	74	47	25	–		371	
1966				22	84	98	102	65	52	20	5		401	
1967				50	95	124	110	73	65	36	9		467	
1968				60	67	115	82	78	49	24	18		391	
1969				43	59	106	100	105	63	28	10		433	
1970				–	93	119	76	79	51	23	18		418	
1971				61	86	79	104	85	44	30	–		398	
1972				43	70	71	74	80	44	25	10		339	
1973				44	66	95	94	85	50	23	8		390	
1974				77	87	89	86	57	36	17	8		355	
1975				42	88	99	89	98	57	25	13		431	
1976				50	75	98	104	103	50	22	–		430	
1977				30	84	84	101	76	67	19	–		412	
1978				53	100	90	70	86	45	24	12		391	
AVER.				47	82	97	90	82	52	25	11		403	

HL 315 – dense screen without sand (ES)

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	May-Sept.	Total
1964				45	85	87	83	84	52	23	11		391	
1965				42	86	88	79	70	46	26	–		369	
1966				18	86	93	100	68	56	24	11		403	
1967				46	73	94	94	76	49	33	14		386	
1968				53	73	109	88	79	53	27	15		402	
1969				39	64	110	108	110	68	32	13		460	
1970				21	95	122	85	75	55	24	16		432	
1971				50	86	80	110	85	45	34	13		407	
1972				44	79	71	79	91	46	27	13		366	
1973				47	72	96	103	97	60	30	13		428	
1974				78	95	85	98	58	48	24	13		384	
1975				40	89	103	95	96	65	31	15		448	
1976				50	78	94	112	108	59	29	–		451	
1977				37	98	95	110	72	71	21	–		446	
1978				60	110	102	82	97	56	27	15		447	
AVER.				45	85	95	95	84	55	28	13		414	

HL 315 – dense screen with sand (ED)

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	May-Sept.	Total
1964				46	86	87	82	78	42	15	11		375	
1965				41	82	88	74	66	40	17	–		350	
1966				19	87	91	95	63	47	17	8		383	
1967				45	73	91	91	73	46	24	11		374	
1968				56	71	110	85	76	48	21	15		390	
1969				44	60	102	107	102	58	23	16		429	
1970				–	89	116	82	72	46	21	18		405	
1971				46	81	74	105	84	37	24	12		381	
1972				49	78	70	79	86	45	21	10		358	
1973				54	69	94	101	89	54	24	13		407	
1974				74	84	96	102	60	42	16	10		384	
1975				42	88	98	93	94	58	24	14		431	
1976				48	76	92	115	95	51	20	–		429	
1977				–	–	–	–	–	–	–	–		–	
1978				–	–	–	–	–	–	–	–		–	
Aver.				47	79	93	93	80	47	21	13		392	

() Values assumed due to inperfect measurements.

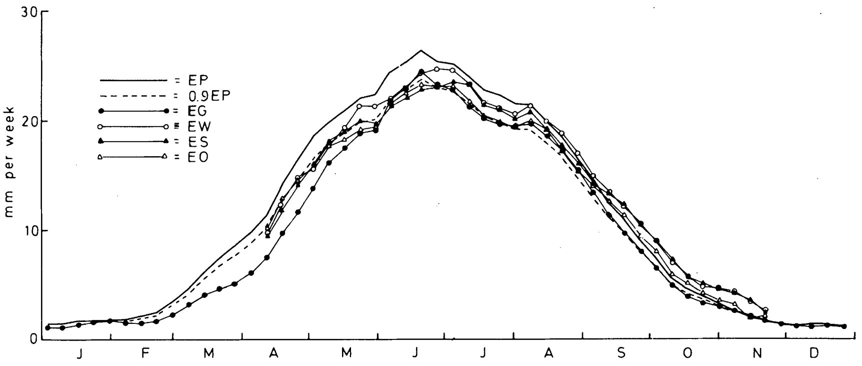

Fig. 3. Evaporation in mm per week as calculated by the Penman method and measured by different evaporimeters.

periods of cooling down.

The method designated ES has been used in Denmark for several years as a standard method for estimating the potential evaporation. As mentioned earlier, the direct water loss (ES') from the pan should be multiplied by season dependent factors in order to give the accepted potential evaporation (ES). The factors used were estimated by comparing ES' and EG (Aslyng and Stendal 1965). The reason for the varying factor may be a greater heat accumulation in water than in soil, combined with the thermal convection. Such effects could be reduced or avoided by filling some porous material into the tank. Filling sand into the tank as shown in the sketch (Fig. 2) will reduce the heat capacity and minimize thermal convection. The effect is shown in Fig. 4, where the accumulated difference (ES' – ED') and the ration (ES'/ED') are depicted. The evaporation is reduced about 30 mm when sand is added to the tank. The difference occurs mainly in the late part of the year, and is assumed primarily to be a result of thermal convection in the evaporimeter without sand.

The dense screen used for measuring ES and ED reduces the amount of energy reaching the water surface, and is further a rather effective shelter against wind movement below the screen level. The effect of the dense screen is demonstrated in Fig. 5, where ED' and EO are compared. The ratio EO/ED' remains relatively constant at about 1.3 during the whole period until the middle of October, when the evaporation becomes very small, and the ratio, therefore, very uncertain. The difference in evaporation amounts to more than 100 mm. The dense screen strongly reduces the amount of water leaving the evaporimeters. The effect of the dense screen is much greater than the effect of thermal convection, the latter mainly being operative in the autumn where evaporation is relatively small.

The results indicate that the potential evaporation from a grass vegetation (EG) can be estimated reasonably well by either the Penman metod, when reduced by 10 per cent, by evaporation from an evaporimeter as described, when supplied

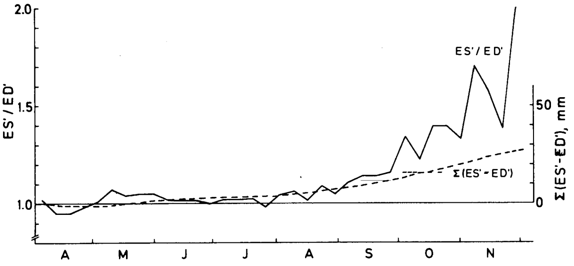

Fig. 4. Evaporation ratio and accumulated difference for the evaporimeters ES and ED. Averaged for the years 1964-1976.

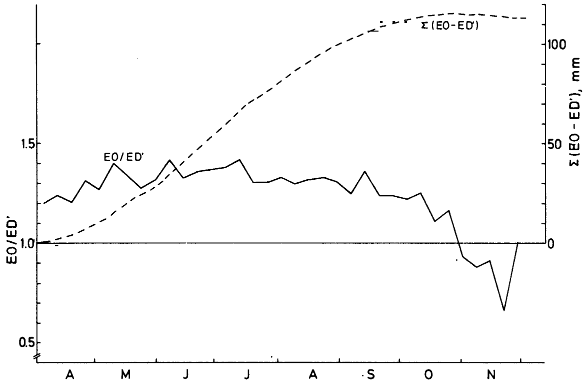

Fig. 5. Evaporation ratio and accumulated difference for the evaporimeters EO and ED. Averaged for the years 1964-1976.

with an open screen, or by the Danish -standard evaporimeter, when season dependent factors are used.

In Fig. 6 the averaged weekly evaporations EG and EP are compared. Except from a few weeks (11 to 18) in the early part of the growing season, a rather good agreement between the two methods is demonstrated.

In Fig. 7 and 8 the pan evaporations ES and EO are similarly compared to EP. Also here a reasonably good straight line relationship is demonstrated. The calculated best fit relationship, however, do not follow the ideal one. The deviation from the ideal function may be explained by a greater heat capacity in the pans than in normal soil. This will cause a somewhat lesser evaporation during periods of heating up, and a similarly greater evaporation during periods of cooling down.

Fig. 9. shows the comparison of the two evaporimeters ES and EO. As an average, the two methods correspond quite well. The average evaporation differs only by 16 mm for the period in question (15th to 48th week). For single years the differences can be greater (about 30 mm), and the points more scattered. The

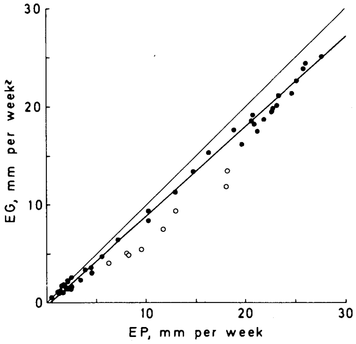

Fig. 6. Relation between calculated potential evapotranspiration (EP) and measured evapotranspiration from grass-covered, weighable evapotranspirometers (EG). 1. to 52. week. Average of the years 1966-1978. The relationship stated is exclusive 11. to 18. week, shown by open dots.

$EG \equiv -0.58 + 0.921\ EP\ (r^2 \equiv 0.938).$

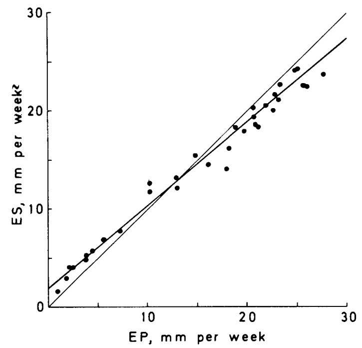

Fig. 7. Relation between calculated potential evaporation (EP) and evaporation from evaporimeter HL 315 with a dense screen and no sand (ES). 15. to 48. week. Average of the years 1966-1978.

$ES \equiv 1.80 + 0.852\ EP\ (r^2 \equiv 0.865).$

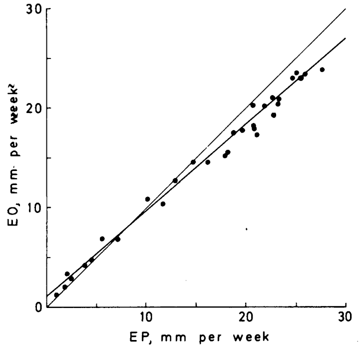

Fig. 8. Relation between calculated potential evaporation (EP) and evaporation from evaporimeter HL 315 with open screen and sand (EO). 15. to 48. week. Average of the years 1966-1978.

$EO = 0.89 + 0.868\ EP\ (r^2 \equiv 0.857).$

method ES, however, without serious complications can be replaced by the method EO, for which a constant factor can be used.

It is suggested that a method similar to the one described for EO is accepted as a standard method for greater regions. When used in short grass, a more shallow depth than 1 m may be acceptable, e.g. 0.6 m, as for the GGI 3000 (W.M.O. 1966), which has been used in the Nordic region during recent years (Waldenström 1977a and b, Järvinen 1978). The depth must be sufficient, however, to prevent root activity below the bottom of the tank. A screen may be nescessary

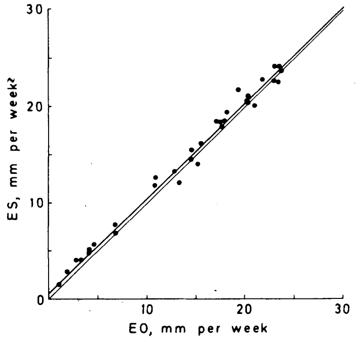

Fig. 9. Relation between evaporation from evaporimeters HL 315 with open screen and sand (EO) and with dense screen without sand (ES). 15. to 48. week. Average of the years 1966-1978.
ES ≡ 0.50 + 1.006 EO (r^2 ≡ 0.987).

when the evaporimeter is operating under field conditions. It might be desirable to reduce the screen density even more than the one used for EO, where the mesh width is 40 mm and the wire thickness 2 mm.

The effect of dry surroundings has been mentioned by Mogensen and Hansen (1979). They found that evaporation from a pan without an irrigated fetch area in dry years was about 80 mm (15-20 per cent) greater than from a pan with an irrigated fetch area. It is suggested, therefore, that the pan should be surrounded by say 10 m fetch area consisting of short grass, that is irrigated whenever needed.

As shown, the potential evapotranspiration from grass (EG) can be estimated with reasonably accuracy by the method described (EO, ES, 0.9 EP). During the years 1969-78 the actual evapotranspiration from some agricultural crops was estimated using the neutron scattering method for measuring the water balance for short periods. For periods with sufficient leaf density an sufficient plant-available water in the root zone to ensure optimum water supply a maximum actual evapotranspiration (EAM) was estimated for these crops.

In Fig. 10 the relation between EAM and EP is shown. The actual evaporation

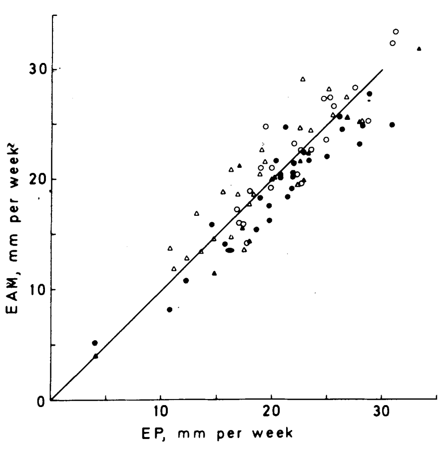

Fig.10. Relation between calculated potential evaporation (EP) and measured maximum evapotranspiration (EAM) from some crops grown under field conditions. Periods with leaf area index greater than 3 and non-limiting water supply are selected among results obtained during the years 1969-1978.

● ≡ Grass: EAM ≡ 1.38 + 0.86 EP (r^2 ≡ 0.882).

○ ≡ Barley: EAM ≡ − 0.24 + 1.02 EP (r^2 ≡ 0.803).

▲ ≡ Winter wheat: EAM ≡ 1.15 + 0.89 EP (r^2 ≡ 0.705).

△ ≡ Sugar beets: EAM ≡ 1.74 + 0.96 EP (r^2 ≡ 0.799).

is assumed to be maximum when the leaf area index is greater than 3.0 (Kristensen 1974), and the soil water deficit in the root zone less than 75 mm for grass and less than 100 mm for other crops. The EAM for grass and winter wheat agrees rather well with 0.9 EP, and consequently with ES and EO as well. For barley and sugar beets the EAM agrees reasonably well with 1.0 EP. This indicates that the evaporative demand for some agricultural crops may exceed the potential evapotranspiration, defined as the maximum evapotranspiration from grass.

Conclusions

The results presented indicate that under climatic conditions as in Denmark, the potential evaporative demand of a vegetation can be estimated reasonably well by sunk iron pans or by the Penman calculating method.

The sunk pan evaporation is proportional to maximum crop evaporation and to the calculated evaporation, provided the thermal convection of the water in the tank is prevented and that a screen, when used, is not impeding the ventilation of the water surface.

The maximum evaporation from a free water surface (12 m^2) is about 10 per cent greater than the potential evaporation from grass.

The maximum actual evapotranspiration from some agricultural crops (e.g. barley and sugar beets) exceeds the potential evapotranspiration from grass by about 10 per cent.

Summary

The potential evapotranspiration has been measured by different methods during a 15-year period. The methods compared were calculation according to Penman's method, evapotranspiration from grass (weighable evapotranspirometers), 12 m^2 free water surface, and sunk pan evaporation.

The potential evapotranspiration from grass is about 90 per cent of the one calculated by Penman's method. Evaporation from a 12 m^2 free water surface, assumed to resemble lake evaporation, is about 3 per cent less than the evaporation calculated by Penman's method. The evaporation measured by sunk evaporimeters (0.315 m^2) is proportional to the potential evapotranspiration from grass and to calculated potential evaporation, when thermal convection in the pan is prevented and the water surface is freely exposed to radiation and wind movement.

The maximum actual evapotranspiration from some agricultural crops, grown under field conditions, corresponds reasonably well to the measured or calculated potential evaporation.

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Address:
Hydrotechnical Laboratory,
Royal Veterinary and Agricultural University,
Højbakkegård
DK-2630 Tåstrup,
Denmark.