8

Journal of Hydrology, 18 (1973) 305–316
© North-Holland Publishing Company, Amsterdam – Printed in The Netherlands

EVAPORATION OF WATER FROM SAND, 3: THE LOSS OF WATER INTO THE ATMOSPHERE FROM A SANDY RIVER BED UNDER ARID CLIMATIC CONDITIONS

D.H.R. HELLWIG

National Institute for Water Research, Ausspannplatz, Windhoek (South West Africa)

(Accepted for publication October 6, 1972)

ABSTRACT

Hellwig, D.H.R., 1973. Evaporation of water from sand, 3: The loss of water into the atmosphere from a sandy river bed under arid climatic conditions. *J. Hydrol.*, 18: 305–316.

The Penman formula was applied to calculate evaporation and evapotranspiration losses under arid climatic conditions from a sandy river bed. Good agreement with measured results was obtained. The loss of water into the atmosphere from a river bed covering 8300 ha was estimated to be $76 \cdot 10^6$ m^3/year. Evapotranspiration contributed 68% and permanently wet areas 19.5% to the total water loss. The rest evaporated from temporary wet areas. Substantial volumes of water can possibly be gained by the removal of phreatophytes.

INTRODUCTION

Investigations on the Swakop river in South West Africa indicated that evaporation seemed to be the most important single factor responsible for the increasing concentration of salts in the water found in the sand bed of that river. To estimate the order of the evaporation losses the Penman formula (Penman, 1948, 1949, 1952) was applied to calculate the loss of water into the atmosphere from the bed of the Swakop river between Okahandja and the sea (between a southern latitude of 21°58′ and a longitude of 16°55′ and a southern latitude of 22°39′ and a longitude of 14°32′).

The vapour transport coefficient (E_a) in Penman's formula (symbols used in formulas are explained in Notation I):

$$E_o = \frac{\Delta H + \gamma\, E_a}{\Delta + \gamma} \qquad (1)$$

was calculated according to Rijtema (1965):

$$E_a = 0.18\, u(e_s - e_d) \qquad (2)$$

NOTATION I

E_o	= evaporation from an open water surface	mm/day
Δ	= slope of the saturation vapour pressure curve at temperature T	mm Hg/°C
H	= evaporation equivalent of net radiation energy available at surface	mm/day
γ	= psychrometer constant; for °C = 0.49	mm Hg/°C
E_a	= vapour transport coefficient	mm/day
u	= wind velocity 2 m high	m/h
e_s	= mean saturation vapour pressure at the temperature T	mm Hg
e_d	= actual vapour pressure of the air	mm Hg
RA	= total daily theoretical radiation energy (Angot value)	cal/cm^2/day
$\frac{RA}{59}$	= evaporation equivalent of RA	mm/day
n	= actual duration of bright sunlight	h
N	= maximum possible duration of bright sunlight	h
r	= reflection coefficient of surface; 0.05 for water, 0.20 for plant cover	
σ	= Stefan-Boltzmann constant	
σT^4	= radiation of a black body at temperature T (T expressed in °K)	cal/cm^2/day

For estimating potential evapotranspiration a slightly modified wind function was used:

$$E_a = 0.15\, u(e_s - e_d) \tag{3}$$

Due to difficulties experienced with the net radiometer, net radiation measurements were available only for short intervals. For estimating net radiation the calculation method recommended by Penman (1948) was applied:

$$H = \frac{RA}{59}\,(0.18 + 0.55\,\frac{n}{N})\,(1 - r) - \sigma T_a^4 (0.56 - 0.09\,\sqrt{e_d})\,(0.10 + 0.90\frac{n}{N}) \tag{4}$$

The duration of actual bright sunlight was obtained from the net radiation charts. Although the net radiation readings were unreliable, the periods of bright sunlight could be determined accurately.

RESULTS

Comparison of measured and calculated evaporation values

To check the reliability of the calculated results monthly average evaporation

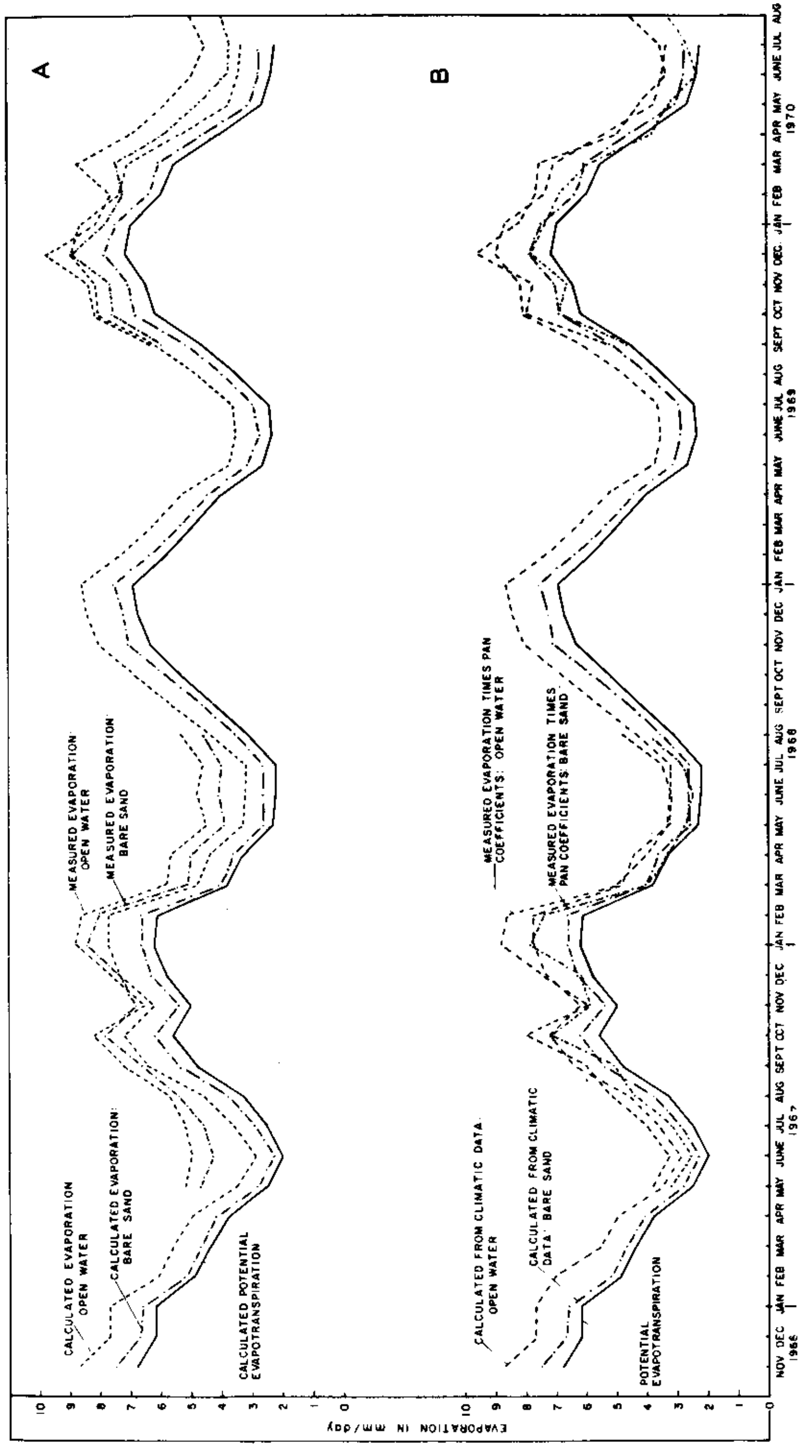

Fig. 1. A. Comparison of measured and calculated evaporation values for Gross Barmen. B. Comparison of evaporation values for Gross Barmen calculated from climatic data and from measured values multiplied with pan coefficients.

TABLE I

Comparison of pan coefficients with the ratio "calculated evaporation over measured evaporation" (pan coefficients from table 6, Kriel, 1963)

	Pan coefficients of 6 stations in the R.S.A.		"Calculated evaporation over measured evaporation" at Gross Barmen			
			open water		barren sand	
	mean monthly values	mean quarterly values	mean monthly values	mean quarterly values	mean monthly values	mean quarterly values
Jan.	0.97		0.97		0.87	
Feb.	0.93	0.96	0.93	0.91	0.86	0.84
March	0.98		0.82		0.80	
April	1.00		0.77		0.75	
May	1.00	0.95	0.68	0.70	0.64	0.67
June	0.86		0.65		0.63	
July	0.71		0.71		0.67	
Aug.	0.74	0.71	0.81	0.82	0.74	0.75
Sept.	0.67		0.94		0.84	
Oct.	0.77		0.94		0.85	
Nov.	0.91	0.84	0.97	0.95	0.86	0.86
Dec.	0.84		0.94		0.88	
Mean	0.87	0.87	0.84	0.84	0.78	0.78

Locality of stations

	6 stations in the Republic of South Africa						Gross Barmen
Latitude	28°03′	29°30′	27°57′	26°34′	28°00′	25°37′	22°07′
Longitude	26°40′	25°13′	26°33′	25°35′	26°41′	28°22′	16°38′

values were calculated for an open water surface and for barren wet sand for the period November, 1966 to August, 1970, using the climatic data collected in the Swakop river bed at the experimental station Gross Barmen (Hellwig, 1973). The results were compared with results measured at the station using round tanks with a surface area of 1 m². The results are graphically demonstrated in Fig. 1A. The trends of the curves show very close agreement. The calculated values were, however, generally too low.

Evaporation losses measured in small tanks are higher than evaporation losses from large surfaces. Calculated results are accepted as being valid for large areas. The ratio "calculated evaporation over measured evaporation" should thus agree with pan coefficients. In Table I ratios of "calculated evaporation over measured evaporation" are compared with pan coefficients determined for 6 different sites (Kriel, 1963), in the Republic of South Africa for square tanks with a surface area of 3,3 m². There is a three months time-lag between the two sets of results for open water, a probable explanation being the different geographical location and the difference in climatic pattern between the sites in the R.S.A. and Gross Barmen. Considering this time-lag the ratio "calculated evaporation over measured evaporation" agrees indeed well with pan coefficients.

The mean pan coefficients determined in the R.S.A. were used to adjust the measured evaporation for open water in order to obtain values valid for large areas comparable with calculated results.

The ratios "calculated evaporation over measured evaporation" for barren wet sand are on the average 0.06 smaller than for open water. The pan coefficients determined in the R.S.A. were reduced by 0.06 and then used to adjust the measured results for barren sand considering a time-lag of 3 h. In Fig. 1B the adjusted measured results are compared with the calculated results. Treated in this way, the results show very good agreement. For the total comparable periods the calculated results for open water totalled 97.3% of the adjusted measured values. For barren wet sand the figure is 97.4%. From these results it is concluded that for long periods the calculated results are reasonably good estimates of actual evaporation under the climatic conditions prevailing at the experimental station.

The results calculated for potential evapotranspiration could, unfortunately, not be compared with actual results determined locally. In Table II the ratios "evapotranspiration over pan evaporation" of the calculated values, for comparable months, are compared with such ratios calculated by Davis (1963) from experimental results obtained in South Pasadena, California.

Lacking a better means of checking the reliability of the calculated evapotranspiration figures, the good agreement of the ratios in Table II is accepted as indicating that for long periods the calculated results can be considered to be reasonably good estimates.

From the results given in Fig. 1B, monthly means were calculated. These are demonstrated in Fig. 2. For open water the calculated **yearly** total is 98.3% of the measured total. For barren sand the figure is 99.4%. All further calculations are based on these results.

TABLE II

Comparison of ratios "evapotranspiration over pan evaporation"

	Ratios of calculated results for Gross Barmen				Ratios calculated in California	
	1966/1967	1967/1968	1968/1969	1969/1970	1961	
December	0.81	0.79	0.80	0.80	0.91	June
January	0.81	0.81	0.80	0.80	0.80	July
February	0.80	0.79	0.79	0.81	0.75	August
March	0.79	0.79	0.79	0.79	0.73	September
April	0.76	0.75	0.75	0.75	0.69	October
May	0.71	0.70	0.70	0.70	0.46	November
Mean	0.78	0.77	0.77	0.78	0.77	

The loss of water into the atmosphere from the Swakop river bed

Assumptions

The yearly temperature mean at Gross Barmen was 24.4° with an average maximum in December of 41°C and an average minimum in June of 4.2°C. Maximum temperatures of 45°C in summer are not exceptional and minimum temperatures of −5 to −10°C occur regularly each winter. The yearly mean humidity was 40.3% with an average maximum in December of 77% and an average minimum in June of 17%. In the desert area, crossed by the Swakop river temperatures are generally higher and humidities lower due to a considerably reduced rainfall. (From Gross Barmen where the average yearly rainfall is approximately 350 mm, rainfall decreases to practically zero at the coast). Climatic records from this area are, however, not available. Since the evaporation estimates calculated for the Swakop river bed are based on the climatic records from Gross Barmen, the results are considered to be under- rather than over-estimated.

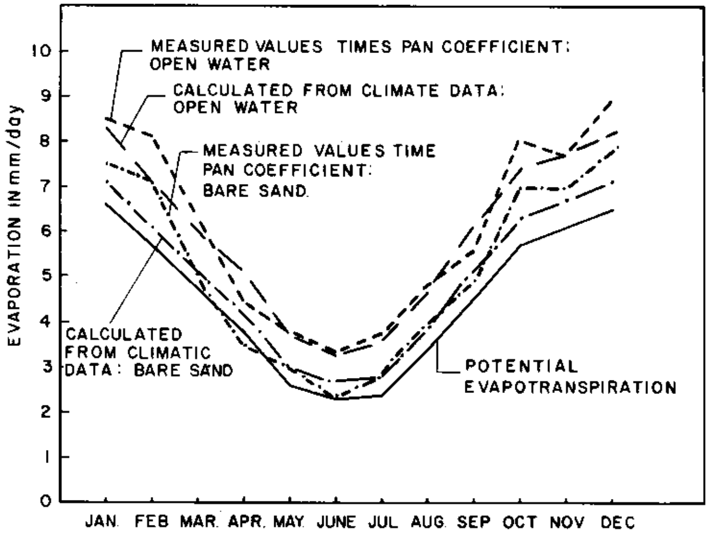

Fig. 2. Comparison of calculated and measured mean evaporation values for Gross Barmen.

The bank vegetation, as well as the vegetation in the river bed, is probably seldom subjected to a water shortage, because the root system of the vegetation is likely to have access to the water in the sand bed of the river at all times. Thus, for the purpose of this paper, it is assumed that the water dissipated into the air by the vegetation in the Swakop river bed by actual evapotranspiration is equal to the potential evapotranspiration.

Statistically the highest precipitation is experienced in the months of January, February and March. This is the period when the Swakop river occasionally flows. It can probably be assumed that an average of about 10 floods are experienced in the Swakop river during the rainy season. For the purpose of this paper it is also assumed that the sand surface of the river bed is under water or wet for 3 to 5 days per flood, and that on the average not more than 50% of the river bed is wetted during that period. It is thus considered that during the rainy season, from 50% of the surface area of the barren sand-covered river bed water is evaporated from wet sand for 1½ months. It is assumed that for another 2 months the same surface area is moist, which might represent conditions as were found in the Gross Barmen experiments in the tanks with the water-table 30 cm below the sand surface, which means an evaporation rate of 50% of that from the wet sand surface. These 2 months comprise periods between floods and a period after the rainy season. Further it is assumed that for the rest of the year no evaporation takes place from the dry and barren sand surfaces. For calculating the evaporation losses from the barren sand during and immediately after floods an average evaporation rate for the months January, February and March was used. To calculate the evaporation losses from the same areas between floods and for a period after the rainy season, 50% of the value obtained for the period during floods was taken and 50% of the evaporation loss calculated for barren wet sand for half the month of April was added.

At certain places in the Swakop river bed the water flowing in the sand bed is forced to the surface forming areas which are permanently wet. In these areas water is assumed to evaporate from a wet sand surface all year round.

TABLE III

The size of various types of areas in the Swakop river bed between Okahandja and the sea

Sand covered areas (permanently wet)		Sand covered areas (temporarily wet)		Vegetated areas		Total area
size (ha)	% of total	size (ha)	% of total	size (ha)	% of total	size (ha)
815.62	9.8	4341.86	52.3	3141.36	37.9	8298.84

Calculation of water losses

The various surface areas of the Swakop river bed, as given in Table III, were measured with a planimeter from maps and aerial photographs.

Based on the considerations discussed in the section "Assumptions" and using the results given in Table III and IV, the evaporation and evapotranspiration losses from the Swakop river bed were calculated for one year. The results are given in Table V.

According to these estimates an average volume of water of $76 \cdot 10^6$ m^3/year is lost from the Swakop river bed between Okahandja and the sea.

TABLE IV

Monthly evaporation in mm calculated using climatic data from Gross Barmen*

	Barren wet sand	Potential evapotranspiration
January	220	205
February	171	160
March	158	146
April	126	114
May	93	81
June	81	69
July	90	74
August	118	105
September	153	135
October	195	177
November	201	183
December	220	202
	1826	1651

* The monthly evaporation totals were calculated using the results given in Fig. 2.

TABLE V

Losses of water by evaporation and evapotranspiration from the Swakop river bed between Okahandja and the sea (m^3/year)

	Potential evapotranspiration of the vegetated area	Evaporation from permanently wet barren sand	Evaporation from temporarily wet barren sand for period when wet	Evaporation from temporarily wet barren sand for period when moist
January	6,439,788.0	1,794,364.0	5,959,202.9	3,663,444.4
February	5,026,176.0	1,394,710.2		
March	4,586,385.6	1,288,679.6		
April	3,581,150.4	1,027,681.2		
May	2,544,501.6	758,526.6		
June	2,167,538.4	660,652.2		
July	2,324,606.4	734,058.0		
August	3,298,428.0	962,431.6		
September	4,240,836.0	1,247,898.6		
October	5,560,207.2	1,590,459.0		
November	5,748,688.8	1,639,396.2		
December	6,345,547.2	1,794,364.0		
	51,863,853.6	14,893,221.2	5,959,202.9	3,663,444.4
% of total	67.9	19.5	7.8	4.8

DISCUSSION

The total figure obtained for the yearly loss of water into the atmosphere from the Swakop river bed must be judged in the light of the reliability of the applied calculation method, as well as the assumptions made. The check of calculated estimates against actually measured results was not completely satisfactory because the ratio "calculated evaporation over measured evaporation" had to be compared with pan coefficients determined at different localities with evaporation tanks of different shape and surface area. Since the locality, as well as the shape and size of evaporation tanks has an effect on the pan coefficient (Sleight, 1917; Rohwer, 1931; Young, 1936; Staley, 1957; Veihmeyer, 1964) the results were, strictly speaking, not directly comparable. The check on the potential evapotranspiration estimates was even more problematical, because locally measured results are not available.

In spite of the shortcomings in checking the reliability of the estimates, it is concluded from the excellent agreement of the results given in the section "Comparision of measured and calculated evaporation values" that for annual periods, calculated results may be considered to be reasonably good estimates of the actual evaporation losses.

Of the assumptions made on pp.310–311 only those on which the calculations are based for the barren sand areas, which are not permanently wet, can be subject to considerable error. The calculated estimates of evaporation losses from these areas comprise, however, only 12.6% of the total evaporation loss. Thus significant errors in the assumptions would have a relatively small effect on the figure for the total water loss.

Results obtained by Culler (1970) in the Gila river bed in Arizona, support the results estimated for the Swakop river bed. The climatic conditions in the Gila river bed are comparable with those in the Swakop river bed. Although the rainfall is low (less than 200 mm/year) the Gila river flows most of the year. Culler determined, with the water budget method, an evaporation loss of 37.1 m^3/ha/day, as an average for 6 months. The equivalent figure determined for the Swakop river bed is 25.2 m^3/ha/day as an average for 12 months. If the loss of water from the surface flow of the Gila river is subtracted from Culler's result a figure of 26.5 m^3/ha/day is obtained. If the same is done for the Swakop river result the equivalent figure is 23.2 m^3/ha/day. Both figures agree very well although they were obtained by using completely different techniques.

CONSIDERATION WITH RESPECT TO THE POSSIBLE REDUCTION OF WATER LOSSES BY EVAPOTRANSPIRATION FROM A RIVER BED IN EXTREMELY ARID REGIONS

The most significant factor contributing 68% to the total water loss into the atmosphere is evapotranspiration from the vegetated areas which are mainly covered by phreatophytes (*Acacia albedo, Acacia karroo, Tamarix austro-africana,* Prosopis and reeds in the permanent wet areas). Evapotranspiration of phreatophytes greatly exceeds that from irrigated fields (Blaney, 1954). Hibbert (1971) reported on a substantial increase in water yield on two small chaparral watersheds in central Arizona following brush control and conversion to grass. Johnston (1970) found for deeprooted aspen an evapotranspiration of almost double that from barren soil. In central New England (Hornbeck et al., 1970), a hardwood forest cover was cleared and regrowth prevented with herbicides. The increase in annual water yield was 8.4 m^3/ha/day. From Culler's results it was calculated that the evapotranspiration losses in the Gila river were reduced by 14.3 m^3/ha/day after the removal of all phreatophytes (88% Tamarisks and 12% Prosopis). This reduction held for the total area of the Gila river under consideration. (The area is not subdivided into vegetated, barren areas, etc.) Because of the good agreement of Culler's (1970) results with those reported in this paper, a similar figure would probably hold for the Swakop river bed. Applied to the total area of 8300 ha the removal of phreatophytes would, according to the results of Culler (1970) result in a reduction of evapotranspiration of $43 \cdot 10^6$ m^3/year. Applied to the vegetated area only (3140 ha), the reduction in water loss would amount to $16 \cdot 10^6$ m^3/year. Thus by the removal of phreatophytes substantial volumes of water can be prevented from being lost to the atmosphere from a river bed in an extremely arid region. Whether such a measure would be of practical value is a question of technical feasibility and economic considerations, and last but not least, a question of how badly the water is needed.

CONCLUSIONS

(1) By applying the Penman formula to estimate evaporation under arid climatic conditions from a sandy river bed good agreement with measured results was obtained.

(2) The loss of water into the atmosphere from a river bed covering an area of 8300 ha was estimated to be $76 \cdot 10^6$ m^3/year.

(3) Evapotranspiration contributed 68% to the total water loss and evaporation from permanently wet areas 19.5%. The rest is evaporated from temporary wet areas.

(4) By the removal of phreatophytes between 16 and $43 \cdot 10^6$ m^3/year could possibly be prevented from being lost to the atmosphere.

ACKNOWLEDGEMENTS

The investigations described in this paper were carried out at the request of the Water Affairs Branch of the South West Africa Administration under the guidance of the Steering Committee for Water Research in South West Africa. Funds were provided by the South West Africa Administration.

The permission of the Director of Water Affairs, South West Africa Branch, to publish this paper is hereby acknowledged.

REFERENCES

Blaney, H.F., 1954. Consumptive use of groundwater by phreatophytes and hydrophytes. *Int. Assoc. Sci. Hydrol. (Gen. Assem., Rome, 1954) Publ.*, 37(2): 53–62.

Culler, R.C., 1970. Water conservation by removal of phreatophytes. *Trans. Am. Geophys. Union*, 51: 684–689.

Davis, J.R., 1963. Relationship of can evaporation to pan evaporation and evapotranspiration. *J. Geophys. Res.*, 68: 5711–5718.

Hellwig, D.H.R., 1973. Evaporation of water from sand, 1: Experimental set-up and climatic influences. *J. Hydrol.*, 18(2): 93–108.

Hibbert, A.R., 1971. Increase in stream flow after converting chaparral to grass. *Water Resour. Res.*, 7: 71–80.

Hornbeck, J.W., Pierce, R.S. and Federer, C.A., 1970. Streamflow changes after forest clearing in New England. *Water Resour. Res.*, 6: 1124–1132.

Johnston, R.S., 1970. Evapotranspiration from bare, herbaceous and aspen plots: a check on a former study. *Water Resour. Res.*, 6: 324–327.

Kriel, J.P., 1963. Recent investigations on the evaporation from large water surfaces and evaporation tanks in South Africa. *S. Afr. Dep. Water Affairs, Tech. Rep.*, 29: 9 pp.

Penman, H.L., 1948. Natural evaporation from open water, bare soil and grass. *Proc. R. Soc. Lond. Ser. A*, 193: 120–164.

Penman, H.L., 1949. The dependence of transpiration on weather and soil conditions. *Brit. J. Soil Sci.*, 1: 74–89.

Penman, H.L., 1952. The physical basis of irrigation control. *Proc. Int. Hortic. Congr., 13th, London*, 2: 913–924.

Rijtema, P.E., 1965. An analysis of actual evapotranspiration. *Agric. Res. Rep.* 659. Centre for Agricultural Publication and Documentation, Wageningen, The Netherlands, 107 pp.

Rohwer, C., 1931. Evaporation from free water surfaces. *U.S. Dep. Agric. Tech. Bull.*, 27: 96 pp.

Sleight, R.B., 1917. Evaporation from the surface of water and river bed material. *J. Agric. Res.*, 10: 209–262.

Staley, R.W., 1957. *Effect of Depth of Water-Table on Evaporation from Fine Sand.* Thesis, Colo. State Univ., Fort Collins, Colo., 101 pp.

Veihmeyer, F.J., 1964. Evapotranspiration. In: Ven Te Chow (Editor), *Handbook of Applied Hydrology*, (Section II). McGraw-Hill, New York, San Francisco, Toronto, London, 38 pp.

Young, A.A., 1936. Discussion on Cummings: evaporation from water surfaces: status of present knowledge and need for further investigation. *Trans. Am. Geophys. Union. Rep. Papers, Hydrology*, 17: 509–512.