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Further Evidence of Hysteresis as a Factor in the Evaporation from Soils

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Abstract. Evaporation studies were conducted on a fine sand which was in contact with a water table and was subjected to diurnal cyclic atmospheric conditions. Previous studies under steady atmospheric conditions showed that an inverse relation between the rate of evaporation from soils and the rate of evaporation from a free-water surface occurred under certain conditions. These studies also showed that this inverse relationship was produced by decreased evaporativity as the depth to the water table was increased. A theoretical explanation of this phenomenon was presented on the basis of a hysteresis in the functional relation between permeability and saturation of soils. The data presented in the present paper show that this phenomenon also occurs under cyclic atmospheric conditions. The conclusion is that the inverse relationship could occur in soils under field conditions, and therefore it could be a significant consideration in predicting evaporation from soils.

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Introduction. Results reported by *Schleusener and Corey* [1959] show that an inverse relation sometimes exists between evaporation rate from a 'free-water surface' and evaporation rate from a soil having a water table at a constant depth below the surface. Figure 1 is taken from the paper by Schleusener and Corey. This figure is typical of the results for various soils; that is, for shallow water tables and low evaporativity, the rate of evaporation from the soils was approximately the same as from the free-water surface. For deeper water tables and higher evaporativity, however, the soils exhibited a maximum value of evaporation rate, so that increased evaporativity produced a decreased evaporation rate in the soils. This result was contrary to previous theory which predicted a limiting evaporation rate from the soils with increasing evaporativity. The existence of this inverse relationship was explained by *Schleusener and Corey* [1959] on the basis of a hysteresis phenomenon. The earlier study was conducted under steady atmospheric conditions. The question arose whether this inverse relation would also occur under cyclic atmospheric conditions similar to those found in the field where the high evaporativity exists for only a short part of a 24-hour period. Experiments have been conducted to study this question.

Definitions.

Free-water surface: A column of sand in which the water table was maintained at the surface.

e_f: Evaporation rate from free-water surface expressed in inches per day. Subscript refers to the period of time for which evaporation was measured; i.e., $e_{f\,1.2}$ refers to the evaporation rate as measured over the 1.2-hour period of maximum evaporation.

e_s: Evaporation rate from soil expressed in inches per day.

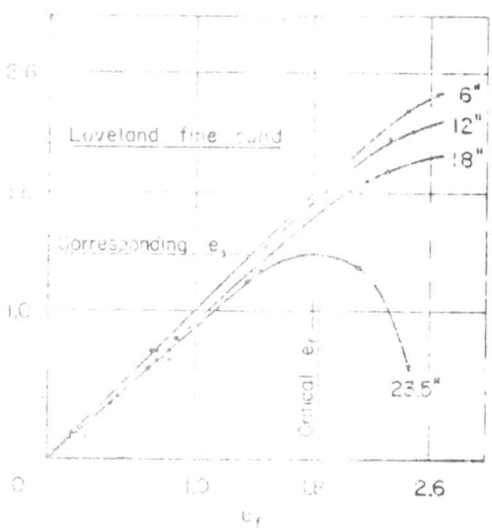

Fig. 1. Evaporation rate from Loveland fine sand (e_s) as a function of evaporation rate from free-water surface (e_f), for water-table depths of less than 23.5 inches. (Evaporation rates are expressed in inches per day and are measured over a 24-hour period of constant atmospheric conditions.)

TABLE 1. Ranges of Ambient Variables and Methods Used for Increasing e_f during Studies of the Effect of Cyclic Variation of Ambient Conditions on Evaporation from Soils in Contact with a Water Table

Run No.	Temp. Range, °F	RH Range, %	Radiation Level	Wind Velocity
8	75–105	10–20	Increasing	Approx. 10 fps at $e_{f\,1.2}$ = 3.07 and 4.37 in/day
9	50–80	25–50	Increasing	Approx. 10 fps at $e_{f\,1.2}$ = 2.28 and 3.62 in/day
10	65–95	20–40	Increasing	Approx. 10 fps at $e_{f\,1.2}$ = 2.76 and 3.84 in/day
11	Increasing from 45–75 to 75–105 in 5° increments	25–50	Constant	None
12	Decreasing from 75–105 to 50–80	25–50	Constant	None
13	60–90	25–50	Constant	Increasing from 0 to 20 fps
15*	60–90	25–50	Increasing	Approx. 10 fps at $e_{f\,1.2}$ = 2.86 and 4.08 in/day
16	60–90	25–50	Constant	Increasing from 0 to 25 fps

* Water-table depths for run 15 were 24, 25, and 26 inches. For all other runs the water-table depths were 18, 24, and 27 inches.

Critical e_f: Value of e_f at which e_s begins to decrease with increasing e_f (see Fig. 1).

Corresponding e_s: Value of e_s when critical e_f occurs (see Fig. 1).

Evaporativity: The potential rate of evaporation produced by ambient conditions (measured by e_f).

Apparatus and procedure. The study was conducted in an environmental chamber with controls modified so that the temperature, relative humidity, and radiation automatically underwent a diurnal cyclic variation as described by *Schleusener and King* [1960]. A fine sand was placed in 3½-inch-i.d. Lucite containers which were placed upon a rotating table at equal radii. Water was supplied to the base of each column at a constant pressure from a Mariotte-siphon bottle. Measurements of evaporation rate were taken for a 1.2-hour period of highest evaporativity and for a 24-hour period (one full cycle). After the rate of evaporation was determined for one set of cyclical conditions, the cycle was changed and measurements were taken for the new conditions. The range of the ambient variables and the method used for increasing the rate of evaporation from the free-water surface e_f are shown in Table 1. (For example, Table 1 shows that for run 16 the ambient temperature range was 60° to 90° F, the range of relative humidity was 25 to 50 per cent, and the radiation was held constant. The evaporativity was increased by increasing the wind velocity from 0 to 25 ft/sec.

Experimental results. The results for the 1.2-hour period are shown in Figure 2. The curves for the 24-hour period are not shown, but they were of similar shape. From examination of Figure 2 it can be seen that, for some conditions, an increase in e_f did result in a decrease in e_s; that is, the inverse relationship mentioned above did exist for some conditions. The value of e_f for which this phenomenon occurred is called the 'critical e_f.' These critical values of e_f for the 27-inch water-table depth and related data are shown in Table 2. The critical values of $e_{f\,1.2}$ and $e_{f\,24}$ occurred during the same cycle of ambient variables.

From examination of Figure 2 and Tables 1 and 2, several factors may be noted:

1. A critical value of $e_{f\,1.2}$ was reached only for water-table depths greater than 24 inches.

2. The inverse relation between e_s and e_f was noted only for conditions of increasing radiant

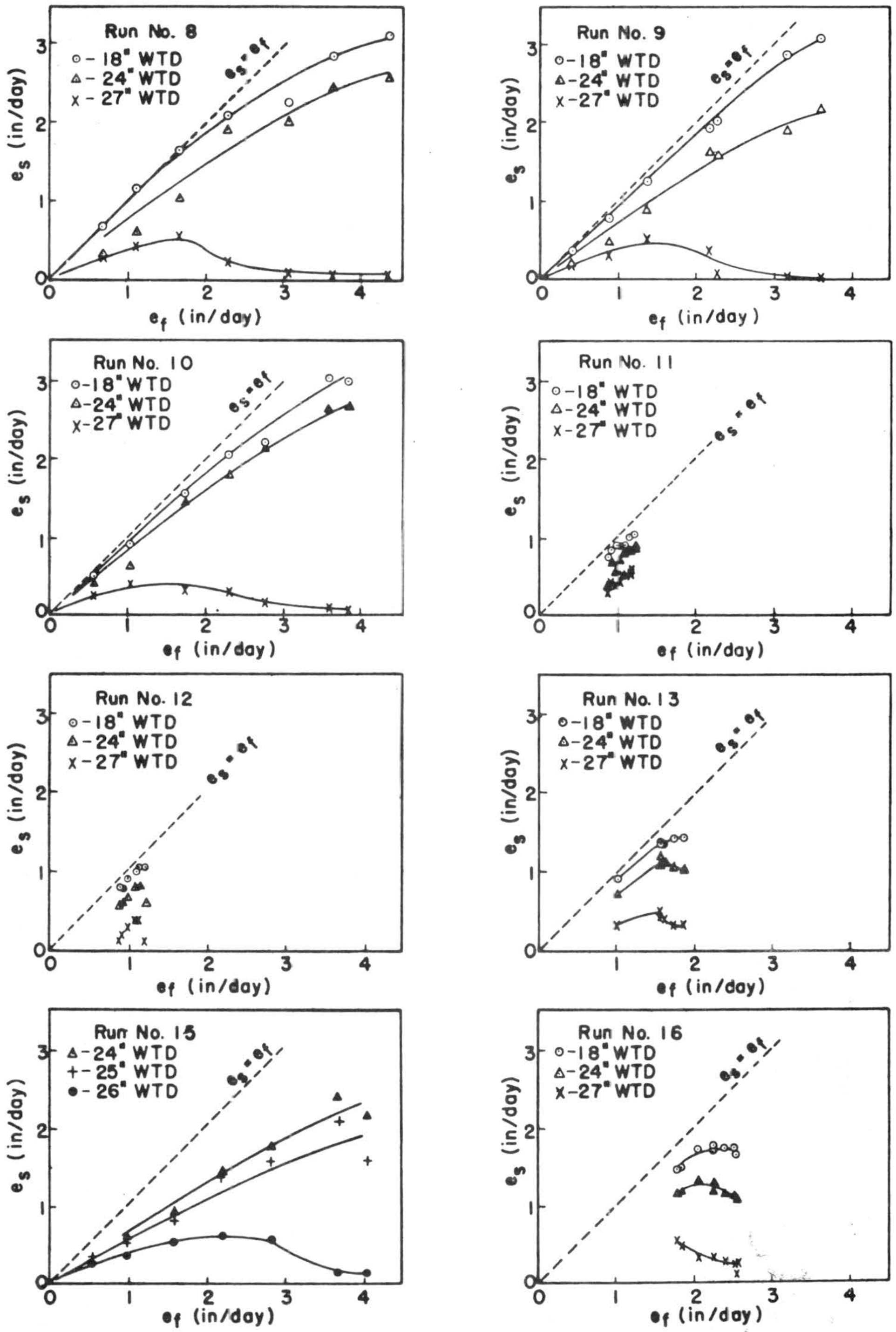

Fig. 2. Evaporation rate from Loveland fine sand (e_s) as a function of evaporation rate from free-water surface (e_f), for various water-table depths. (The cyclic ambient conditions and method of changing e_f are specified in Table 1. All rates are expressed for the 12-hour period of highest evaporativity.)

TABLE 2. Critical Values of e_f and Related Data

Run No.	Critical $e_{f\,1\text{-}2}$, in/day	Corresponding $e_{s\,1\text{-}2}$, in/day	Critical $e_{f\,24}$, in/day	Corresponding $e_{s\,24}$, in/day	Critical $\frac{e_{s\,1\text{-}2}}{e_{f\,1\text{-}2}}$	Critical $\frac{e_{s\,24}}{e_{f\,24}}$	Temperature of Soil Surface, °F	Temperature of Free-Water Surface, °F
8	1.6	0.55	0.9	0.4	0.34	0.44	127	115
9	1.5	0.5	0.7	0.3	0.33	0.43	110	106
10	1.5	0.4	0.7	0.3	0.27	0.43	104	102
11	*	*	*	*	*	*	*	*
12	*	*	*	*	*	*	*	*
13	1.5	0.5	0.7	0.3	0.33	0.43	92	79
14	*	*	*	*	*	*	*	*
15	2.3†	0.6†	1.0†	0.4†	0.26†	0.40†	138†	119†
16	1.8 or less	0.5 or more	0.9	0.3	0.28 or more	0.33	135	121

* Inverse relation between e_s and e_f was not observed during these runs (see Fig. 2).
† Depth to the water table was 26 inches.

energy (runs 8, 9, 10, and 15) or for conditions of increasing wind velocity (runs 13 and 16). In each of these runs, $e_{f\,1.2}$ exceeded about 1.5 in/day and $e_{f\,24}$ exceeded about 0.7 in/day. The inverse relationship was not noted for conditions such that $e_{f\,1.2}$ did not exceed about 1.2 in/day (runs 11 and 12), or when $e_{f\,24}$ did not exceed about 0.5 in/day. This result appeared to be independent of whether the ambient temperature range was increased or decreased with time.

3. The critical value of $e_{f\,1.2}$ was approximately 1.5 in/day for the 27-inch depth to the water table. The corresponding value of $e_{s\,1.2}$ was about 0.5 in/day.

4. The critical value of $e_{f\,24}$ was approximately 0.7 in/day for the 27-inch depth to the water table. The corresponding value of $e_{s\,24}$ was about 0.3 in/day.

5. The critical values of $e_{s\,24}/e_{f\,24}$ were larger than $e_{s\,1.2}/e_{f\,1.2}$ in each run for which a critical e_f occurred, the values being approximately 0.4 and 0.3, respectively.

6. Soil-surface temperature and the temperature of the free-water surface were erratic and appeared to follow no consistent pattern in relation to critical values of e_f.

7. An inverse relation between e_s and e_f can be produced under cyclic ambient conditions.

Discussion of results. Both Figure 2 of *Schleusener and Corey* [1959] and Figure 2 of this paper show that the inverse relation between the rate of evaporation from a free-water surface and the rate of evaporation from soils in contact with a water table is produced by smaller and smaller evaporativity as the depth to the water table is increased. This trend is also predicted by the theoretical considerations presented in detail by *Schleusener and Corey* [1959].

Let us consider a saturated soil in contact with a water table at a constant depth. As long as the rate of evaporation from the surface does not exceed the rate at which water can be conducted upward from the water table, e_s should be proportional to e_f. Whenever the rate of evaporation from the surface exceeds the rate at which water can move upward through the soil, the surface must dry out. Subsequent to such drying of the surface, the water to be evaporated must be imbibed by the drier surface layer. At this time, the inverse relation occurs because of hysteresis in the functional relation between permeability and saturation as discussed in detail by *Schleusener and Corey* [1959]. For the same evaporativity, as the water table becomes deeper, the gradient for upward flow becomes smaller, and as a result the rate of movement of water upward from the water table decreases. Hence, a smaller evaporativity is required to produce the inverse relation as the water table becomes deeper.

The conditions reported here are probably more severe than would be encountered in the field. However, water tables in the field are often much deeper than 27 inches. Thus, the inverse relationship may exist under certain conditions in the field.

The results given in this paper are noteworthy in that they are compatible with the hysteresis hypothesis presented earlier. Further, they support the implications given by *Schleusener and Corey* [1959]: (1) that measurements from evaporation pans are unreliable as an estimate of the evaporation from bare soils and (2) that treatments which cause rapid initial drying of the soil surface should conserve soil moisture under most conditions.

References

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