COLORADO AGRICULTURAL EXPERIMENT STATION
and
AGRICULTURAL RESEARCH SERVICE

Progress Report No. 3

Colorado Contributing Project

Study of Evaporation from Soil Surfaces in Terms of Soil and Micrometeorological Factors

of the

Western Regional Research Project W-32

Basic Hydrological Factors Relating to Water Conservation

November 22, 1957

COLORADO AGRICULTURAL EXPERIMENT STATION
and
AGRICULTURAL RESEARCH SERVICE

PROGRESS REPORT NO. 3

Colorado Contributing Project

Study of Evaporation from Soil Surfaces
in Terms of Soil and Micrometeorological Factors

of the

Western Regional Research Project W-32

Basic Hydrological Factors Relating to
Water Conservation

November 22, 1957

COLORADO CONTRIBUTING PROJECT W-32

PROGRESS REPORT NO. 3

Project Leader: Arthur T. Corey, Civil Engineer

Other Personnel: Richard A. Schleusener, Graduate Assistant

Robert W. Staley, Graduate Assistant

Cooperating Agencies: Colorado Agricultural Experiment Station, Agricultural Research Service, U.S.D.A.

Objectives:

The project is a comprehensive study of moisture transfer from soil by evaporation from the soil surface. The objectives are to evaluate the variables known to affect evaporation from soil and to search for relationships among the pertinent variables which will permit quantitative estimates of evaporation from a given soil under prevailing ambient conditions.

Nature of Work:

Completed and current experiments have been concerned with evaporation from soil profiles in contact with a water table. In previous reports studies conducted in the Colorado State University wind tunnel were described. In these experiments, the depth of water table and wind velocity were varied independantly, but humidity, the ambient temperature, and radiant energy input were not under control. Currently the experiments are being conducted in a chamber (12' x 12' x 12') which provides control over each of these variables.

Only one soil, a fine sand, was used in the wind tunnel whereas a clay loam, a sandy loam, and a fine sand are being investigated in the air-conditioned chamber. Experiments currently in operation are described in the next section.

Equipment and Procedure:

Soil columns were placed on a turntable in the air-conditioned chamber at equal radii from the axis of rotation. Initially, each column consisted of a number of 3-inch sections of lucite tubing 4-inches in diameter, each section being filled with the same dry weight of a homogenous soil. There was one column of each of the three soils and a fourth column that was used as a control. The latter column was also filled with sand but the water table was maintained at the surface so that the rate of evaporation from this column could be used as a measure of the ambient evaporating conditions.

The table was turned under a group of 36 infra-red lamps of 250 watts each. The radiant energy input to the soil surfaces could be controlled by raising or lowering the bank of lamps and also by varying the number of lamps that were turned on. The sides of the columns were protected from radiation by a transite shield at the plane of the soil surfaces and also by glass-wool pipe insulation around the columns. The latter helped to prevent radial temperature gradients in the columns.

Vertical temperature gradients were measured by means of thermocouples placed at intervals along the central axes of the columns. In recent runs three pencil-type tensiometers were placed thru the soil columns (one at about the middle of the column and one each near the top and bottom) for the purpose of determining the capillary pressure at these points. A semi-automatic method of measuring and recording the temperature profiles was devised. For high water-table depths and rapid evaporation rates, the water-table depths were maintained by Mariotte siphons and the evaporation rates were determined by periodically weighing the water supply bottles. In order to simulate greater water-table depths, capillary barriers were placed at the bottom of 2-ft. soil columns and the Mariotte siphons were modified so that they could supply water to the bottom of the columns at pressures less than atmospheric. For small evaporation rates the Mariotte siphons were made from burettes and the rates were determined from volumetric measurements. The latter arrangement is shown in Figure 1.

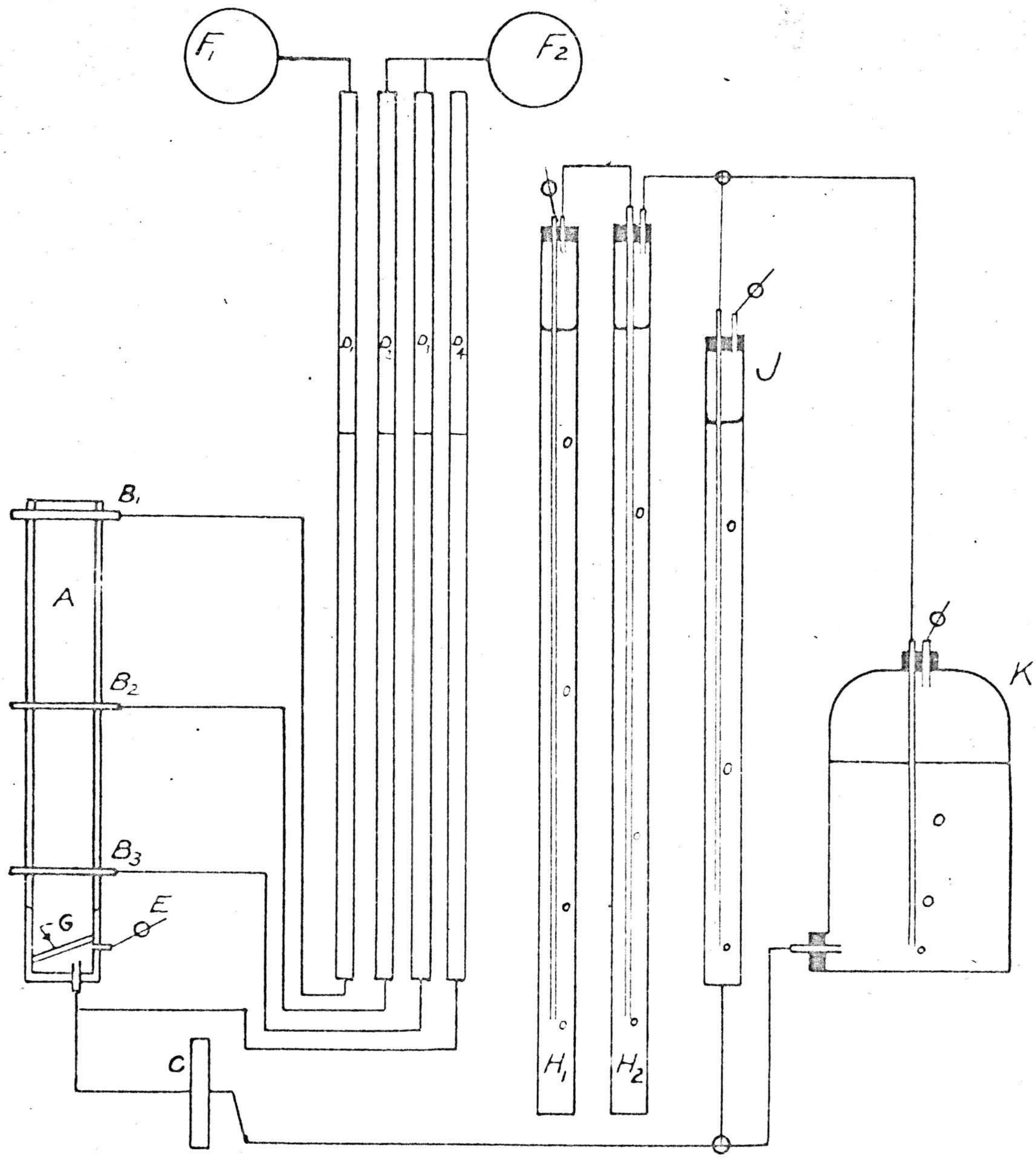
With these two setups it was possible to vary the water table from the surface to almost any depth desired. Of course, the method of simulating deep water tables by means of capillary barriers does not reproduce precisely all the conditions of long soil columns, but it is believed that the pertinent variables are reproduced with sufficient accuracy for most purposes.

The air-conditioning equipment was sufficient to control ambient temperatures to within ± 1/2°F over the range of 60° to 110°F and the relative humidity to within ± 1/2 percent over the range of 20-80 percent.

In an attempt to correlate the results of evaporation studies with measurable soil properties auxiliary measurements were made on the several soils. The measurements which have proved most significant to date are capillary pressure-desaturation curves. The equipment used to measure saturation as a function of capillary pressure differs from the conventional apparatus used by soil physicists in that a complete curve can be obtained on a single sample, the saturation being determined volumetrically rather than gravimetrically. This equipment was devised specifically for the purpose of this experiment in order to determine the air-entry pressures with much greater precision than is possible with the conventional procedures. Unsaturated conductivities were computed using the capillary pressure-desaturation curves by a method proposed by Burdine.*

---

* Burdine, N. T., Journal Petroleum Technology, No. 3, March, 1953



A Soil
B Tensiometers
C Filter
D Manometers
E Air bleed
F Vacuum gages
G Ceramic plate
H Pressure reduction devices
J Mariotte siphon burette
K Mariotte siphon bottle

—o— Pinchcock
—o— Stopcock, 3 way

Fig 1. Apparatus for simulating increased water table depths.

All evaporation runs were carried on until a steady rate of water loss from the Mariotte siphons was obtained. All measurements were made on the drainage cycle, i.e., the soil columns were first saturated fully by filling the voids with CO_2 and then raising the water table to the surface. the water table was then lowered to the desired depth and evaporation was induced. A number of runs were made with the water table at particular depths. Each run at a particular depth was made with evaporation rates greater than the preceding run. In order to avoid hysteresis the evaporation rates (from the free water surface) were never decreased until the water table was lowered to the next greater depth.

The rate of evaporation was increased primarily by increasing the input of radiant energy to the surface and to a lesser extent by adjusting the humidity, temperature, and air circulation within the chamber. This is in contrast with the wind-tunnel experiments wherein the evaporation was increased by increasing the wind velocity only. At the time the present experimental procedure was started there was no evidence to indicate that the relationship between evaporation from any soil profile and evaporation from a free-water surface would be dependent on the method of increasing evaporation from the surfaces. Evidence is presented later which indicates that such a dependence may actually exist.

A more detailed description of the equipment and procedures will be presented in a thesis being prepared by Richard A Schleusener.

Analysis of the Problem:

A detailed analysis of the variables pertinent to the movement of water from a water table to the surface of a homogeneous soil is presented in a Master's thesis by Robert W. Staley. Subsequent experimental evidence has changed the author's thinking somewhat and consequently a detailed presentation of this analysis will not be given here.

The analysis was based on the assumption that the conductivity of a soil to water at a saturation less than 100%. can be expressed in terms of the capillary pressure by the relationship

$$C_e = C\left(\frac{P_d}{P_c}\right)^n \tag{1}$$

where C_e is the effective hydraulic conductivity at some capillary pressure P_c defined by the relationship

$$P_c = P_a - P_w \tag{2}$$

P_a is the pressure of the soil air and P_w is the pressure of the water. The pressure P_d is the displacement pressure often called the air-entry pressure which is the maximum value of P_c at which the soil can be fully saturated. The conductivity C is the value of C_e when $P_c \leq P_d$ and n is some exponent which is a characteristic of the soil. This expression for C_e was based on the author's previous research on flow through porous rock.* A somewhat similar relation has been proposed by Williford Gardner.**

The additional assumptions were made that water transport in the vapor phase would be unimportant and that temperature gradients would have negligible effect on the movement of the liquid through the soil.

---

* Corey, A. T., The Interrelation Between Gas and Oil Relative Permeabilities. Producer's Monthly, XIX, No. 1: 38-41, November, 1954.

Corey, A. T., Measurement of Water and Air Permeability in Unsaturated Soil., S.S.S.A. Proc., Vol. 21, No. 1, Jan.-Feb., 1957, pages 7-10.

** Literature soon to be published in Soil Science

With these assumptions it is possible to derive an expression for the flow of water from the water table to the surface. If n is known, the system at steady state can be described by

$$f(P_c, Z, e, C, P_d, w) = 0 \tag{3}$$

where Z is the elevation above the water table, e is the rate of evaporation expressed as a velocity, and w is the specific weight of water.

The differential equation for flow above the fully saturated zone (expressed in dimensionless terms) is

$$\frac{d(P_c/P_d)}{d\left(\frac{Z}{P_d/w}\right)} = 1 + \frac{e}{C}\left(\frac{P_c}{P_d}\right)^n \tag{4}$$

Having derived this equation from Darcy's law it is possible to describe the system by

$$f\left(P_c/P_d, \frac{Z}{P_d/w}, e/C\right) = 0 \tag{5}$$

and if the assumptions are valid, Equation 4 should give the relationship between the parameters in Equation 5. At any rate, the three parameters in Equation 5 should serve as a basis for conducting the evaporation experiments. It is evident also that experiments to determine the value of n by independent measurements would be helpful. The variables P_d and C are soil properties which must be measured independently.

It will be helpful in visualizing the significance of Equation 5 if one thinks of P_c/P_d as a capillary pressure scaled in terms of P_d, of $\frac{Z}{P_d/w}$ as an elevation above the water table scaled in terms of the height of the fully saturated zone in a static system, and e/C as the velocity of flow scaled in terms of the hydraulic conductivity.

Equation 4 has solutions in closed form if $n \leqq 4$ otherwise it can be solved by numerical methods. R. W. Staley has obtained solutions with $n = 3$ by the latter method. It is believed that the value of n decreases at a capillary pressure greater than about 1/3 atmosphere. Consequently it is planned either to confine the analysis to the more moist portion of the profile or to use a different value of n when $P_c > 1/3$ atmospheres. The former method will probably be preferable for reasons that will be explained in the discussion.

Results and Discussion:

Unfortunately, the experimental setups employed to date have not been adequate to make quantitative evaluations of the theory previously described. The chief experimental difficulty has been the problem of obtaining sufficiently precise measurements of P_c at critical points in the soil columns. Nevertheless, certain qualitative conclusions based on the theory apparently were verified by the results from the wind-tunnel experiments.

The theory indicates that as the value of P_c at some point (such as the surface) increases, the water table being held at a constant depth, the value of e should increase until a limiting value of e is reached. Since the value of P_c at the surface increases as the severity of the ambient evaporation conditions increases, a similar relationship should exist if the rate of evaporation from any soil profile e_s is plotted as a function of the rate of evaporation e_f from a free water surface which is in the same environment. The results (shown in Figure 2) for a fine sand in the wind tunnel indicate that such is the case. These same results were plotted in a different manner in last year's report.

As was pointed out in the previous report, these results indicate a critical water-table depth for this sand of about 24 inches. With the water table below this depth there is a sharp reduction in evaporation rates.

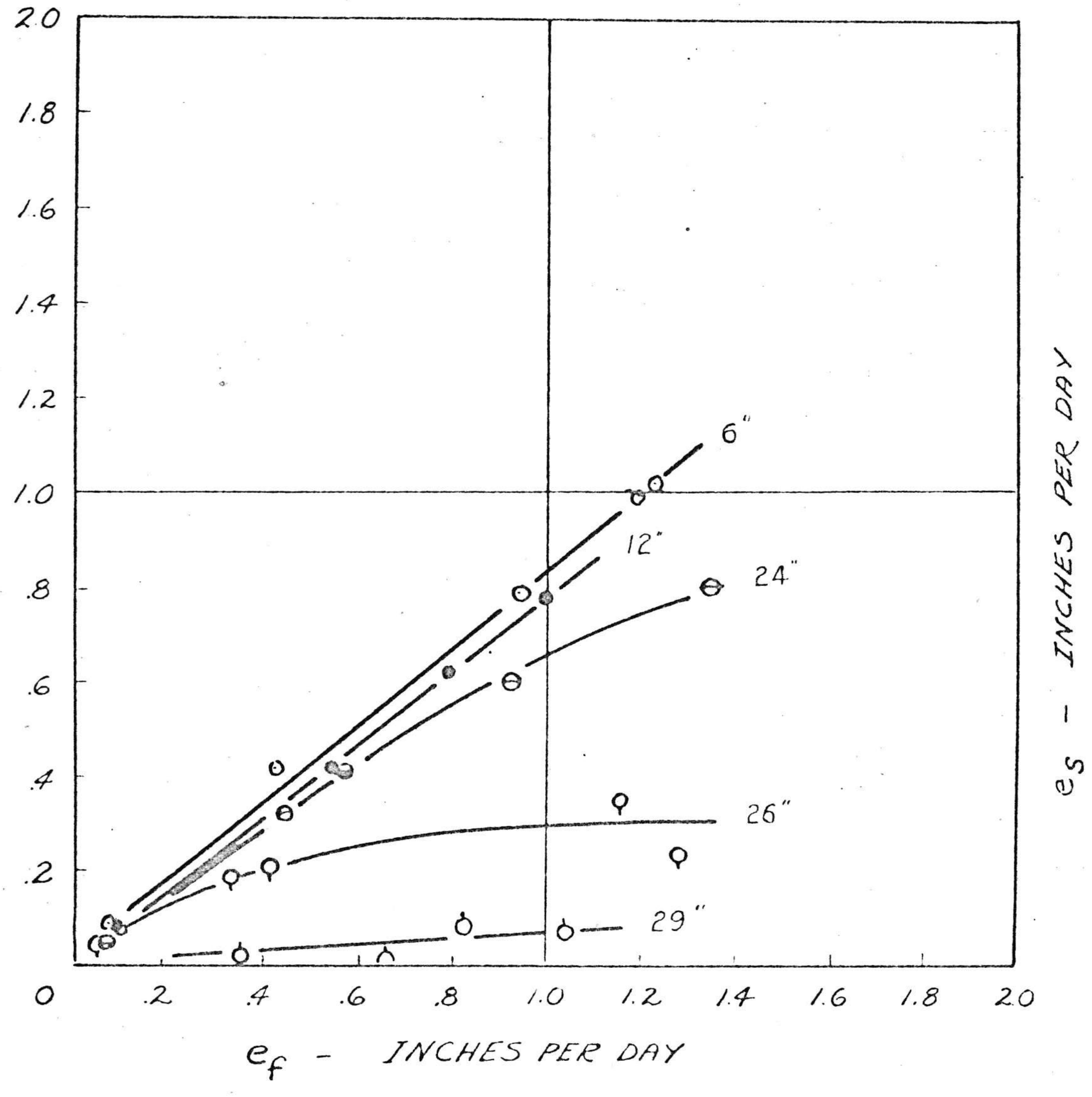


FIG. 2 - EVAPORATION RATES FROM A FINE SAND AS A FUNCTION OF EVAPORATION RATES FROM A FREE WATER SURFACE AND DEPTH OF WATER TABLE - WIND TUNNEL EXPERIMENTS.

The probable reason for this can be deduced from the results of the capillary pressure-desaturation measurments shown in Figure 3. It will be noted that the critical water-table depth corresponds very closely to the value of P_d/w measured in inches. It will also be noted that the curve is very flat over a considerable range of saturations for this sand which probably accounts for the decrease in evaporation rates being very rapid when the critical water table depth is exceeded. Computations of C_e/C vs P_e/P_d using Burdine's method indicate that n for this sand is about 17. The large value of n is a result of the very flat curve of P_e vs saturation, the flat curve being an indication of a uniform pore size. The term saturation as used here refers to the fraction of the pore volume that is occupied by water.

In the previous report it was pointed out that the probable reason for the plot of e_s vs e_f having a slope smaller than 1:1 was that the control column apparently received a greater amount of stray radiation than the other column. Data obtained using the same sand in the air-conditioned room substantiates the assumption that the plot should have a slope of 1:1 as will be seen from Figure 4. The same is true for the other soils as is evident from Figures 5 and 6.

Figures 4, 5, and 6 indicate a phenomenon not encountered in the previous experiment and not predicted by the theory. It will be noted that with the water table at about the critical depth or at greater depths, the value of e_s reaches a maximum rather than a limiting value. As e_f is increased still further the value of e_s actually decreases.

It does not seem likely that the increase in e_f per se is responsible for the decrease in e_s. It has been noted that the reduction of e_s is accompanied by very high surface temperatures. The most probable explanation for reduction in evaporation rates is that large temperature

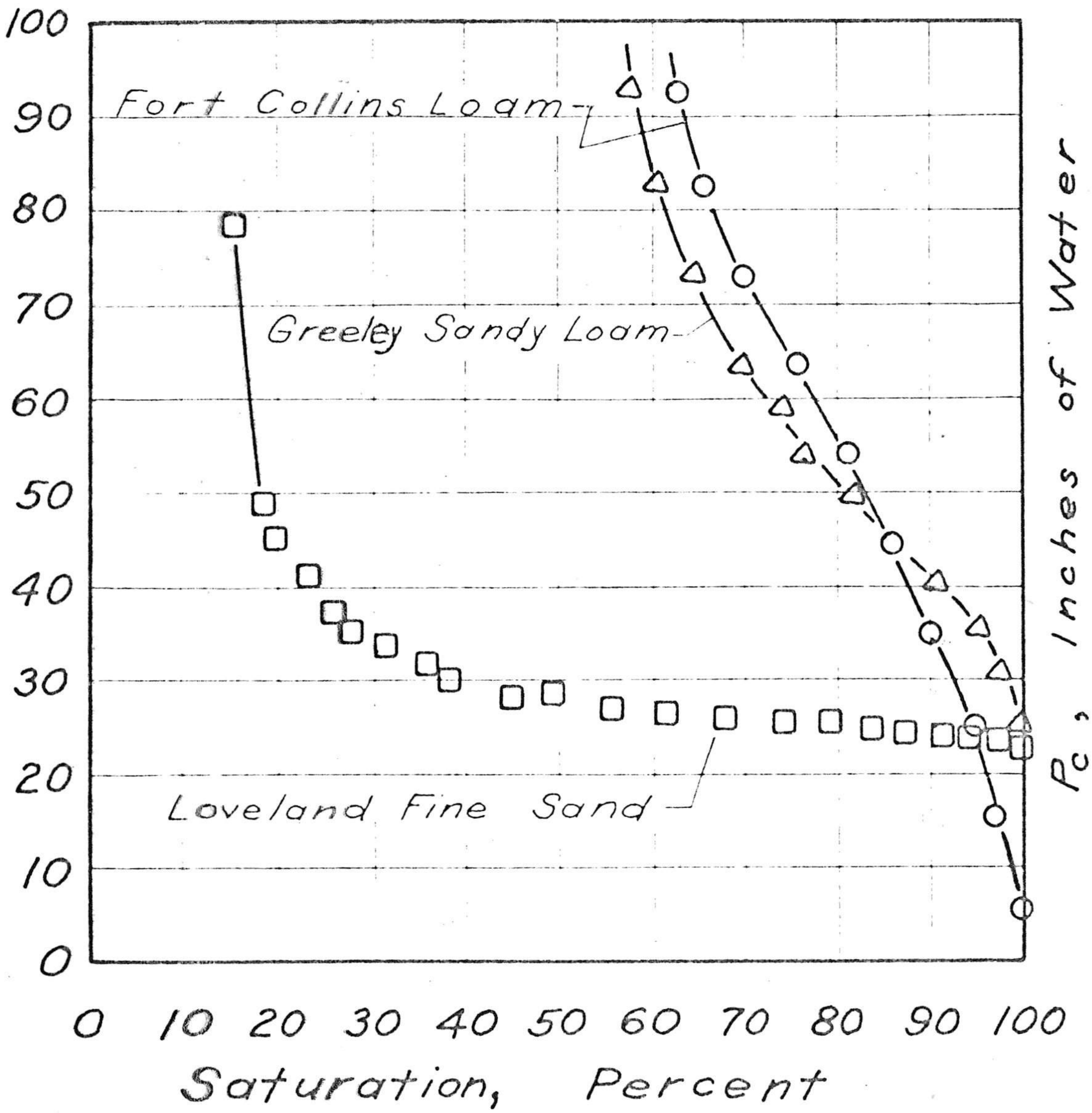


Fig 3. Capillary pressure as a function of saturation on three soils.

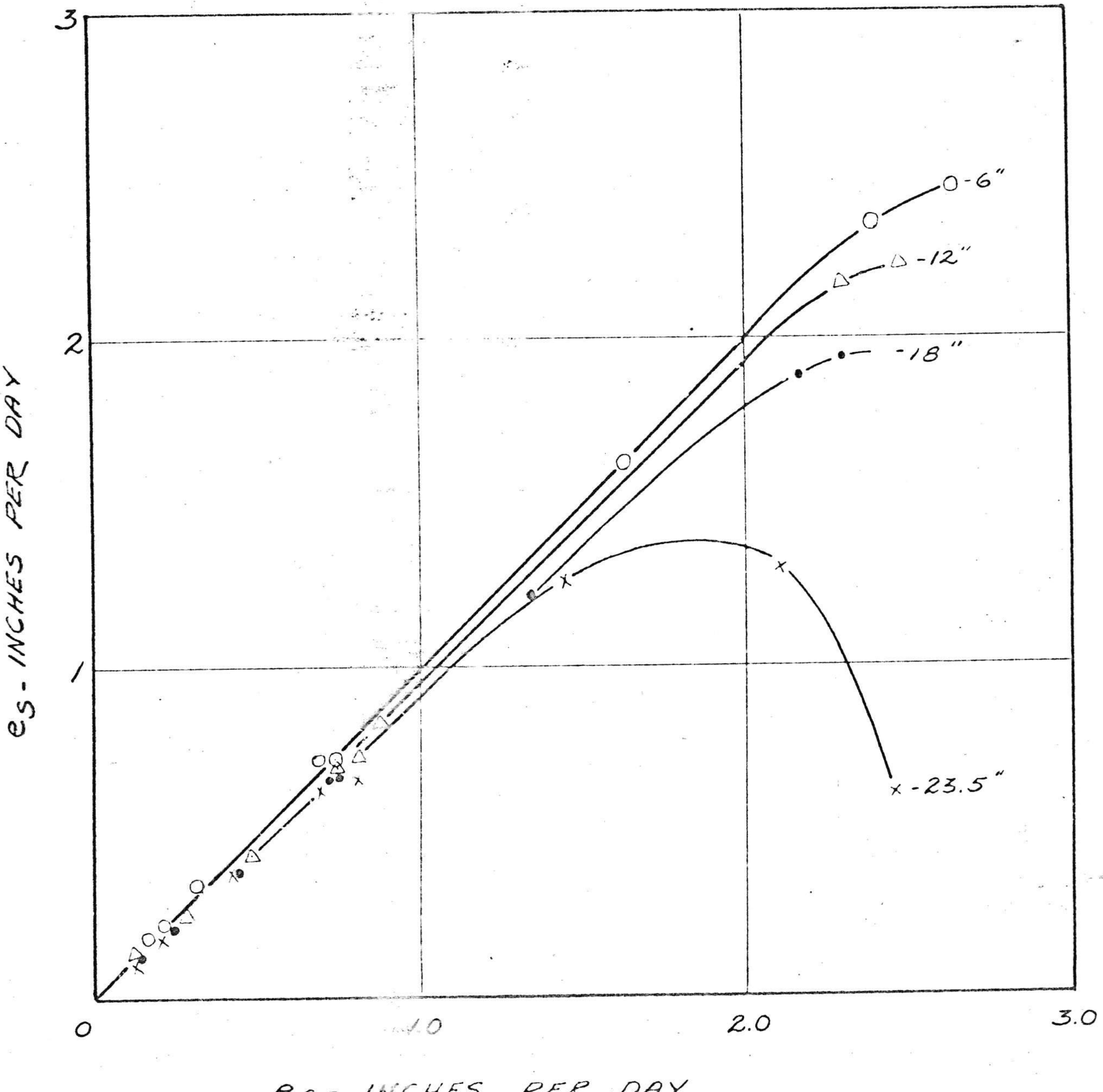


FIG. 4 - EVAPORATION RATES FROM A FINE SAND AS A FUNCTION OF EVAPORATION RATES FROM A FREE WATER SURFACE AND DEPTH OF WATER TABLE.

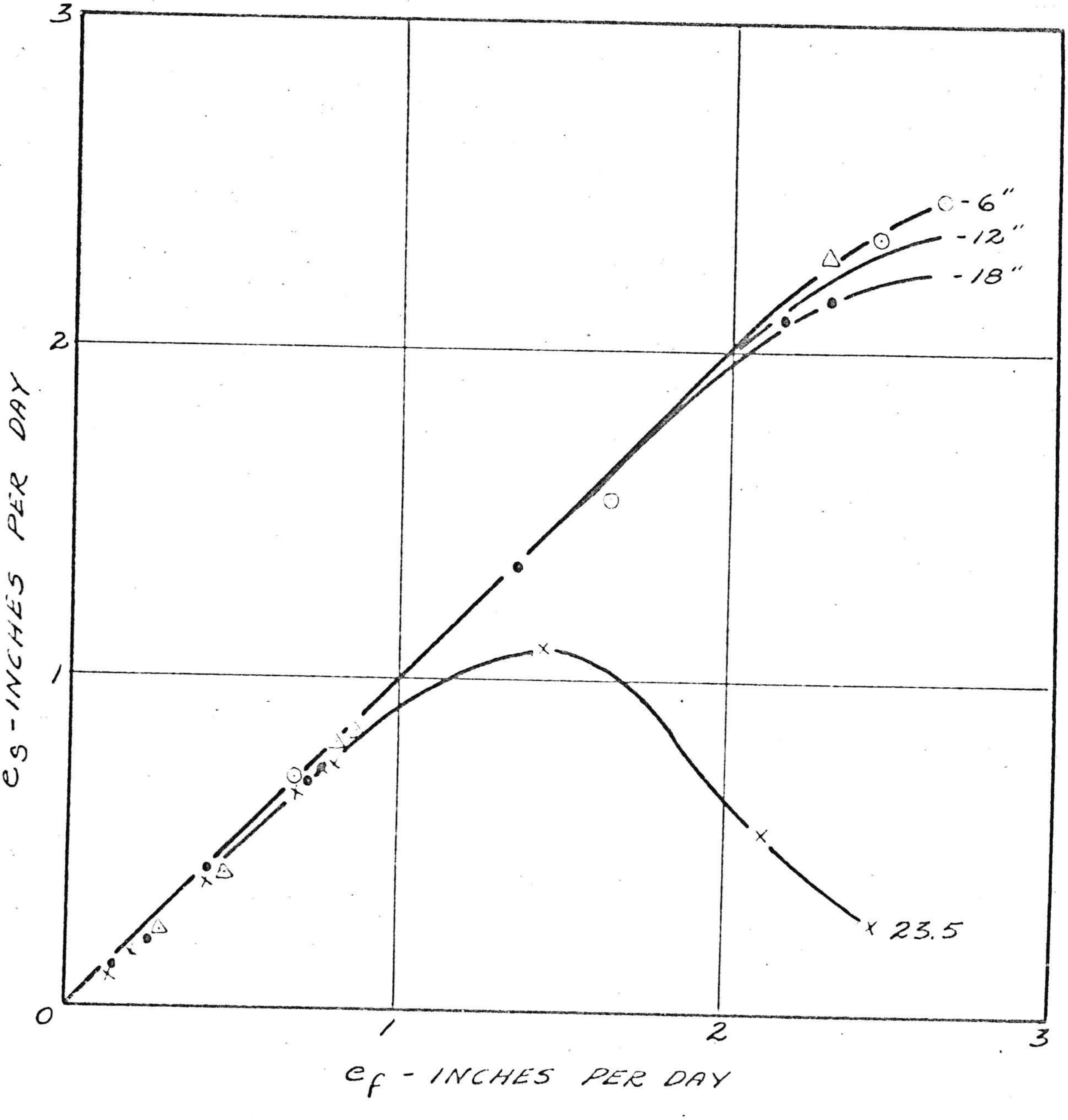


FIG. 5 - EVAPORATION RATES FROM A FINE SANDY LOAM AS A FUNCTION OF EVAPORATION RATES FROM A FREE WATER SURFACE AND DEPTH OF WATER TABLE.

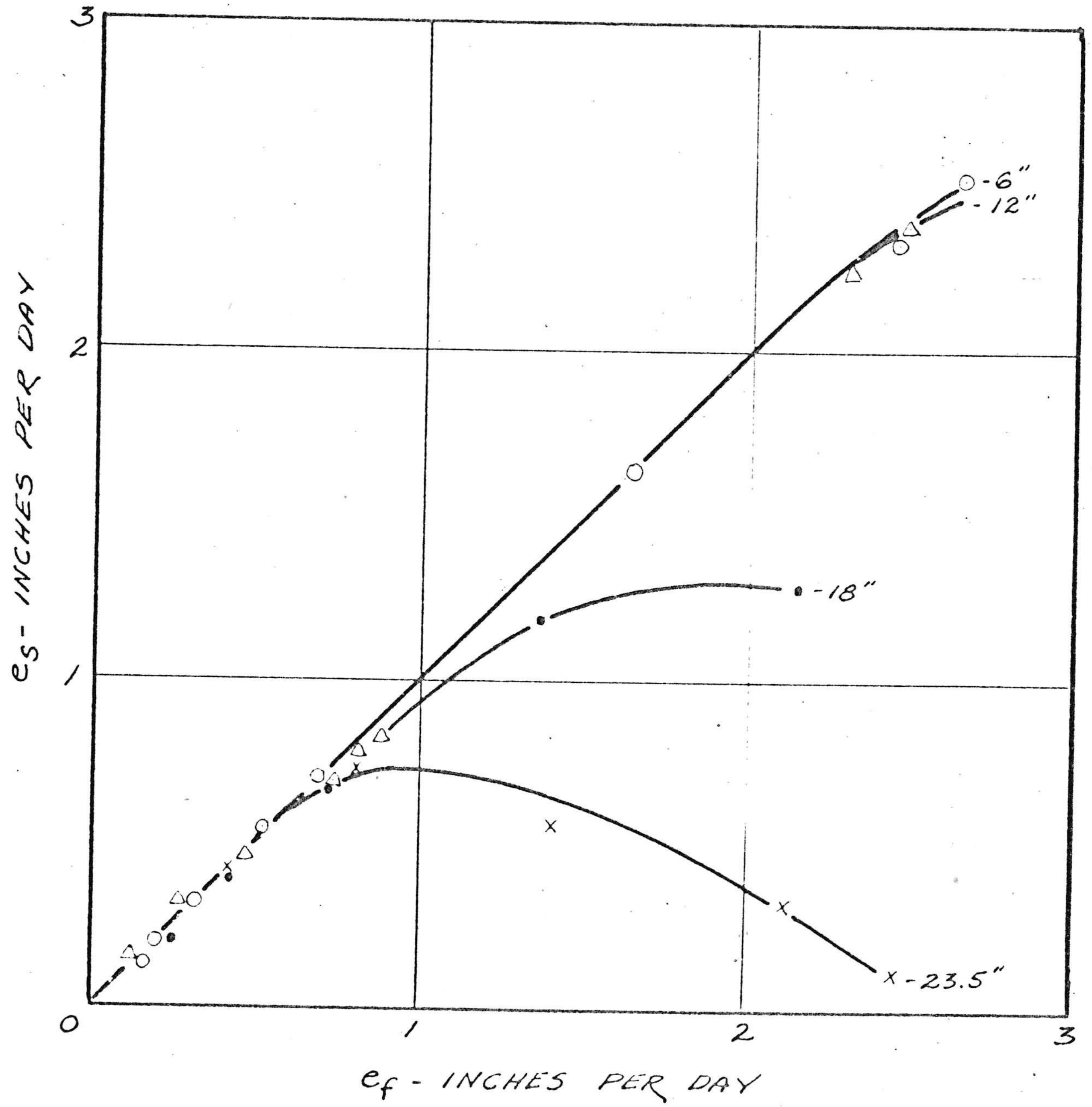


FIG. 6 - EVAPORATION RATES FROM A CLAY LOAM AS A FUNCTION OF EVAPORATION RATES FROM A FREE WATER SURFACE AND DEPTH OF WATER TABLE.

gradients decreasing from the surface downward interfere with the imbibition of water by the surface layer of soil. It has been observed that under these conditions there exists a sharp discontinuity in moisture content immediately below the hot surface layer. The fact that this phenomenon was not observed in the wind tunnel could be explained by the fact that e_f was increased by increasing the wind velocity rather than by adding increments of radiant energy.

If these suppositions are correct it probably means that the experimental procedure should be revised in future studies in order to delimit the independent effectsof humidity, wind velocity, and radiant energy on the e_s vs e_f relationship. Moreover any analysis such as was given in the preceding section can be valid only for the soil profile below the zone of significant temperature gradients.

Anomalous behavior was also encountered with very high water tables and high rates of evaporation. In this case, it was observed that evaporation rates decreased systematically with time, the rate of decrease being associated with the rate of evaporation. The reduction in evaporation rates was accompanied by a concurrent increase in surface temperature. When a very thin layer of surface soil was removed and replaced by fresh soil, the evaporation rate immediately increased to its starting value and the surface temperature dropped to normal. This phenomenon is shown in Figure 7. At first it was thought that the formation of a scum from microbiological activity was producing the anomaly and accordingly several steps were taken to prevent such a formation. Chemicals were added to the water and a germicidal lamp was directed onto the surfaces. This procedure produced no change in the behavior. It was finally discovered that the water was being blocked by an extremely thin layer of amorphous salts, primarily gypsum. Unless

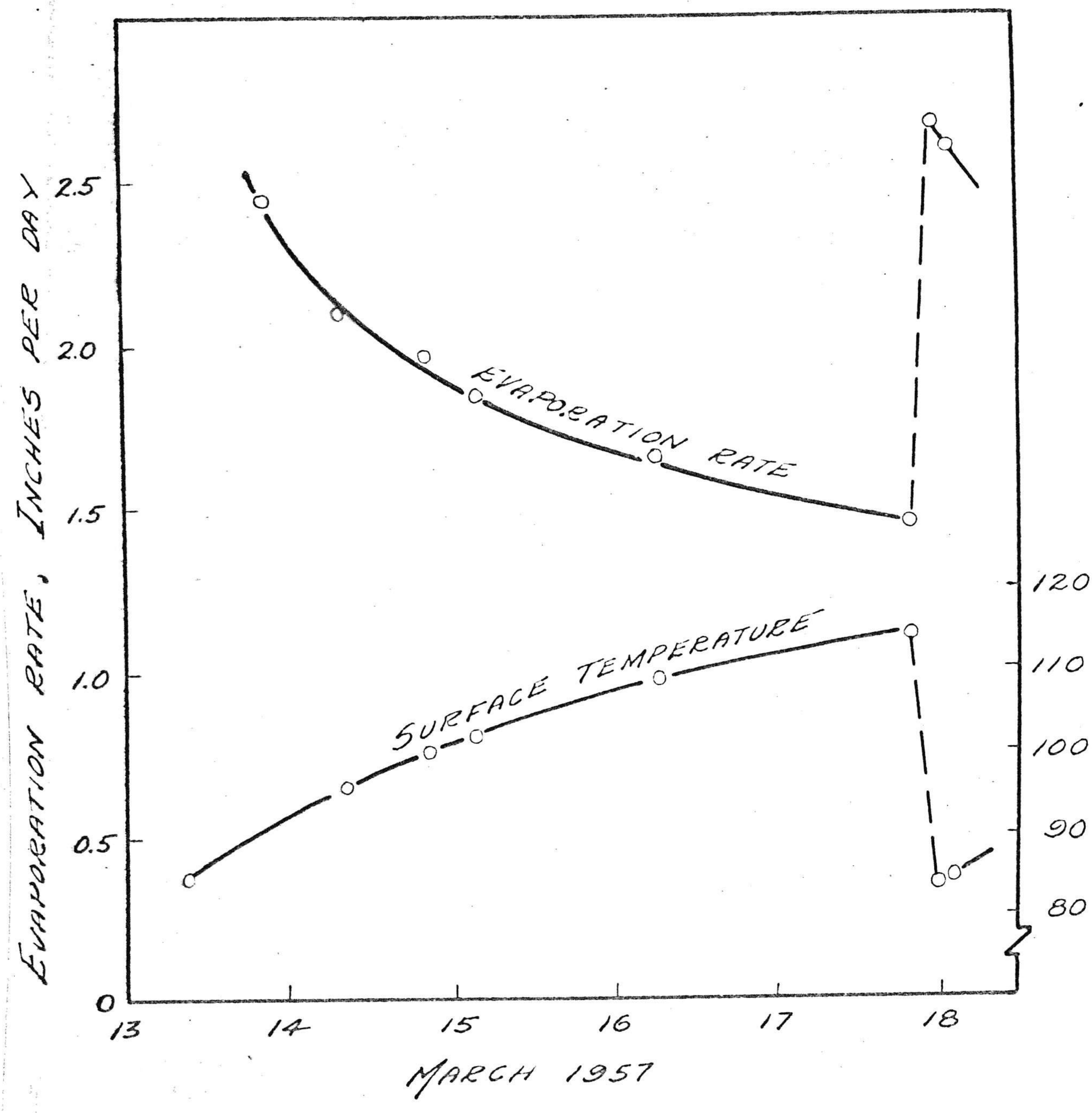


FIG. 7 EFFECT OF AMORPHOUS SALT SCUM ON EVAPORATION RATES FROM A FINE SANDY LOAM.

the surface remains saturated these salts apparently become granular and do not interfere materially with the evaporation.

Plans for Improving and Expanding the Project

It is hoped that in the future it will be possible to measure the capillary pressure gradients with sufficient precision to make quantitative checks of the theory. Equipment has been devised to measure the relationship C_e/C vs P_e/P_d directly in order to determine the value of n in Equation 1. This equipment should be in operation within a few weeks and it is hoped that unsaturated conductivities computed by the Burdine method can be compared with measured values for a number of soils.

It is planned to make future runs in such a manner as to delimit the independent effects of humidity, air circulation, and radiant energy on the e_s vs e_f relationship. Plans have been made to expand the investigation to include non-homogeneous profiles, the dynamic case, evaporation from a profile not in contact with a water table, the effect of chemical additives, etc. It is hoped that the project can be expanded to include field investigations. The latter possibility will depend primarily on the amount of financial support available.

In connection with any field study it would be helpful to devise laboratory measurements of C_e/C vs P_e/P_d and P_e vs saturation on relatively undisturbed samples.