CONSERVATION OF SOIL WATER BY GRAVEL MULCHES

by

A. T. Corey and W. D. Kemper

September, 1968

HYDROLOGY PAPERS
COLORADO STATE UNIVERSITY
Fort Collins, Colorado

30

CONSERVATION OF SOIL WATER BY GRAVEL MULCHES

by

A. T. Corey and W. D. Kemper

HYDROLOGY PAPERS

COLORADO STATE UNIVERSITY

FORT COLLINS, COLORADO

September, 1968 No. 30

ABSTRACT

Studies to discover methods of reducing evaporation from soils have been conducted at Colorado State University since 1956. Results of this research have shown that a gravel mulch on a fallow soil surface is the most promising method for increasing infiltration of precipitation.

This paper reports the results of a series of related experiments which, heretofore, had been reported only in miscellaneous progress reports. These studies have demonstrated conclusively the great potential of gravel mulches for increasing soil moisture and recharge to groundwater aquifers. In one experiment, the use of a gravel mulch 5 cm thick, resulted in an additional accumulation of 14 inches of water during one year, as compared to that which accumulated under the bare soil.

The results of this research indicate the need for further studies to overcome economic and other difficulties which might be encountered in the practical use of gravel mulches.

ACKNOWLEDGMENTS

The research reported here was undertaken with the assistance of a number of graduate students who worked on various phases of the study and helped in the preparation of the progress reports from which the material in this paper was assembled. The authors acknowledge, particularly, the major contributions of the following former graduate assistants:

1. Dr. Richard A. Schleusener, Director, Institute of Atmospheric Sciences, South Dakota School of Mines and Technology, Rapid City, South Dakota.
2. Dr. Larry G. King, Senior Scientist, Battelle Northwest Laboratory, Richland, Washington.
3. Dr. Robert W. Filmer, Assistant Professor of Civil Engineering, Oregon State University, Corvallis, Oregon.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CONSERVATION OF SOIL WATER BY GRAVEL MULCHES[1]

A. T. Corey and W. D. Kemper[2]

BACKGROUND

Beginning in 1956 and continuing to the present time, studies have been conducted at Colorado State University on factors affecting evaporation from fallow soils and on methods of reducing evaporation. These studies have been conducted by the Agronomy, Civil Engineering, and Agricultural Engineering Departments and the U.S. Department of Agriculture. The outcome of this research has been the conviction that a gravel mulch on a fallow surface is the most promising method for increasing infiltration of precipitation.

Most of the studies of mulches in the United States in recent decades have been concerned with plant residues. These are not as effective in reducing evaporation as gravel mulches, because the residues themselves absorb water and conduct it upward from the soil. Furthermore, plant residues are difficult to maintain at the soil surface, being easily moved by wind when not anchored in the soil, and rapidly decayed when anchored.

Maintaining cultivated land in a fallow condition is another practice for conserving water, and this helps in many cases. There is evidence (4), however, that present techniques of summer fallowing in the Western United States do not always result in accumulation of substantial quantities of soil water.

The idea of using a gravel mulch to reduce evaporation and increase infiltration is very old. There is evidence that the ancient Hebrews employed gravel mulches in the Sinai Desert thousands of years ago. Recently, there has been a revival of interest in the ancient idea of gravel mulches at Colorado State University and elsewhere. Dr. S. Richards (5) at Riverside, California, for example, has investigated the feasibility of placing precast porous plates of cemented gravel over the soil surface as a method of reducing evaporation. These have the advantage of not moving during wind storms. They also facilitate the control of weeds and other vegetation.

Mulches have potential for use either in association with crop culture to retain moisture within the root zone, or as a device to increase infiltration to a groundwater aquifer under uncultivated land. In either case, the big problem with this or any other method of conserving water is to find a way of accomplishing the conservation economically.

The studies described in this paper have previously been reported in a number of progress reports and theses (1, 3, 6). They are summarized here for the purpose of showing the potential benefit which might be obtained from future development of economical methods for establishing and maintaining gravel mulches on fallow soils.

---

[1]Contribution from the Agricultural Engineering Department and the Agronomy Department, Colorado State University, and the Soil and Water Conservation Research Division, Agricultural Research Service, U.S.D.A.

[2]Professor (Agricultural Engineering), Colorado State University; and Professor (Soils), Colorado State University and Research Soil Scientist, U.S.D.A., Fort Collins, Colorado, respectively.

THEORY

The objective of any method for increasing infiltration from precipitation is to facilitate entry of water into the soil, while preventing exit of water from the surface. A mulch, therefore, is designed to act as a one-way valve, permitting water to pass in a downward direction only.

No device has been conceived which can prevent entirely the exit of water from the soil surface, while at the same time permitting it to pass into the soil. Water can always move outward into the atmosphere by diffusion in the vapor state through any space permitting the entry of liquid water.

Fortunately, the quantity of water that can move through the soil by diffusion alone is relatively small. Pressure gradients within the gaseous phase, necessary to produce substantial convection of vapor, are typically not present for more than a few millimeters beneath the soil surface. Consequently, the transport of a substantial amount of water from beneath the soil surface depends upon the existence of bulk flow of liquid water in response to a gradient of hydraulic head.

The physics of bulk flow of liquid in porous media has been discussed adequately in numerous publications including the CSU Hydrology Papers 3, 7, 9 and 17. The following discussion is provided to help the reader visualize the function of a gravel mulch without reference to other literature.

Bulk flow of liquid proceeds according to Darcy's law, that is, the volume flux of liquid is proportional to the gradient of hydraulic head, and if the soil is isotropic, the maximum component of flux is in the direction of the negative gradient of head. The coefficient of proportionality is a function of the geometry of the pore space and the volume fraction of the pore space occupied by liquid, as well as the viscosity and specific weight of the water solution.

The volume fraction of the pore space occupied by liquid is called "saturation" and this depends upon the "capillary pressure" of the liquid-air interfaces. Capillary pressure p_c is defined as the difference between the pressure of the air p_a and the pressure of the liquid p_ℓ at points on the interfaces, that is,

$$p_c = p_a - p_\ell \quad . \tag{1}$$

Capillary pressure depends upon the surface tension of the water solution and the curvature of the interfaces according to the relationship

$$p_c = \sigma\left(\frac{1}{r_1} + \frac{1}{r_2}\right) \quad , \tag{2}$$

σ being the surface tension and r_1 and r_2 being any mutually perpendicular radii of curvature at a point on an interface. Interfaces positioned across pore spaces of small dimensions have radii of curvatures smaller than interfaces in large pore spaces, and as a consequence, have a greater capillary pressure.

In soil profiles, the air is practically at atmospheric pressure except in entrapped air pockets. Consequently, the capillary pressure can be regarded as the negative liquid pressure. When expressed as a head of water, it is often called soil water "tension" or "suction head" by agronomists. In any case, it represents a pressure less than atmospheric.

When the pore space of a soil is occupied entirely with liquid, interfaces exist only at the soil surface, and the negative pressure at the surface may be relatively small. If the liquid pressure is reduced relative to the air pressure, a critical pressure will be reached at which air penetrates the soil and the interfaces retreat to smaller pore spaces. The soil, therefore, loses some of its water, and the more the liquid pressure is reduced, the more the saturation is reduced. The larger the dimensions of the pore space, the smaller will be the negative pressure at which desaturation begins; consequently materials consisting of coarse aggregates desaturate at much smaller negative pressures than do finer textured soils which are not aggregated.

The reduction of soil saturation is accompanied by a reduction in the conductivity of soil for water. The reduction in conductivity is relatively much greater than the reduction in saturation, because the largest pores desaturate first. Materials such as gravel desaturate almost completely at very small negative pressures, the conductivity becoming practically zero.

When water moves downward in a soil profile, it is possible for it to do so at pressures approaching atmospheric, especially near the surface where it enters. In order to move upward, however, the pressure must become negative at the surface. The reason for this is demonstrated by the following considerations:

The hydraulic head h of soil water is given by

$$h = \frac{p}{\rho g} + z \quad , \tag{3}$$

p being the water pressure, ρ the water density, g the acceleration of gravity, and z the elevation above a datum. For vertical flow, the volume of flow per unit area per unit time, q , is given by

$$q = -K\left(\frac{1}{\rho g}\frac{dp}{dz} + 1\right) \quad , \tag{4}$$

K being the conductivity with dimensions of velocity and q and z being positive upward. It is informative to write equation 4 explicitly for the pressure gradient, that is,

$$\frac{dp}{dz} = -\rho g\left(1 + \frac{q}{K}\right) \tag{5}$$

Note that when flow is downward, the pressure gradient is numerically smaller than for upward flow, q being negative. The pressure will not increase toward the surface unless water is ponded on the surface, but the decrease, if any, will be much less than if the flow is upward against gravity. It is possible, in fact, for the pressure gradient to be zero if the water supply is steady (7) during infiltration.

The result is that water can enter the soil pores from above the surface at pressures close to atmospheric, but if it moves toward the surface from below, the pressure must become substantially negative. During upward flow, any large pores at the surface will be desaturated and the conductivity will be reduced. In fact, if gravel is at the surface, its conductivity is virtually zero and water transferred upward through the gravel layer is by vapor diffusion only.

A layer of material at the surface will be a poor conductor for upward flow, if most of its pores are larger than those of the underlying soil. Such a layer could consist of fine sand as well as gravel if the underlying material is finer textured than the sand.

The experiments described in the following sections were carried out over a period of more than ten years. Rather than attempting to summarize them as a single research endeavor, the authors have found it convenient to describe the objectives and results of each phase separately.

A. Comparison of Surface Treatments

The first studies were undertaken to compare the effect on evaporation of a number of ways of treating fallow soil surfaces. This was a laboratory study in which loss of water as a function of time was measured using two soil types, a clay loam and a fine sand. The soils were placed in plastic tubes 8½ inches long with an I.D. of 3½ inches. The soils were first saturated with water and then placed on a turntable in a chamber with controlled temperature, humidity, and radiation. The design of the chamber and turntable has been described in detail in a thesis by R. A. Schleusener (6).

Only the tops of the soil columns were exposed to radiation. The sides of the columns were insulated by a plastic enclosure and a dead-air space. The rate of water loss as a function of time was determined by periodically weighing the soil columns with the exception of one column in which free water was maintained at the upper soil surface. In the latter case, the evaporation rate was determined by periodically weighing a Mariotte-syphon bottle which supplied the water at constant head. The evaporation rate was used as a measure of the evaporativity of the ambient conditions.

Two soil columns for each of the two soils were provided with the following surface treatments:

1. Surface made white with chalk
2. Surface made black with carbon powder
3. A compacted surface
4. A compacted layer at a depth of 1 inch
5. A surface loosened by periodic stirring
6. A mulch of sawdust, ¼ inch thick
7. A mulch of fine gravel, ¼ inch thick
8. A 10% solution of Lux detergent, sprayed on surface
9. Control columns with no special treatment
10. A column with free water maintained at soil surface.

Runs were made using several levels of evaporativity as measured by the evaporation from the soil with the water table at the surface.

Results - The differences in evaporation were not statistically significant between the several runs, except where the surface was covered with the mulches. Consequently, the results of only the first run are reported, since subsequent runs produced no additional information. The accumulated water loss for the two soils is shown as a function of time in Figures 1a and 1b, respectively. It appears that for the fine sand, there was more spread in the results for several of the treatments than was the case for the clay loam. In the case of the clay loam, it is believed that the differences were not significant except for those of the gravel and sawdust mulches.

In every case, the most effective treatment was the gravel mulch, and the next most effective was the sawdust mulch. The other treatments, including the Lux detergent, produced no substantial reduction in evaporation. Subsequently, other surfactants* (Triton GR-5 and GR-7) were tried on the fine sand. Both of these surfactants produced a very substantial reduction in evaporation, the larger concentrations being even more effective than the gravel mulch alone. The results of one of the runs (GR-7 in various concentrations) are shown in Figure 2.

Both of the Triton surfactants are of the anionic type, whereas Lux is a non-ionic surfactant. Lux probably increases the wettability of the soil about as much as it reduces the surface tension of the water, and thus has little net effect on capillary retention of water. Triton, however, causes the surface layer of soil to lose its water and, in effect, creates a mulch of dry soil at the surface.

Subsequent experiments with Triton, however, showed that periodic wetting of the surface reduced the effectiveness of the surfactant. This fact, combined with the relatively high cost for an effective treatment, made its use for reducing evaporation impractical under present economic conditions. Consequently, research with the use of surfactants was discontinued.

Compacting the surface or loosening the surface by stirring (as in cultivation) seemed to have produced little effect on evaporation. The same was true for surface coloring. Probably the reason that stirring the surface produced little effect on evaporation is that the soil surface was not actually loosened unless it was already dry, at which time the rate of evaporation was very small in any case.

The sawdust mulch was less effective than the gravel mulch and, consequently, it seemed reasonable to concentrate future research on the use of gravel mulches.

B. Design of Gravel Mulches

The objective of this phase of the research was to determine the kind of gravel mulch that is most suitable under various soil and atmospheric conditions. Because it was desired to control the soil and atmospheric variables, the study was conducted in a chamber within which temperature, relative humidity, radiation, and to some extent air movement were controlled.

Three soil types were employed, columns of which were contained in Lucite cylinders, 3½ inches I.D. and 8½ inches in depth. The soil columns with various kinds of gravel mulches were saturated under vacuum and then allowed to drain approximately 36 hours. The samples were then placed on a rotating table at equal radii from the axis of rotation. This procedure was followed in order to insure that all samples during particular runs were subjected to identical environmental conditions.

The environmental conditions were constant during a particular run, but were changed from run

* Manufactured by Rohm and Haas Co., Washington Square, Philadelphia, 5, Pa.

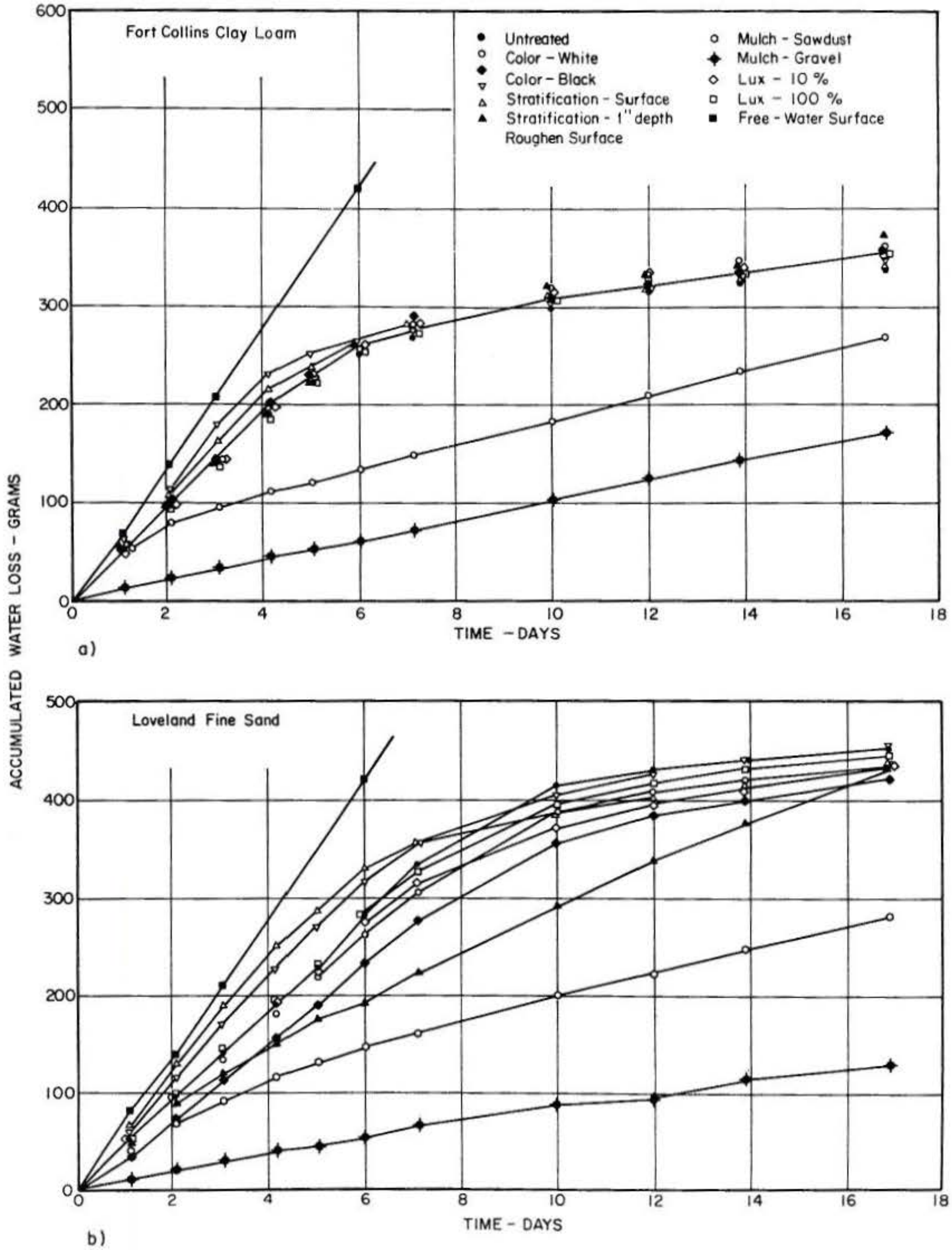

Figure 1. Effect of surface treatment on evaporation from fallow soil

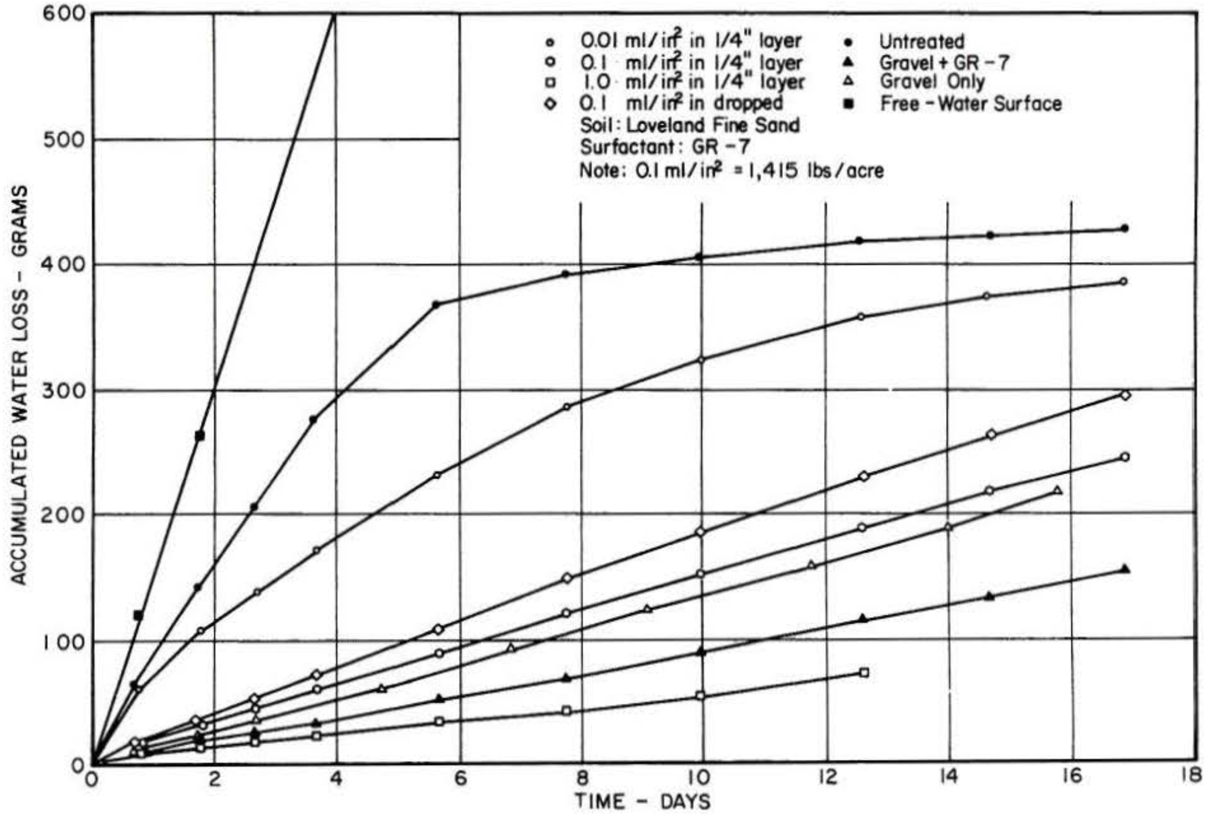

Figure 2. Effect of Triton (GR-7) on evaporation from fallow soil

to run. The radiation was supplied by infrared lamps. The temperature and relative humidity were controlled by an air-conditioning unit, and when air-movement was used, it was supplied by a blower placed to cause a horizontal movement of air across the upper surfaces of the soil columns. When the blower was used, each sample was subjected to the blast from the blower during about 1/5 of each rotation of the turntable. This situation, therefore, was somewhat analagous to gusty wind conditions often existing in nature. The wind velocities given in this report are the velocities of the air as it came from the blower, and are the maximum velocities to which the soil surfaces were subjected as each column passed directly through the path of the blast from the blower during the rotation of the turntable.

Loss of moisture was determined by periodically weighing the soil columns. The loss of water from the columns with gravel mulches was compared with that from columns not protected by mulches. One column for each of the three soils was not covered by a mulch. A measure of the severity of the evaporating conditions for each run was obtained by measuring the evaporation from one column of sand in which the water table was maintained at the surface. This was accomplished by periodically weighing a Mariotte-syphon bottle which supplied water to this sand column under constant head.

Two sets of nine runs each were made. During the first set of nine runs, the gravel mulches varied with respect to thickness and with respect to the grain size. Three increments of each were used, making a total of nine mulches per soil. A uniform grain size was used for all the mulches during this set of runs. During the second set of nine runs, the mulches varied with respect to the grain size and the uniformity of the grain-size distribution. The grain size was characterized by the diameter of grain for which 50 percent of the material (by weight) was smaller. This is designated as the D_{50} size. The uniformity of the grain size was characterized by the ratio D_{60}/D_{10} , meaning the ratio of diameter of grain for which 60 percent of the material was smaller, to the diameter of grain for which 10 percent was smaller. This is called Hazen's uniformity coefficient u . Three increments of each variable were employed in this set of runs also. All mulches were one inch thick. For both sets of runs, the temperature was constant at 90°F, and the relative humidity was constant at 30 percent.

Each successive run in a set was carried out at increasingly severe evaporativity. This was brought about by increasing the number of lamps. For each level of radiant energy, the wind velocity was varied. Three increments of radiation and of wind velocity were employed, requiring nine runs for each set.

During each run there were 31 samples on the turntable. Nine different mulches were provided for each of three soil types, plus a single sample with no mulch for each soil type, and one sand column with the water table at the surface. Tables 1 and 2 describe the experimental design in tabular form.

Note that the grain-size of the mulch is expressed as a ratio of median sizes, that is, the median size D_{50} of the mulch to the median size of the soil. This procedure was employed because the grain size of the mulch is thought to be significant mostly in relation to the grain size of the soil. The grain-size distribution of the mulches along with the grain-size distribution of the soils are shown in Figure 3. The increments of the several variables were chosen to cover the range of greatest practical interest, based on experience from the previous experiments.

The experiments were designed in the manner described in order to permit suitable statistical analyses of the results, that is, five-variable analyses of variance. In these analyses the dependent variable was the amount of moisture conserved after a specified period of time, that is, 96 hours. The amount of moisture conserved was defined as the difference between the moisture lost in 96 hours from a soil with a mulch, and that lost from the same soil without a mulch.

Results - The two five-variable analyses of variance are shown in Tables 3 and 4, respectively. Both tables show that all main effects are significant. Some of the most significant results are also shown graphically in Figure 4.

TABLE 1. VARIABLES STUDIED DURING RUNS 3-7 AND 9-12 OF EXPERIMENTS ON THE EFFECT OF GRAVEL MULCHES ON EVAPORATION FROM SOILS

Variables Studied	Increments of Each Variable
Soils (s)	(1) Loveland fine sand (LFS)
	(2) Greeley loam (GL)
	(3) Fort Collins clay loam (FCCL)
Gravel Mulches*	
Thickness (t)	(1) ¼ inch
	(2) ½ inch
	(3) 1 inch
Median Size (m) - - $\frac{(D_{50})\text{ gravel}}{(D_{50})\text{ soil}}$	(1) 5
	(2) 20
	(3) 60
Uniformity (u) $\frac{D_{60}}{D_{10}}$ (Hazen's uniformity coefficient)	All layers uniform; i.e., passed one sieve but retained on next size smaller.
Atmospheric Conditions	
Incident Radiation (r)	(1) 0 lamps
(No. of 250-w lamps)	(2) 2 lamps
	(3) 4 lamps
Wind Velocity (w)	(1) 0 fps
(Gusty Conditions--no	(2) 8 fps
velocity 80% of the time)	(3) 25 fps
Temperature (Constant)	90^{o} F
Relative Humidity (Constant)	30%

* See Figure 3

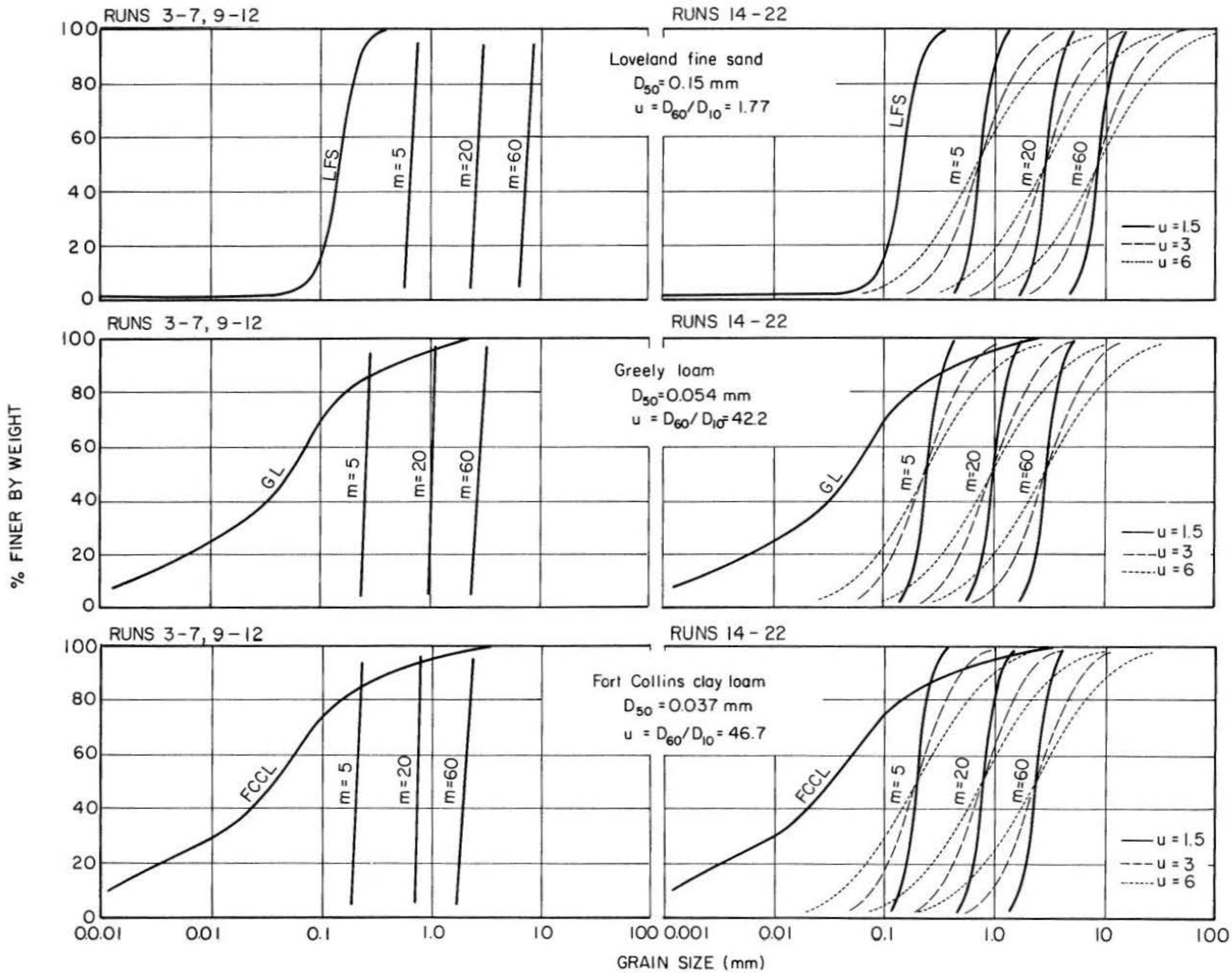

Figure 3. Size distributions of soils and gravel layers

TABLE 2. VARIABLES STUDIED DURING RUNS 14-22 OF EXPERIMENTS ON THE EFFECT OF GRAVEL MULCHES ON EVAPORATION FROM SOILS

Variables Studied	Increments of Each Variable
Soils (s)	(1) Loveland fine sand (LFS)
	(2) Greeley loam (GL)
	(3) Fort Collins clay loam (FCCL)
Gravel Mulches*	
Thickness (t)	All layers--1 inch thick
Median Size (m)	(1) 5
$\frac{(D_{50})\text{ gravel}}{(D_{50})\text{ soil}}$	(2) 20
	(3) 60
Uniformity (u) --	(1) 1.5
$\frac{D_{60}}{D_{10}}$ (Hazen's Uniformity Coefficient)	(2) 3
	(3) 6
Atmospheric Conditions	
Incident Radiation (r)	(1) 0 lamps
(No. of 250-w lamps)	(2) 2 lamps
	(3) 4 lamps
Wind Velocity (w)	(1) 0 fps
(Gusty Conditions--no	(2) 10 fps
velocity 80% of the time)	(3) 25 fps
Temperature (Constant)	90^{o} F
Relative Humidity (Constant)	30%

* See Figure 3

TABLE 3. ANALYSIS OF VARIANCE FOR RUNS 3-7 AND 9-12 OF EXPERIMENTS ON THE EFFECT OF GRAVEL MULCHES ON EVAPORATION FROM SOILS

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square
Main effects:			
Soils (s)	2	661,975	330,988**
Median Size (m)	2	9,754	4,877**
Thickness (t)	2	98,986	49,493**
Radiation (r)	2	11,228	5,614**
Wind Velocity (w)	2	2,675	1,338**
First order interactions:			
s x m	4	48,401	12,100**
s x t	4	8,209	2,052**
s x r	4	34,162	8,540**
s x w	4	35,172	8,793**
m x t	4	13,618	3,404**
m x r	4	628	157
m x w	4	13,793	3,888**
t x r	4	3,305	826**
t x w	4	2,249	562**
r x w	4	4,625	1,156**
Second order interactions:			
s x m x t	8	1,427	178
s x m x r	8	751	94
s x m x w	8	14,920	1,865**
s x t x r	8	269	34
s x t x w	8	1,776	222*
s x r x w	8	8,770	1,096**
m x t x r	8	818	102
m x t x w	8	2,025	253**
m x r x w	8	1,120	140
t x r x w	8	1,149	144
Third order interactions:			
s x m x t x r	16	838	52
s x m x t x w	16	1,891	118
s x m x r x w	16	1,423	89
s x t x r x w	16	506	32
m x t x r x w	16	2,399	150
Fourth order interaction (or error):			
s x m x t x r x w	32	2,592	81
TOTAL	242	991,454	

* Significant at 95% confidence level
** Significant at 99% confidence level

TABLE 4. ANALYSIS OF VARIANCE FOR RUNS 14-22 OF EXPERIMENTS ON THE EFFECT OF GRAVEL MULCHES ON EVAPORATION FROM SOILS

Source of Variation:	Degrees of Freedom	Sum of Squares	Mean Square
Main effects:			
Soils (s)	2	1,993,249	996,624**
Median Size (m)	2	85,663	42,832**
Uniformity Coefficient (u)	2	33,627	16,814**
Radiation (r)	2	39,275	19,638**
Wind Velocity (w)	2	3,339	1,670**
First order interactions:			
s x m	4	12,015	3,004**
s x u	4	10,500	2,625**
s x r	4	43,870	10,968**
s x w	4	33,003	8,251**
m x u	4	93,710	23,428**
m x r	4	1,610	402**
m x w	4	5,878	1,470**
u x r	4	80	20
u x w	4	1,144	286*
r x w	4	25,689	6,422**
Second order interactions:			
s x m x u	8	26,212	3,276**
s x m x r	8	3,445	431**
s x m x w	8	3,446	431**
s x u x r	8	2,405	301**
s x u x w	8	543	68
s x r x w	8	25,453	3,182**
m x u x r	8	667	83
m x u x w	8	1,303	163
m x r x w	8	2,218	277**
u x r x w	8	487	61
Third order interactions:			
s x m x u x r	16	7,475	467**
s x m x u x w	16	3,724	233**
s x m x r x w	16	4,558	285**
s x u x r x w	16	1,899	119
m x u x r x w	16	598	37
Fourth order interaction (or error):			
s x m x u x r x w	32	2,709	85
TOTAL	242	2,469,794	

* Significant at 95% confidence level
** Significant at 99% confidence level

Figure 4a shows the interaction among soils, median size, and uniformity. For all three soils, the combination of a median size ratio of five and a uniformity coefficient of six was very ineffective in comparison to the other mulches. For Greeley loam and Fort Collins clay loam, with median size ratios of 20 and 60, the uniformity of the gravel layer had very little effect on the amount of moisture conserved. For Loveland fine sand, the same result was observed with a median size ratio of 20. For the latter soil, the median size ratio of 20 was more effective than the median size ratio of 60, especially for a coefficient of 1.5. For the loam and clay loam, however, there was little difference between the effectiveness of the median size ratios of 20 and 60.

Figure 4b shows the interaction among soils, median size, and wind velocity for runs 14-22. For the loam and clay loam, the increase of wind velocity from 0 to 10 ft/sec caused a reduction in the effectiveness of the mulches, but there was very little change in effectiveness as the wind velocity increased from 10 to 25 ft/sec. The latter observation was true of all median size ratios used. For the loam and clay loam, there was little difference between the effectiveness of the median size ratios of 20 and 60, but both were considerably more effective than the median size ratio of five. For the fine sand, with median size ratios of five and twenty, an increase in wind velocity caused an increase in the effectiveness of the mulch. For a median size ratio of 60, the effectiveness increased as the wind velocity increased from 0 to 10 ft/sec, and then decreased as the wind velocity increased from 10 to 25 ft/sec.

The interaction among soils, median size, and wind velocity for runs 3-7 and 9-12 is shown in Figure 4c. All the observations previously noted also apply to these runs except that with the fine sand there was little difference in effectiveness between the median size ratios of five and twenty.

Figure 4d shows the interaction among soils, median size, and radiation for runs 14-22. An increase in radiation caused a decrease in the effectiveness of the gravel mulch, regardless of the median size ratio with the loam and clay loam. With these two soils there was little difference between the effectiveness of the mulches with median size ratios of 20 and 60, but both were considerably more effective than the median size ratio of five. With the fine sand, an increase in radiation caused an increase in the effectiveness of the gravel mulches, especially for the median size ratio of twenty.

The interaction among median size, thickness, and wind velocity is shown in Figure 4e. For all thicknesses, and for median size ratios of five and twenty, wind velocity had very little effect on the amount of water conserved. For all thicknesses, and for a median size ratio of sixty, there was a marked decrease in the effectiveness of the mulches as the wind velocity increased from 8 to 25 ft/sec. At a wind velocity of 25 ft/sec the mulches with a median size ratio of sixty were significantly less effective than the other mulches. This effect was most pronounced with a mulch thickness of ¼ inch, less pronounced with ½ inch, and still less pronounced with a mulch thickness of one inch.

The interaction among soils, uniformity coefficient of the mulch, and radiation is shown in Figure 4f. The uniformity coefficient of six was least effective for all three soils at all three radiation levels; this was especially true in the case of the fine sand. The uniformity coefficient of three was most effective for nearly all soils and radiation levels.

The interaction among soils, mulch thickness, and wind velocity is shown in Figure 4g. For all soils and wind velocities, the relative effect of thickness was the same. A substantial increase in effectiveness occurred as the thickness was increased from ¼ to ½ inch, and the effectiveness leveled off at about one inch except on the fine sand, in which case the mulches consisted of much larger grains. A thicker layer may thus have been substantially more effective for the fine sand.

Figure 4h shows the interaction among soils, median size, and thickness. For all three soils, with a median size ratio of five, the one-inch mulch was less effective than the ½-inch mulch, which is hard to explain unless the loss of water from the mulches themselves was significant in this case. For the fine sand, the most effective layer had a thickness of one inch and a median size ratio of twenty. For the loam and clay loam, however, the most effective layer had a thickness of one inch and a median size ratio of sixty.

The ineffectiveness of a gravel mulch with a median size ratio of five and a uniformity coefficient of six can be explained as follows: Figure 3 shows that this layer had a considerable amount of particles smaller than a significant amount of the base soil. It is probable that this fraction of the mulch retained its ability to conduct water to the surface until a substantial amount of water had been lost from the soil below.

The relative ineffectiveness of the layer with a median size ratio of sixty and a uniformity coefficient of 1.5 on the fine sand was probably due to the fact that the pores of this mulch were very large. When wind blows across the surface, turbulence and convection can occur within the large pores of this mulch. Thus, water can be removed from this mulch faster than by the diffusion process occurring in mulches with smaller pores. The median grain-size of this layer was 9 mm or approximately 1/3 inch. The effect of high wind velocity on the mulch with a median size ratio of sixty on Loveland fine sand is also shown by Figures 4b and 4c.

The increasing effectiveness of the gravel mulches on the fine sand with increasing radiation may at first seem to be an error. However, it may be that the increase in radiation had little effect on the amount of water evaporated through the mulches, but increased the water loss from the bare soil. Thus the difference in loss of moisture may increase with increasing radiation.

The use of a 96-hour period as a standard for measuring the effectiveness of gravel mulches may at first seem unreasonable. Most of the loss of water from bare soils, however, occurs shortly after rains when the soil surface is moist. In climates where most of the water is applied by infrequent irrigations or heavy rains, bare soils accumulate a large portion of the water applied and the increase in accumulation as a result of gravel mulches is relatively smaller.

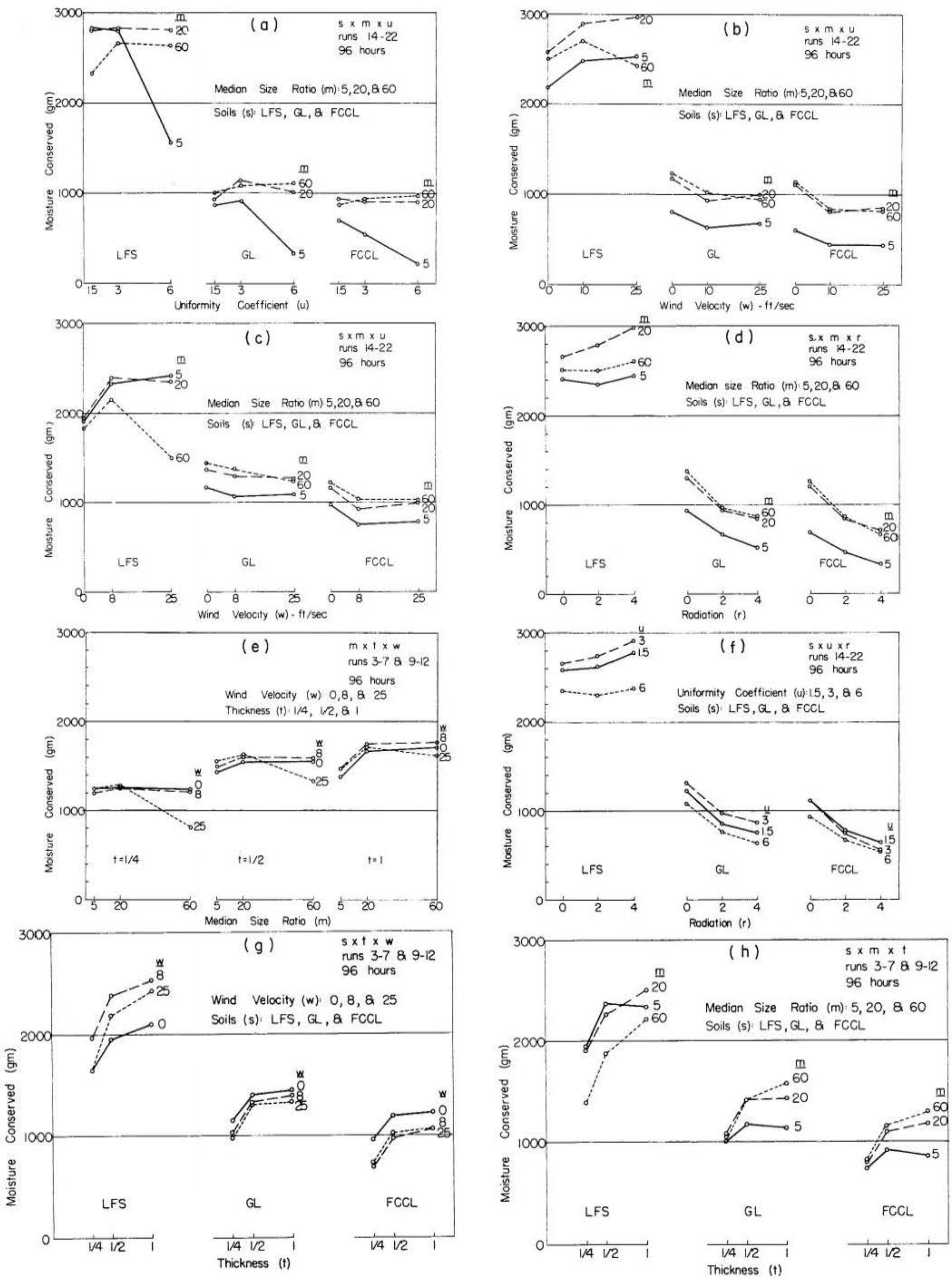

Figure 4. Moisture conserved as a function of soils, type of mulch, and atmospheric variables

Short soil columns were adopted for this study on the theory that most of the water lost by evaporation from bare soils is lost from the soil near the surface. Subsequent research, described under Phase C of this paper, as well as research reported by Gardner and Hanks (2), indicates, however, that had longer columns been employed, the water conserved by the gravel mulch would have been substantially greater.

Conclusions - From the observations and analyses described in the foregoing, we may conclude the following concerning the characteristics of a suitable gravel mulch for general atmospheric conditions:

1. The thickness should exceed ½ inch; but except where the mulch necessarily must consist of grains larger than about ¼ inch, the thickness need not exceed about one inch.

2. The mulch should not contain a substantial fraction of grain-sizes that are smaller than the larger grains of the underlying soil--at least than the larger grains that make up a substantial fraction of the underlying soil. In other words, nearly all of the pores of the mulch should be larger than the largest pores of the soil below. A median-size ratio of approximately twenty will usually meet this requirement.

3. If in order to meet requirement No. 2, a layer of gravel containing grains larger than about ¼ inch diameter is necessary, the thickness of the layer probably should be greater than one inch.

C. Influence of Initial Soil Water Conditions

All of the preceding experiments were carried out with relatively short columns containing very wet soil at the time evaporation measurements were started. The question remained as to whether gravel mulches would be equally effective if the soil was initially at field capacity or some lesser moisture content. An additional question remained as to whether the depth of soil initially wetted might be a factor.

This phase of the research was carried out with the same laboratory set-up as previously described except that in some of the runs, columns of several different lengths were employed. The objective was to answer the questions mentioned above, these answers being necessary to permit an extrapolation of the results of laboratory experiments to field conditions. Mulches conformed to specifications which the previous study indicated would be effective. They consisted of a 1-inch layer of gravel having a D_{50} of 0.8 mm and a "u" of 3.0.

Initial water concentration - The first set of runs was designed to determine the effect of initial water concentration. For these runs, all of the columns were 8½ inches long by 3½ inches I.D. Two soil types, a sand and a moderately heavy clay loam, were employed. Varying quantities of water were added to the soil columns. For each soil type and water content, there was a column with a bare soil surface, and a second column covered with gravel.

The columns were then placed on a rotating turntable and exposed to uniform applications of radiant energy. The air velocity across the soil surface was about six feet per second. The relative humidity and air temperature were held at about 30% and 78°F, respectively. Periodic weighings provided data on evaporation as a function of time.

The following initial conditions of soil moisture were employed:

1. Vacuum saturation followed by 24-hour drainage with zero tension, i.e., atmospheric pressure, at the base of the column.

2. Vacuum saturation followed by 24-hour drainage with three feet of water tension at the base of the column.

3. Vacuum saturation followed by a 24-hour drainage with six feet of water tension at the base of the column.

4. An initially saturated column drained with air-dried soil at its base for 24 hours, i.e., a column at approximately field capacity.

5. Two inches of water added to the column of air-dried soil.

6. One inch of water added to the column of air-dried soil.

7. One-half inch of water added to the column of air-dried soil.

The results of the first set of runs are presented in Figure 5. Evidently, evaporation from the soil columns covered with gravel was practically independent of the starting water condition for the period of this experiment, 12 days, the soil surface initially being moist in every case. Soil columns not covered by gravel lost water much more rapidly for the first 3 or 4 days, after which the rate of loss was equal to or less than that from the columns with the mulch. Obviously, the greater the beginning water content, the greater and more prolonged was the initial period of rapid water loss from the unprotected soil. These results were not qualitatively different for the contrasting soil types.

Depth of wetted soil - In order to evaluate the results of measurements of evaporation from short soil columns in terms of what might be expected in the field, it is desirable to understand the effect of the depth of wetted soil on the benefits from gravel mulches. Soil profiles are ordinarily deeper than the length of columns that are ordinarily convenient for use in a laboratory. Frequently, soil profiles are wetted throughout their depth in the field. For this reason a study of the effect of length of wetted column was undertaken.

In this experiment, the initial water content was approximately field capacity, and the soil was sandy loam. Columns of various length were employed, and just enough water was added to each to permit the water to spread to the bottom of the column in a period of a few days, the amount having been predetermined by trial. The same amount of water per weight of dry soil was added to all of the columns, and gravel was added to the surface of half of the columns of each of three lengths: 3.5, 7.5, and 11 inches.

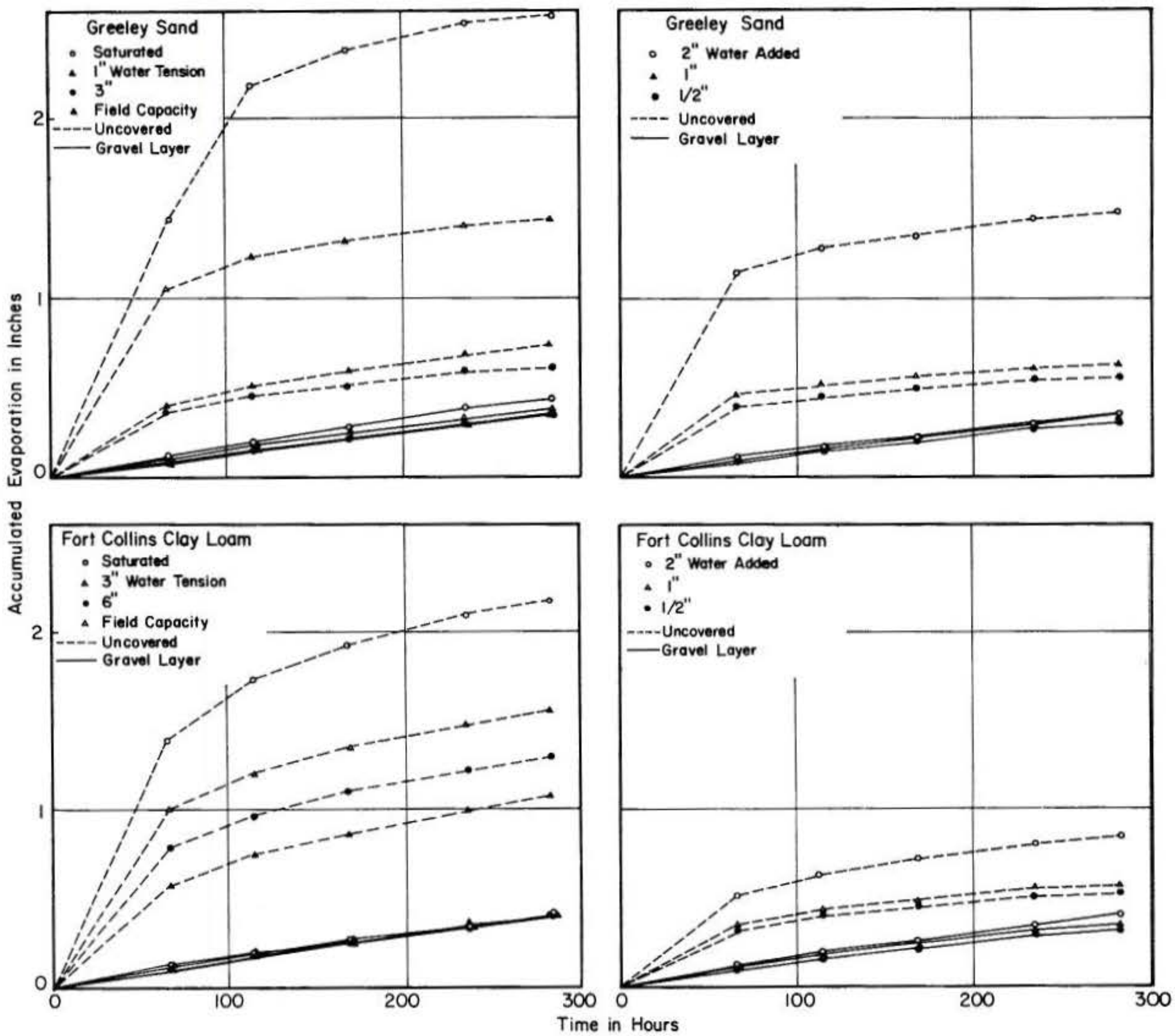

Figure 5. Effect of initial soil water content on conservation of water by a gravel mulch

The columns were placed on the turntable in the environmental-control chamber previously mentioned. The humidity, air temperature, and radiation were maintained at constant values such as to produce evaporativity comparable to what could be found in the field. Periodic weighings provided data on evaporation loss as a function of time. The accumulated evaporation was expressed as a percentage of the initial weight of water in each soil column.

Figure 6 shows that the accumulated evaporation, during the first 48 hours, increased faster for the bare soil than for the gravel mulch. After this, the bare soil became dry and the rates of evaporation became equal to or less than that from the columns with a gravel cover.

During the initial 48 hours, especially the first 24 hours, the rate of evaporation from the bare columns was vastly greater than from the columns covered by gravel. Almost 60 percent of the total water in the 3.5-inch uncovered columns was lost by the end of two days. For the 11-inch column, nearly 40 percent of the water was lost in this time.

For the shortest columns, ten days (240 hours) had elapsed before the accumulated evaporation from the mulched columns equaled that from the bare soil. In the case of the 7.5-inch columns it was 54 days, and with the 11-inch columns, the accumulated evaporation from the mulched columns was substantially less than from the bare columns when the experiment was terminated after 58 days.

It would seem that for rainfall distributions such as those usually occurring in Eastern Colorado, a soil with a gravel mulch could be expected to accumulate substantially more water than a bare soil. It would be expected, however, that the mulch would be relatively less effective in situations where only very small rains occur at long intervals of time because most of this water might evaporate in spite of the gravel mulch. Also, in places where very heavy rains occur at long intervals, much of the precipitation might be conserved without a mulch.

Conclusions - The results of the several laboratory experiments indicate that gravel mulches

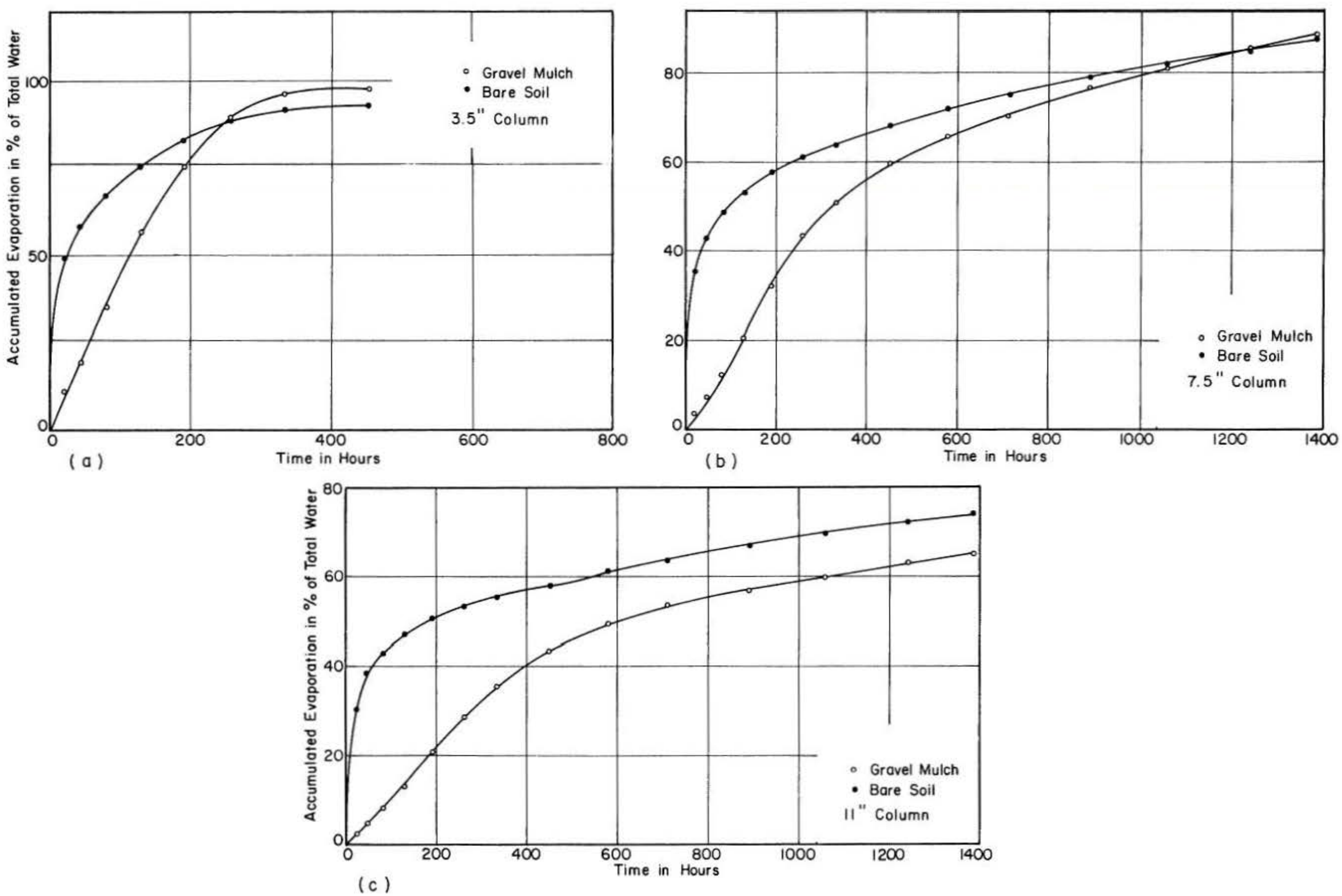

Figure 6. Accumulated evaporation as a function of time from columns of sandy soil (of various lengths) initially at field capacity

are a promising method of conserving water from precipitation. They also indicate what is required for a satisfactory mulch and under what rainfall distributions such a mulch is likely to be effective. In order to achieve more or less quantitative estimates of the amount of water that could be conserved by mulches under particular field conditions, however, it was concluded that field trials would be necessary.

D. Seed Emergence

A possible use for gravel mulches might be to conserve moisture around seeds to increase germination. This possibility was investigated in a preliminary way and some encouraging qualitative results were obtained.

Using clay loam soil columns and the environmental-control equipment previously mentioned, a study was made of the emergence of sugar beet seedlings in mulch-covered soils as compared with the emergence in soils having a bare surface. Warm and dry conditions prevailed beginning at the time of planting.

Percent of germination as well as rate of germination seemed to be favorably affected by the gravel mulch. There was also a very noticeable difference in emergence. The exposed surface of the unmulched columns dried and formed a crust which often separated from the soil, pulling the roots of the seedlings out of the soil below. The shoots, which easily emerged through the gravel mulch, appeared much healthier than the ones which emerged through the crust formed on the exposed soil surface. These tests were preliminary and there was insufficient data to justify any statistical or quantitative treatment of the results. Investigation in the field to evaluate the effect of narrow bands of gravel or moisture levels under the bands seemed to be desirable.

E. Retention of Water in Field Soils

The purpose of this phase of the research was twofold: First, it was considered necessary to verify the conclusions of previous laboratory studies regarding the ability of the gravel mulch to conserve moisture in field soils, and secondly, it was desired to determine how much of an area at the soil surface surrounding a given point in the soil should be covered with a band or a small patch of gravel in order to conserve a significant quantity of moisture at that point.

The study was conducted at the Colorado State University Agronomy Experimental Farm in an area with clay loam soil and where the mean annual precipitation is about 15 inches per year, a substantial percentage of which often occurs as relatively light spring and summer rains. The layout of the plots is shown in Figure 7. In the spring, the area was plowed, disked, dragged and floated to provide a reasonably smooth and level surface. The gravel layers were one inch thick and conformed very closely to specifications which a previous laboratory study (Phase B) had indicated would be effective.

A series of rain gages were installed around the perimeter of the bench to record all rainfall following installation of the plots. After drying periods of five days or more, gravimetric samples were taken with a tube-type sampler to determine differences in water content at various depths and positions in both the mulches and fallow plots.

Results - This study was carried out over two summer seasons. Unfortunately, the rainfall records obtained during the first season were not significant because of an accidental wetting of the plots during irrigation of adjoining farm land. All that is significant from the data obtained during the first season is the result that at the end of the season, the upper three feet of soil contained 2.3 inches more water under the mulched plots than under the fallow plots. It was also observed that the amount of moisture conserved at the center of mulched plots was noticeably larger than that conserved at the edge of the continuous plots.

More complete data were obtained from the second season (1963). Table 5 shows the distribution of rainfall on the plots during this season. Figure 8 shows the moisture status in the soil at the end of the study in October. In this figure, moisture data taken from under strips of gravel are also shown. The strips were of varying widths, the smallest being 2 inches and the widest 12 inches. The effect of the width of the strips was not clearly evident, and insufficient measurements were made to examine the data statistically. The measurements from all the strip plots, therefore, were averaged to obtain the middle curve shown in Figure 8. The results indicate that more moisture was retained under the strips than in the fallow soil, but not as much as under a continuous gravel mulch.

The quantity of water in the soil beneath the continuous gravel mulch, to a depth of 3 feet, exceeded that in the fallow soil by an amount equivalent to 1.5 inches, at the time of the last sampling in October. This compares with a 2.3-inch difference at the end of the 1962 study. The amount of water that can be stored is, of course, limited by the unfilled storage capacity of the soil. This unfilled storage capacity was substantially greater in 1962 due to the fact that the plots had not been fallow preceding the spring of that year.

Conclusions - Evidently a gravel mulch placed on a soil with an unfilled storage capacity can result in conservation of a substantial quantity of water, at least under the climatic conditions of Eastern Colorado. This assumes that the soil is maintained free of vegetation.

A quantitative estimate of the total amount of increased infiltration produced by gravel mulches cannot be deduced from these experiments because the increase in deep percolation was not measured. The total of increased infiltration, however, is certainly greater than the increase in water stored in the root zone of the soil. This can be deduced from the fact that the increase in water stored was substantially greater when the initial soil moisture was the least.

F. Effect on Total Infiltration

A possible use of gravel mulches is to increase recharge to groundwater aquifers by increasing infiltration from precipitation. In order to evaluate the effectiveness of gravel mulches for this purpose, it is necessary to measure not only water retained in the soil but also water that may

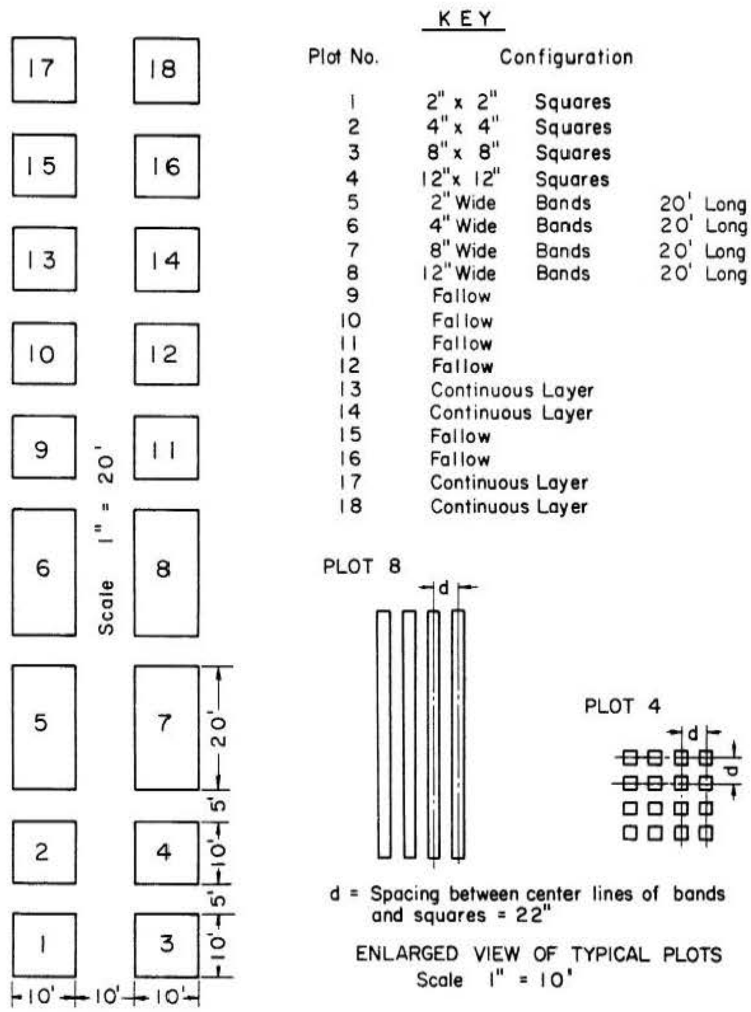

Figure 7. Plot layout

TABLE 5. RAINFALL DISTRIBUTION AT SITE OF FIELD STUDIES IN 1963

May		June		July		August		September	
Date	Amount (inches)	Date	Amount (inches)	Date	Amount (inches)	Date	Amount (inches)	Date	Amount (inches)
15-16	.06	2-3	.09	10-11	.08	1-3	.16	6-8	.14
18-19	.12	9-10	.50	15-16	.03	6-8	.35	18-21	.86
21-25	.24	13-18	1.33			13	.42		
						17	.03		
						22-23	.20		
						25-26	.89		
						31	.12		
Total for season - 5.6 inches									

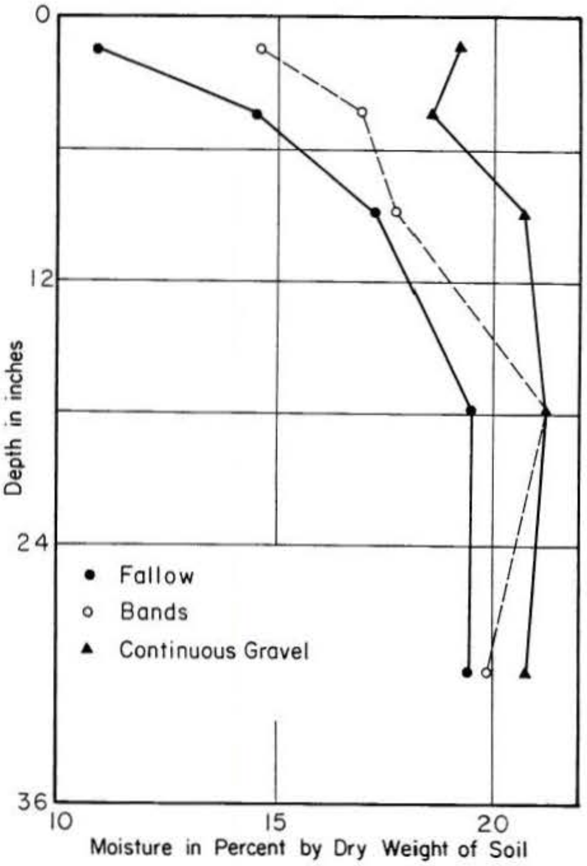

Figure 8. Water content in soil under field plots at end of experiment in October 1963

pass through the soil by deep percolation. Furthermore, the measurements should be continued over at least an entire year rather than over a growing season only.

It is difficult to determine the amount of deep percolation under undisturbed field conditions. For this reason, the experiments undertaken during this phase of the research were conducted using soil in cylinders which, however, were placed in the field under environmental conditions as near as possible to those of the natural soil. This phase of the research was conducted by the Agronomy Department, whereas the other phases were conducted by the Civil and Agricultural Engineering Departments.

Aluminum cylinders 36 inches long and 6 inches in diameter were constructed and filled with soil, except for a gravel layer 5 cm thick in the bottom, from which free water was extracted as it accumulated. Various depths, sizes and colors of gravel were placed at the surface, the top of the gravel layer being about 1 cm below the top of the cylinder. The cylinders were placed in pits in the soil so that the surface of the gravel layers was at approximately the same elevation as the surrounding ground surface. The cylinders containing the different treatments were removed and weighed at least twice weekly, and more often when precipitation occurred. Two inches of water were applied to each cylinder on August 14, 1966, and again on December 15, 1967. All the rest of the "rainfall" was natural.

The question arose as to whether temperature gradients would influence the evaporation from the cylinders. Since the outsides of the aluminum cylinders were exposed to air convection, the gradients in the soil would undoubtedly be different from gradients in field soils. To evaluate the temperature factor, one cylinder was constructed of lucite with 1/8-inch wall thickness, and the sides were wrapped with 3 inches of glass-wool insulation enclosed in waterproof paper. The bottom of the cylinder was not insulated and rested on the soil at the bottom of the pit.

The gravel mulches consisted of particles ranging in size from 0.4 to 1 cm in diameter. The red gravel was a crushed red sandstone, and the white was a crushed feldspar. The grey gravel was a crushed granitic material characteristic of river deposits. Another treatment consisted of a sand mulch. All treatments were duplicated, and the data reported are averages of the duplicates.

Results - In Figure 9, the amount of precipitation that was retained by the soil, plus that which passed through the soil, is plotted as a function of time. Four curves are shown representing the accumulation for mulches of 5 cm, 2 cm and 1 cm thickness, compared with that for a bare soil. Note that when 5 cm of gravel was placed on the soil, approximately 19 of the 23 inches of rain was potentially available for recharge to the groundwater. This is compared to only about 4 inches available for recharge with the bare soil.

Table 6 shows that when the mulch was 5 cm thick, the color of the gravel was of minor importance. For thinner layers, the white gravel was substantially more effective. This was undoubtedly a result of the greater amount of radiant energy reflected by the white gravel. The 5 cm sand mulch was only slightly less effective than its gravel counterparts, whereas for thinner layers, it was actually more effective. Evidently, sand also would be an effective material for mulches if it could be prevented from blowing.

Temperature gradients apparently had negligible effect on the results of this experiment, because the insulated cylinder with a grey-gravel mulch of 2 cm thickness accumulated essentially the same amount of water as did its counterpart which was not insulated.

Conclusions - The difference in amount of water accumulated under the 5 cm gravel mulch, compared to that accumulated under the bare soil (14 inches), demonstrates the great potential of such mulches for increasing recharge to groundwater aquifers. Under some climatic conditions the potential might be less, but under other conditions it could be even greater.

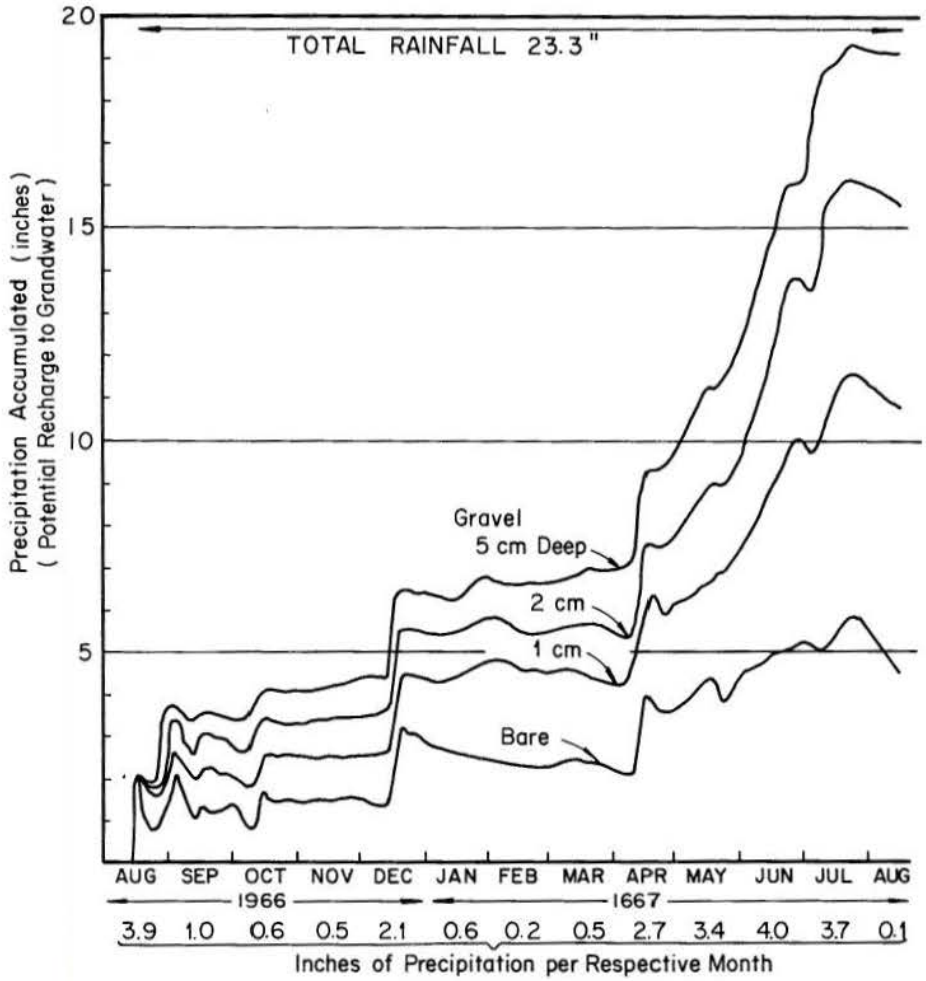

Figure 9. Potential recharge to groundwater as affected by gravel mulches on a soil surface

TABLE 6. WATER ACCUMULATION OVER THE STUDY PERIOD OF AUGUST 14, 1966, TO SEPTEMBER 6, 1967

Treatment		Water Accumulation (inches)
bare soil		4.2
red gravel	1 cm	10.1
	2 cm	13.9
	5 cm	19.0
white gravel	1 cm	12.7
	2 cm	17.0
	5 cm	19.6
grey gravel	1 cm	10.5
	2 cm	15.0
	5 cm	19.0
grey gravel insulated	2 cm	15.0
grey sand	1 cm	11.9
	2 cm	13.7
	5 cm	17.4

IMPLICATIONS FOR FUTURE INVESTIGATIONS

There are several possible ways in which gravel mulches might be employed. One way might be to increase the effectiveness of a program of summer fallowing, in which case the gravel theoretically could be removed during the season of cultivation and reapplied for the fallow period. Another possibility would be to develop cultivation practices which would not interfere with the maintenance of a gravel mulch. In either case, the objective would be to retain additional water within the root zone of the soil. A third possibility would be to employ a gravel mulch in narrow bands or other local areas to retain moisture for the germination of seeds. Another potentially extensive possibility is the use of gravel mulches on non-agricultural land to increase recharge to groundwater aquifers. For each of these uses, the gravel mulch would have to be accompanied by some program of weed and shrub control.

It is possible to conceive of many difficulties with gravel mulches which might arise in use. It might be necessary, for example, to develop machinery which would periodically re-establish the mulch after winds or surface runoff had misplaced the gravel or after the large pores of the gravel had been filled with blowing soil.

Perhaps the greatest difficulty would be the problem of finding economical ways of establishing and maintaining a mulch. With soils containing some gravel or coarse sand, it might be possible to develop machinery to concentrate the larger particles at the surface.

Noting that the field experiments (reported under Phase F in this paper) showed a possibility of conserving 14 inches of water in a single year by use of a gravel mulch, further intensive investigations are justified. These investigations should seek to solve the practical and economic problems which would be encountered in the use of gravel mulches. It would also be desirable to investigate the effects (on the hydrology of fairly extensive watersheds) which might be produced by the use of gravel mulches.

BIBLIOGRAPHY

1. Corey, A. T., et al., Colorado Contributing Project to W-32, Progress Reports Nos. 4 and 5; and to W-73, Project Reports Nos. 1, 2, and 3.

2. Gardner, H. R., and Hanks, R. J., Effect of sample size and environmental conditions on evaporation of water from soil. Conservation Research Report No. 9, Agricultural Research Service, U.S.D.A., in cooperation with Colorado Agricultural Experiment Station.

3. Kemper, W. D., Annual Report on Micro-Watershed Studies, 1963, 1964, and 1965.

4. Kuska, J. B., and Mathews, O. R., Dryland crop rotation and tillage experiments, U.S.D.A. Cir. No. 979, June 1956, and Mathews, O. R., Summer Fallow at Ardmore, South Dakota, U.S.D.A. Cir. No. 213, February 1932.

5. Richards, S. J., Porous block mulch for ornamental plantings, California Agriculture, December, 1965.

6. Schleusener, R. A., Factors affecting evaporation from soils in contact with a water table. Ph.D. Dissertation, Colorado State University, Fort Collins, Colorado, 1958.

7. Scott, V. H. and Corey, A. T., Pressure distribution during steady flow in unsaturated sands. Proceedings, Soil Science Society of America, 25: 270-274, 1961.

Key Words: Gravel mulches, Mulches, Evaporation, Reduction of evaporation, Infiltration, Groundwater recharge, Recharge to groundwater, Infiltration increase.

Abstract: Beginning in 1956 and continuing to the present time studies have been conducted at Colorado State University to discover methods of reducing evaporation from soils. The outcome of this research has been the conviction that a gravel mulch on a fallow soil surface is the most promising method for increasing infiltration of precipitation.

This paper reports the results of a series of related experiments which, heretofore, had been reported only in miscellaneous progress reports. These studies have, in the opinion of the authors, demonstrated conclusively the great potential of gravel mulches for increasing soil moisture and also for increasing recharge to groundwater aquifers. In one experiment, the use of a gravel mulch 5 cm thick, resulted in an additional accumulation of 14 inches of water during a period of one year, compared to that which accumulated under the bare soil.

The results of this research indicate the need for further studies to overcome economic and other difficulties which might be encountered in the practical use of gravel mulches.

Reference: Kemper, W. D., and Corey, A. T., Colorado State University, Hydrology Paper No. 30 (July 1968), "Conservation of Groundwater by Gravel Mulches."

Key Words: Gravel mulches, Mulches, Evaporation, Reduction of evaporation, Infiltration, Groundwater recharge, Recharge to groundwater, Infiltration increase.

Abstract: Beginning in 1956 and continuing to the present time studies have been conducted at Colorado State University to discover methods of reducing evaporation from soils. The outcome of this research has been the conviction that a gravel mulch on a fallow soil surface is the most promising method for increasing infiltration of precipitation.

This paper reports the results of a series of related experiments which, heretofore, had been reported only in miscellaneous progress reports. These studies have, in the opinion of the authors, demonstrated conclusively the great potential of gravel mulches for increasing soil moisture and also for increasing recharge to groundwater aquifers. In one experiment, the use of a gravel mulch 5 cm thick, resulted in an additional accumulation of 14 inches of water during a period of one year, compared to that which accumulated under the bare soil.

The results of this research indicate the need for further studies to overcome economic and other difficulties which might be encountered in the practical use of gravel mulches.

Reference: Kemper, W. D., and Corey, A. T., Colorado State University, Hydrology Paper No. 30 (July 1968), "Conservation of Groundwater by Gravel Mulches."

Key Words: Gravel mulches, Mulches, Evaporation, Reduction of evaporation, Infiltration, Groundwater recharge, Recharge to groundwater, Infiltration increase.

Abstract: Beginning in 1956 and continuing to the present time studies have been conducted at Colorado State University to discover methods of reducing evaporation from soils. The outcome of this research has been the conviction that a gravel mulch on a fallow soil surface is the most promising method for increasing infiltration of precipitation.

This paper reports the results of a series of related experiments which, heretofore, had been reported only in miscellaneous progress reports. These studies have, in the opinion of the authors, demonstrated conclusively the great potential of gravel mulches for increasing soil moisture and also for increasing recharge to groundwater aquifers. In one experiment, the use of a gravel mulch 5 cm thick, resulted in an additional accumulation of 14 inches of water during a period of one year, compared to that which accumulated under the bare soil.

The results of this research indicate the need for further studies to overcome economic and other difficulties which might be encountered in the practical use of gravel mulches.

Reference: Kemper, W. D., and Corey, A. T., Colorado State University, Hydrology Paper No. 30 (July 1968), "Conservation of Groundwater by Gravel Mulches."

Key Words: Gravel mulches, Mulches, Evaporation, Reduction of evaporation, Infiltration, Groundwater recharge, Recharge to groundwater, Infiltration increase.

Abstract: Beginning in 1956 and continuing to the present time studies have been conducted at Colorado State University to discover methods of reducing evaporation from soils. The outcome of this research has been the conviction that a gravel mulch on a fallow soil surface is the most promising method for increasing infiltration of precipitation.

This paper reports the results of a series of related experiments which, heretofore, had been reported only in miscellaneous progress reports. These studies have, in the opinion of the authors, demonstrated conclusively the great potential of gravel mulches for increasing soil moisture and also for increasing recharge to groundwater aquifers. In one experiment, the use of a gravel mulch 5 cm thick, resulted in an additional accumulation of 14 inches of water during a period of one year, compared to that which accumulated under the bare soil.

The results of this research indicate the need for further studies to overcome economic and other difficulties which might be encountered in the practical use of gravel mulches.

Reference: Kemper, W. D., and Corey, A. T., Colorado State University, Hydrology Paper No. 30 (July 1968), "Conservation of Groundwater by Gravel Mulches."

PREVIOUSLY PUBLISHED PAPERS

Colorado State University Hydrology Papers

No. 20 "Accuracy of Discharge Determinations," by W. T. Dickinson, June 1967.

No. 21 "Water Quality of Mountain Watersheds," by Samuel H. Kunkle and James R. Meiman, June 1967.

No. 22 "Prediction of Water Yield in High Mountain Watersheds Based on Physiography," by Robert W. Julian, Vujica Yevjevich, and Hubert J. Morel-Seytoux, August 1967.

No. 23 "An Objective Approach to Definitions and Investigations of Continental Hydrologic Droughts," by Vujica Yevjevich, August 1967.

No. 24 "Application of Cross-Spectral Analysis to Hydrologic Time Series," by Ignacio Rodriguez-Iturbe, September 1967.

No. 25 "An Experimental Rainfall-Runoff Facility," by W. T. Dickinson, M. E. Holland and G. L. Smith, September 1967.

No. 26 "The Investigation of Relationship Between Hydrologic Time Series and Sunspot Numbers," by Ignacio Rodriquez-Iturbe and Vujica Yevjevich, April 1968.

No. 27 "Diffusion of Entrapped Gas from Porous Media," by Kenneth M. Adam and Arthur T. Corey, April 1968.

Colorado State University Fluid Mechanics Papers

No. 4 "Experiment on Wind Generated Waves on the Water Surface of a Laboratory Channel," by E. J. Plate and C. S. Yang, February 1966.

No. 5 "Investigations of the Thermally Stratified Boundary Layer," by E. J. Plate and C. W. Lin, February 1966.

No. 6 "Atmospheric Diffusion in the Earth's Boundary Layer--Diffusion in the Vertical Direction and Effects of the Thermal Stratification," by Shozo Ito, February 1966.

Colorado State University Hydraulics Papers

No. 1 "Design of Conveyance Channels in Alluvial Materials," by D. B. Simons, March 1966.

No. 2 "Diffusion of Slot Jets with Finite Orifice Length-Width Ratios," by V. Yevjevich, March 1966.

No. 3 "Dispersion of Mass in Open-Channel Flow," by William W. Sayre, February 1968.