

CHANGES IN WATER INFILTRATION CAPACITIES FOLLOWING THE APPLICATION  
OF A WETTING AGENT ON A PONDEROSA PINE FOREST FLOOR

by

Marc Gabriel Kaplan

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SIGNED: Marc D. Kaplan

APPROVAL BY THESIS DIRECTOR

This thesis has been approved on the date shown below:

Malcolm J. Zwolinski  
M. J. ZWOLINSKI  
Professor of Watershed Management

Feb. 15, 1973  
Date

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## ABSTRACT

An infiltration-wetting agent study, using the wetting agent "WATER-IN", was conducted in the ponderosa pine forest type of east central Arizona, near McNary, Arizona. An application rate of 10 gallons of wetting agent per surface acre was used both on bare mineral soil and on ponderosa pine litter. The infiltration rate was measured by a modified North Fork infiltrometer. It was found that "WATER-IN" significantly increased water runoff, when applied to litter, but when applied to bare mineral soil, "WATER-IN" caused a significant increase in water infiltration. The wetting agent did not significantly affect antecedent moisture, soil particle distribution, litter water holding capacity, or litter bulk density. It is presently hypothesized that the increase in water infiltration on treated bare mineral soil is due to a decrease in the average bulk density of the surface inch of soil. The data strongly suggests this hypothesis to be correct. The increase in runoff when litter is treated is probably due to an interaction, either physical, chemical, or both, between the humus layer and "WATER-IN", creating a hydrophobic condition where one did not exist before.

## INTRODUCTION

Wetting agents are becoming increasingly important in the field of watershed management. Of particular interest in Arizona is how non-ionic wetting agents can be used to increase subsurface flow on forested areas.

This study was designed to investigate some of the effects of a specific wetting agent on water infiltration when applied to a site within the ponderosa pine (Pinus ponderosa Laws.) forest type in the White Mountains of Arizona.

### The Problem

Land management agencies on the national, state, and local level have been reexamining their overall management plans, placing increasing emphasis on increased water yield for downstream uses. Their attention is being drawn especially to forest vegetation, since a large number of watershed studies have shown that forested areas are the best suited for more intensive water yield management.

In Arizona, the ponderosa pine forest is the vegetation type most suited to more intensive water yield management, because of the large area this forest type covers, 3.7 million acres (McGinnies, McComb, and Fletcher, 1963), and the relatively high amount of

precipitation received. The largest part of this area is in the White Mountain region in the east central part of the state, drained by the Salt River.

The report, "Recovering Rainfall" (Barr, 1956), concluded that water yields from the Salt River drainage could be increased by proper manipulation of vegetation types, particularly forest types. This report showed that the pine zone is the largest single contributor of water to the Salt River, supplying nearly one-half of the total runoff. Because of this, the greatest total increase in water yield can be expected from the ponderosa pine zone.

#### Purpose of This Study

The overall purpose of this study was to examine the ability of a forest soil type to absorb water after the surface litter had been treated with a nonionic wetting agent. The study area, situated on the Fort Apache Indian Reservation, has been treated periodically with prescribed fire for the last fifteen years.

#### Specific Objectives

The specific objectives of this study were to determine:

1. If any changes occur in the infiltration capacities of a soil after field application of a wetting agent of known concentration.
2. If physical properties of the soil under study are affected by treatment with a wetting agent.

3. If the water-holding capacity of ponderosa pine litter is affected by treatment with a wetting agent.

#### Definitions of Terms

There are several terms which are used often in this paper and need to be defined. These terms are:

1. Infiltration--the downward movement of water through the soil surface.
2. Infiltration run--the period over which infiltration occurs.
3. Infiltration rate--the maximum rate at which a soil, in a given condition at a given time, can absorb water (Richards, 1952).  
The infiltration rate is an instantaneous value which can be defined at any given time during an infiltration run after surface runoff has occurred.
4. Infiltration capacity--the maximum rate at which a soil can absorb water after maintaining a stable runoff condition for at least 20 minutes.
5. Liquid-Solid contact angle--the angle that is made by a liquid droplet at the liquid-solid interface. If the contact angle is near zero degrees, then the liquid spreads freely over the solid surface. When the angle is significantly larger than zero, the liquid will form droplets on the surface. The formation of droplets is indicative of a reduction in wettability. When the contact angle is greater than 90 degrees, the surface is said to be liquid repellent and the liquid will roll over the surface without spreading.

6. Water repellent soil--a soil where the water-soil contact angle is greater than 90 degrees. A soil of this nature is also referred to as a hydrophobic or nonwetable soil.
7. Wetting agent--any one of a large number of chemical compounds which reduce the surface tension of water to a small degree and decrease the water-soil contact to a large degree. Wetting agent is synonymous with surfactant.

## LITERATURE REVIEW

### Water Repellent Soils

Water repellent soils are not an isolated curiosity. They are found in many parts of the world--from Australia to the United States. These soils have widespread implications for land management. Nonwetable soils can be a serious problem on steep slopes, where they reduce infiltration of rainwater and cause serious erosion problems.

Soils having extremely low permeabilities, i.e., soil with a very high clay content or hardpan, are not considered water repellent in the sense used in this study. Limited macro pore space is not a problem in hydrophobic soils because many of them have sandy textures and would be highly permeable if water could penetrate the surface.

Water repellency affects both the stability and the usability of soils. Severe water repellency can alter soil moisture relationships and severely impair the growth of vegetation.

#### General Nature of Wetting and Infiltration

Debano (1969a) has an excellent description of the general nature of wetting and infiltration (pp. 12-14):

Water quickly penetrates a dry wettable soil because of a strong attraction between it and the soil particles. The water films and the soil particles attract each other at the point where air, water, and soil meet. This attraction can easily be illustrated if the soil is visualized as a bundle of small glass capillary tubes. When the ends of the tubes are immersed in water, the water will rise because of an attraction between the

water molecules and the wall of the tube. Surface tension at the meniscus moves the water not in contact with the walls. The attraction between the capillary tube wall and water can be considered somewhat analogous to that between the water molecules and the soil particle surfaces in a more complex soil system.

When water moves up a capillary tube, a definite and measurable angle is produced between the meniscus and the wall. The capillary rise equation defines how high water rises in the tube:

$$h = \frac{2n}{rpg} \cos\theta \quad (1)$$

in which

h = height of rise

n = surface tension

r = radius of the capillary

p = density of the liquid

g = gravitation term

$\theta$  = angle between the water meniscus and the wall.

If the capillary wall is made of clean glass, the angle ( $\theta$ ) is small and assumed to be zero. If the angle is zero, the height of rise is directly related to the surface tension and is inversely related to the tube radius; that is, the smaller the radius of the tube the higher the capillary rise.

Coating the walls of the capillary tube with hydrophobic substances (e.g., waxes and oils) can reduce the attraction between water and the glass walls. The water then will not rise as high as in a clean tube. Wetting angles calculated for the treated capillary tube are considerably greater than zero--sometimes exceeding  $90^\circ$ . Such angles can also be obtained with other liquids.... In soils, the common liquid present is water, and the wetting angle is determined primarily by the wettability of the particle surfaces.

The concept of a wetting angle provides a useful method for quantifying soil wettability. For example, the capillary rise equation (1) has been used to calculate a quantity known as the apparent liquid-solid contact angle. This angle increases as the water repellency in a soil increases. Angles up to and above  $90^\circ$  have been reported for soils that are highly water repellent.

Water infiltrates rapidly into a dry wettable soil. The initial intake is high and decreases exponentially over time (Fig. 1). At first, the adsorptive forces of the soil particles can draw water quickly into the soil. At later infiltration times, water applied at the surface must move through a nearly

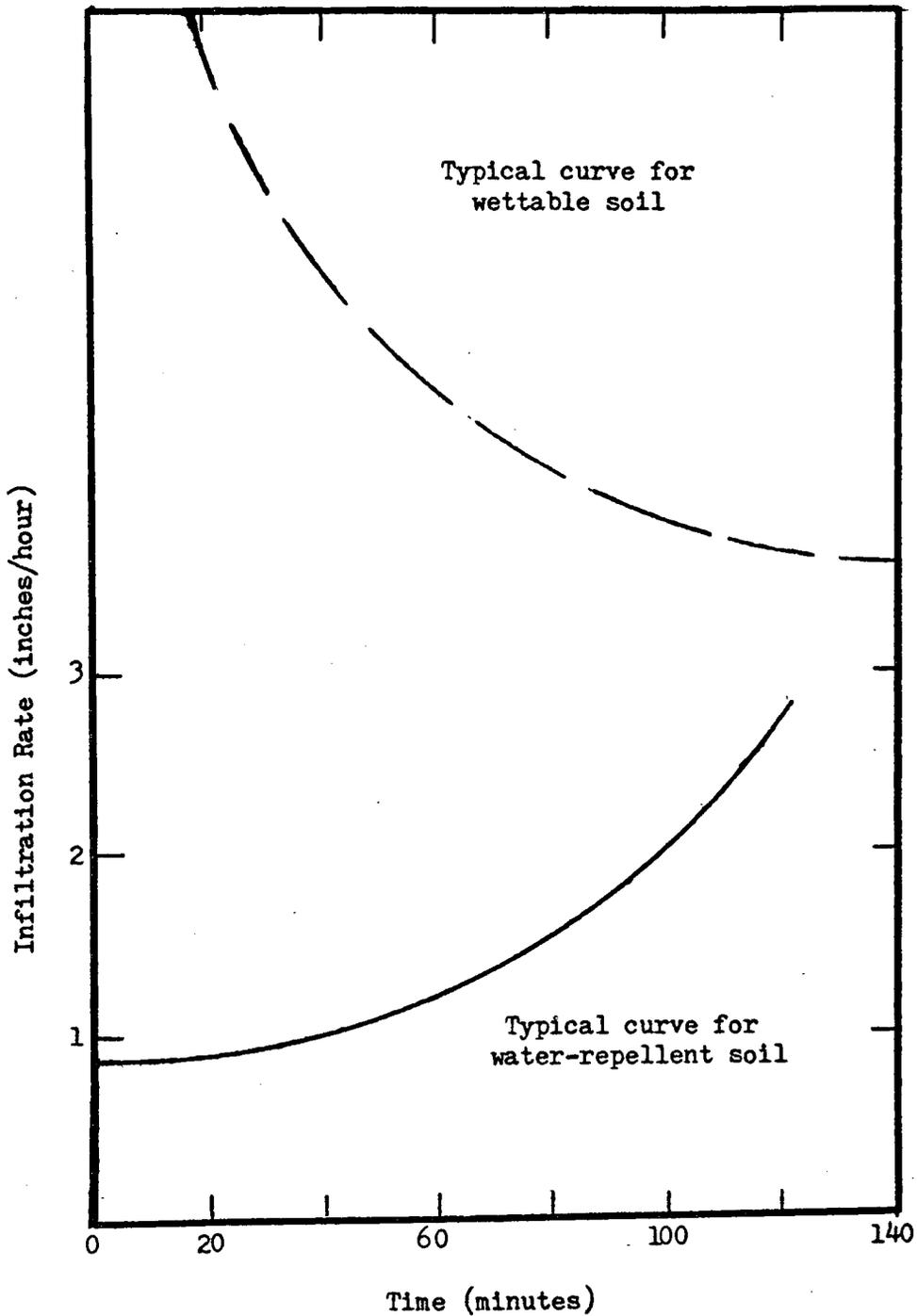


Fig. 1. Typical infiltration curves for water-repellent and wettable soils (Letey et al., 1962) -- DeBano, 1969a, p. 72.

saturated soil layer before reaching the wetting front. The rate water can be transported through this saturated zone above the wetting front controls the infiltration rate.

Water infiltration into a water repellent soil is not the same as that into a wettable soil (Fig. 1). In water repellent soils, water infiltrates slowly at first because the particles resist wetting. However, as the surface layer wets up, a positive head begins to develop. The head helps push the water into the soil. The wetting front continues to move downward over time, and the increasing positive head accelerates the rate of water movement into the soil. Although the rate continues to increase over time in the water repellent soil, it is still significantly less than that in a wettable soil.

The slower infiltration rate in water repellent soils can produce serious erosion problems on steep hillside areas, where a water repellent layer lies below and parallel to the soil surface (e.g., southern California). The soil at or near the surface may be wettable, but a layer of varying thickness below it repels water. This layered arrangement allows incoming rainfall to infiltrate only to a limited depth before the wetting front reaches the water repellent layer.... When the thin mantle above the water repellent layer becomes saturated, water flows laterally and runs off. Soil from this upper layer, along with some from the water repellent layer, is carried away by surface runoff and is an important source of debris from freshly burned foothill areas.

#### Factors Responsible for Water Repellent Soils

Water repellency is a phenomenon occurring at or near the soil surface and is induced by organisms and/or organic chemicals in the soil. Causes of water repellency under natural conditions can be attributed to the coating of soil particles by organic chemicals washed down from foliage or derived from organic matter, a high organic matter content in the surface soil, or a combination of these (Qashu and Evans, 1969). Hydrophobic conditions have been found on forest, chaparral, farmland, and citrus grove soils all over the world.

Where fungi mycelia are responsible in whole or in part for water repellency, a seasonal change in wettability of soil can be expected. Water repellency will be highest during the season in which the fungi has its most rapid growth. The intensity of repellency also will vary with the species of fungi causing the hydrophobic condition (Bond, 1969). Leaf drip, organic material in the soil, and certain species of fungi such as Sarcosphaera ammophila (Bond, 1969) and Agaricus tabularis (Schantz and Piemeisel, 1917) can cause water repellency by coating soil particles and especially sand particles with their small specific surface area with an organic film. The chemical composition of the coating is not known. However, it seems certain the film is neither a wax nor an oil because Jamison (1946), van't Woudt (1959), and Bond (1962) tried unsuccessfully to remove the coating with three good solvents of waxes and oils; ether, methyl alcohol, and ethyl alcohol. Work done by Morris and Natalino (1970) using thin layer chromatography and infrared spectrophotometry have shown that polymerism is present in extracts from manzanita, snowbush, and pine. Individual compounds in the polymers revealed the presence of unsaturated carboxylic acids.

Fire also plays a role in making soils more hydrophobic on chaparral watersheds. According to Debano (1966), a number of chaparral species in southern California produce organic materials which can make soils hydrophobic. Leachate from brush and decomposing plant parts accumulate in the upper part of the soil profile during the years between fires. Before a fire, the transition zone between the litter and

the uppermost mineral soil horizons contains the highest concentration of hydrophobic material. Infiltrating water may carry small amounts of hydrophobic substances down below this region, while more of the hydrophobic substances may remain in undecomposed plant material. Over time, the hydrophobic properties of soil become more pronounced, indicating that hydrophobic substances accumulate.

The hydrophobic intensity depends upon the species of plant growing in the area and the amount of time between fires. The type of vegetation may affect water repellency in several ways. First, plants probably have organic substances which can induce water repellency without being altered by microorganisms. Second, vegetation may affect the type of microbial population present, and thereby cause different degrees of water repellency. For example, fungi decomposition products seem to be an important source of hydrophobic substances in some sandy soils in Australia (Bond, 1969). Vegetation probably alters the effect fire has on water repellency. If large volumes of fuel are consumed during a fire, a more intense fire can be expected for a longer duration than if smaller amounts of fuel are burned. An intense fire would probably produce a more severe water repellency than a less intense fire burning at lower temperatures (Debano, 1966).

During the course of a fire, the chaparral cover and underlying litter may be partially or wholly consumed. According to Countryman (1964), temperatures above the soil surface may become as hot as 2000 F, while the temperatures at the soil surface are less than 1200 F.

Because of the soil's low heat conductivity, the temperature drops rapidly within the soil. Bentley and Fenner (1958) and Sampson (1944) reported the temperatures at two inches below the soil surface to be a maximum of 350 to 550 F. Debano and Krammes (1966) concluded that the temperatures existing at various depths may intensify any incipient water repellency at different depths. More important are the large temperature gradients in the upper few inches of the soil. Debano felt these differences cause vaporized hydrophobic substances to move downward in the soil profile, where they condense on soil particles (Debano, 1969b). After a fire has gone through an area, a distinct water repellent layer exists. Its depth and thickness depend on the kind and amount of plant litter present and upon the intensity of the fire. The water repellent layer may be at or near the soil surface under burning conditions where the surface temperatures were not high. However, the hydrophobic layer could be located in a much deeper layer if the surface temperatures were high (Debano and Krammes, 1966). A significant decrease in the rate of soil wettability and water penetration has been shown to occur following forest fires. This effect has been simulated under laboratory conditions by firing soils treated with an extract of the representative ground cover composed of manzanita, snowbush, and pine species (Morris and Natalino, 1970). Studies by Cory and Morris (1968) have suggested that the organic materials, from which these extracts have been taken, migrate deeper into the soil by diffusion or distillation when subjected to high surface temperatures such as during a forest fire.

Numerous soil physical properties probably influence the degree of water repellency in soils. If particle coating produces water repellency, the amount and nature of the particle surfaces should be important. For a given amount of hydrophobic material, only so much surface could be coated. Clay soils having large specific surface areas would be less completely coated than sandy soils having less surface area. For this reason, coarse textured soils would be expected to be more susceptible to water repellency than finer textured soils. Recent laboratory experiments support this expectation (Debano, 1966).

Other physical properties may also affect the degree of water repellency in a soil. The nature and strength of the charges on the surfaces of individual soil particles probably influence the manner in which hydrophobic organic materials are adsorbed. A host of mineralogical properties could affect water repellency. Little is now known about the role these factors play.

#### Water Repellent Soils--Good or Bad?

In areas of brush covered watershed, water repellency effects are often apparent after wildfires. Depending on the land management objectives, the hydrophobic condition can be considered as having damaged or improved the watershed. For example, the objective of increased water yield would be furthered by an increase in runoff due to hydrophobicity. Conversely, a hydrophobic soil condition would be detrimental to an area subject to excessive erosion, since water flows from non-wettable watersheds often develop into mudflows (Debano, 1969a).

### Wetting Agents

The main use of wetting agents in land management has been in southern California to reduce hydrophobic soil conditions after a wild-fire. By applying a wetting agent with the active ingredient alkyl-polyoxyethylene ethanol, Krammes and Osborn (1969) were able to significantly reduce the erosion and surface runoff from several post-fire study areas in the San Dimas Experimental Forest, the Santa Ana Mountains, and the San Gabriel Mountains. This same study indicated that the use of wetting agents on nonwetable soils may increase both germination and establishment of grass by decreasing the number of seeds that are washed away. Studies by Osborn et al. (1967) and Osborn (1969) showed that an increase in available moisture is also a factor.

The wetting agents used on water repellent soils are of the non-ionic type, as opposed to the anionic and cationic types, for several reasons. Nonionic surface-active agents are relatively unaffected by acids or alkalis with the exception of the esters which are subject to hydrolysis under alkali conditions. These compounds contain a variety of nonionic polar groups capable of being hydrated in an aqueous media. Such polar groups are not as heavily hydrated as ionic groups, giving them several advantages. The nonionic compounds are less affected by strong electrolyte concentrations. The degree of solubilization, important to adsorptive behavior, can be varied with more sensitivity using nonionic compounds (Black, 1969), and nonionic wetting agents are not poisonous to plants.

Several brand name wetting agents are available. The factor which they have in common is that their addition to water results in a solution which has a lower surface tension than the original water. When this solution is placed in contact with a solid, the liquid-solid contact angle may be decreased. A decrease in the liquid surface tension would cause a decrease in infiltration, whereas a decrease in the liquid-solid contact angle would cause an increase in infiltration rate. The effect of a wetting agent solution on infiltration rates depends upon which factor predominates, the decrease in liquid surface tension or the decrease in the liquid-solid contact angle. The effect a wetting agent solution will have on infiltration is dependent upon the water-soil contact angle. If the contact angle is high, a wetting agent solution will penetrate more rapidly than ordinary water. If the contact angle is low, the wetting solution will penetrate more slowly than water. If the surface tension is reduced more than the contact angle (this could happen on wettable soils) then the wetting agent would have the effect of lowering the infiltration rate. The most desirable wetting agent would create a more hydrophobic soil surface and not redissolve into the water to lower its surface tension. This would maintain the high surface tension of water and the contact angle would be made lower, thus creating a greater capillary force (Pelishek, Osborn, and Letey, 1962).

In a personal communication, Dr. Debanò indicated that there are a number of ways that a wetting agent can be applied (April, 1972):

...One way would be to apply the wetting agent either concentrated or diluted with water directly to the soil surface. A

second way would be to make up a powdered form of the wetting agent by adsorbing the concentrated wetting agent on perlite and making a dry powder by dusting this mixture with diatomaceous earth. The powder could then be sprinkled on the soil surface and be allowed to remain there until artificial or natural rainfall occurs....one must apply probably at least 6 gallons of active ingredients per acre and perhaps up to 50 gallons per acre to obtain an observable result. The amount required depends on a number of variables which we have not fully measured but do have some intuitive feelings about. For example, we know that the degree of water repellency can vary considerably between soils. This difference in water repellency will dictate to a certain extent the application rate required to effectively treat the water repellent layer. As yet we do not have a quantitative way of assessing the degree of water repellency and other characteristics of the water repellent layer so we cannot precisely prescribe the right amount of wetting agent....

A pilot watershed test in southern California, using a wetting agent called Emery 3685 with a concentration of 6.6 gallons per acre active ingredients, found the treatment ineffective in controlling post-fire erosion. It was hypothesized that the lateness of winter rains caused the wetting agent to be exposed to the elements for an unusually long period of time, leading to the decomposition and significant reduction in amount of active ingredient (Rice and Osborn, 1970).

Other studies on small infiltration or erosion plots using "WATER-IN", Aqua Gro, Morgan's Thin Water, or Emery 3685, have generally concluded that a wetting agent can increase the infiltration rate and decrease runoff and erosion.

The wetting agent, "WATER-IN", was selected for my study because of its availability and relatively low cost compared to other commercially available surfactants. "WATER-IN" is a liquid wetting agent with a pH of 7 and a specific gravity of about 1.02 at 21 C. The

chemical composition given was Alkyl Polyethylene Glycol Ether, 95% by weight, and inert ingredients, 5% by weight. "WATER-IN" Inc. did not furnish the structural formula or molecular weight of its product. However, after consulting with Dr. Marvel, a University of Arizona organic chemist, an estimated molecular weight of between 561 and 585 and a possible structural formula was arrived at:  $R-(O-CH_2CH_2)_n-OH$  where R is either a 16 or 18 carbon chain and n is either 8 or 9.

#### Measurement of Infiltration

Water infiltration into soils can be measured by several different methods (Pearse and Woolley, 1936; Arend and Knight, 1940; Johnson, 1963). The American Society of Range Management and the Agricultural Board (1962), and publications by Davidson (1940), Wilm (1941), Meyer (1958), and Parr and Bertrand (1960) contain very good discussions on water infiltration.

According to Zwolinski (1966), rainfall simulators (sprinkling-type infiltrometers) have been in use since the latter part of the 1930's. The North Fork infiltrometer, designed and used by Rowe (1940) was one of the first to be utilized. This instrument measured infiltration on a 12-inch by 30-inch plot. Infiltrometers were introduced later that could measure the infiltration of areas up to 6 ft. by 12 ft. Both types of infiltrometers gave satisfactory rainfall application (Wilm, 1943). The North Fork infiltrometer was modified by Dortignac (1951) by replacing the hand pump with a power pump and substituting F-type nozzles for the standard fog nozzles. This modified instrument is now referred to as the Rocky Mountain infiltrometer.

## DESCRIPTION OF STUDY AREA

### Location

The study was conducted in east central Arizona on the Fort Apache Indian Reservation at an elevation of approximately 7600 feet above mean sea level. All three study sites were located within a one-half square mile area,  $5\frac{1}{2}$  miles east of McNary on the south side of State Highway 73, Section 26, Township 8 North, Range 24 East (Fig. 2). The research sites and surrounding region are relatively flat, with an overall exposure to the south and southwest toward the North Fork of the White River.

### Climate

Two factors dominate the climatic conditions of the study area: 1) the patterns of air mass movement during the winter and summer months, and 2) orographic lifting caused by the higher elevations of the Mogollon Plateau and the White Mountains.

Since long term climatological records of the study area were not available, climatological data from the nearest record keeping station, McNary, Arizona, were used. The average annual precipitation for McNary during the period from 1940 to 1970 was 23.30 inches (U. S. Weather Bureau, 1940-1970). Nearly 80% of the precipitation occurs

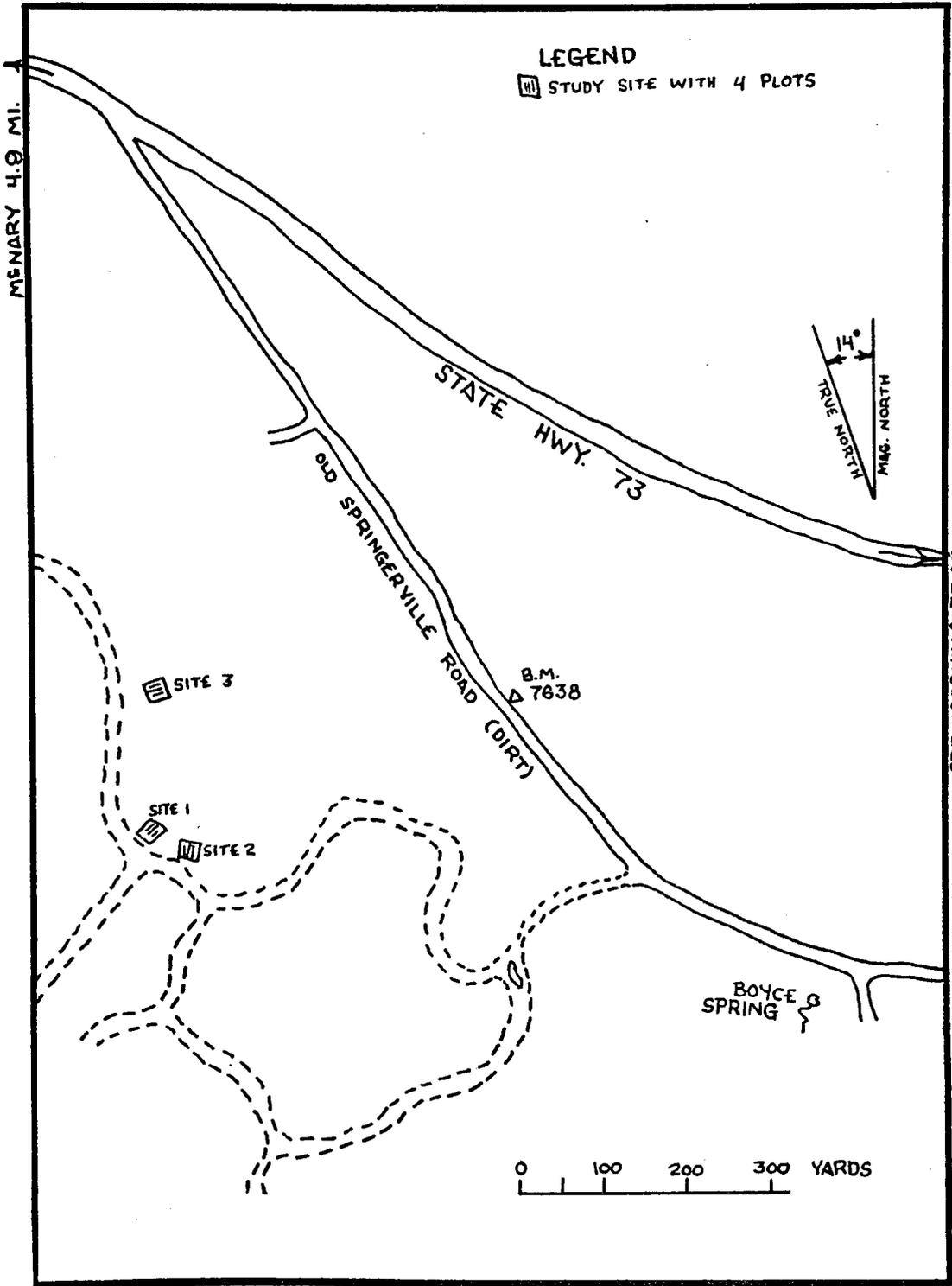


Fig. 2. Map of the study area showing study sites, plots, and roads.

during the three summer months and four winter months (Green and Sellers, 1964). Normally May and June are dry months, and, together, their average total rainfall is approximately 1.25 inches (Zwolinski, 1966). Moist tropical air from the Gulf of Mexico is forced upward by the White Mountains from early July to mid-September. Because of this, afternoon thunderstorms form over the peaks, and moderate to heavy localized showers occur over the entire area. Late in September and early October, the summer convective pattern diminishes. Eastward moving air from the Pacific Ocean gradually replaces moist air from the Gulf of Mexico or Gulf of California. Originating from cyclonic storms in the winter months, widespread precipitation of longer duration than the summer storms occurs. About 80% of the winter precipitation is hail, snow, or sleet, amounting to about 9.4 inches total depth (approximately 9.4 inches water equivalent) for the winter months (Green and Sellers, 1964).

According to Green and Sellers (1964), McNary and the surrounding region is characterized by cold winters and cool summers. Maximum daily temperatures average about 80 F with minimums in the high 40's during the warmest month, July. The coldest month is normally January with minimum daily temperatures around 16 F, and average maximums of 44 F. The mean temperature is 46.5 F in summer and 27 F in winter. Temperatures during the summer rarely exceed 90 F, and temperatures below 0 F occur several times during the winter.

### Soils

Soils in this region are derived from a mixture of basalt slag and volcanic cinders under ponderosa pine vegetation and are silt loam in texture. The soils in the study area belong to the Western Brown Forest Soils. Buol (1965) recognized several local soil series which belong to this great soil group. The Siesta and Broliar series are fine textured soils found on basalt; the Sizer series consist of gravelly textured soils which form on deep beds of volcanic cinders; and the Sponseller series is made up of moderately fine textured soils developed from volcanic cinders and ash over basalt.

Examination of exposed soil profiles in the study area by the soil survey team and University of Arizona soil specialists led to a tentative classification in the Sponseller series with some gradation into the Broliar series.

The Sponseller series is a member of a fine loamy, mixed, frigid family of Andic Argiborolls. These soils are deep to moderately deep with light clay loam or heavy loam B horizons, an A, B, C-R horizon sequence, and are well drained (Zwolinski, 1966).

The Sponseller series prevails on gently sloping to steep side slopes of cinder cones and basalt flows in the ponderosa pine region of New Mexico and Northern Arizona. These soils occur at elevations from 7000 to 8400 feet above mean sea level where average annual precipitation ranges from 20 to 28 inches and the mean annual temperature is about 40 to 45 F (Zwolinski, 1966).

### Vegetation

The most prevalent tree species occurring in the study area is ponderosa pine. Cooper (1961, p. 493) described this area as having "a mosaic of even-aged groups, averaging about one-fifth acre in size." In the study area, the average stocking density was 1350 trees per acre with a total basal area of about 134 square feet per acre. An over mature tree in the 30 or 40-inch class was encountered occasionally, but in general the diameters at breast height ranged from 0.75 to 27 inches. Tree heights ranged from 18 to 63 feet with an average height of about 39 feet. According to Zwolinski (1966, p. 70) the "stand age was quite variable due to the prevalence of small even-aged groups. The majority of trees occupied the 40 to 80-year age class."

Numerous genera of ground cover vegetation were found in the study area. Kentucky blue grass (Poa pratensis L.) and Arizona fescue (Festuca arizonica Vasey) were the two grass species found. In the open pine stands, bracken fern (Pteridium aquilinum L.) was common. Several sedges (Carex spp.) were identified. Strawberry (Fragaria ovalis (Lehm.) Rydb.), beard-tongue (Penstemon spp.), evening primrose (Oenothera hartwegii Benth.), thistle (Cirsium grahami Gray), and wild daisy (Erigeron divergens Torr. and Gray) were the forbs identified. Additional forbs reported by Zwolinski (1966) are cranesbill (Geranium spp.), pseudocymopterus (Pseudocymopterus montanus (Gray) Coult. and Rose), mullein (Verbascum thapsus L.), wormwood (Artemisia ludoviciana Nutt.), and groundsel (Senecio neomexicanus Gray, S. wootonii Greene,

S. actinella Greene). Mace (1962) reported the following additional forbs and grasses: squirrel tail (Sitanion hystrix Nutt.), wild carrot (Lomatium dissectum (Nutt.) Mathias and Constance), muhly (Muhlenbergia virescens (H. B. K.) Kunth.), and aster (Aster commutatus (Torr. and Gray) Gray).

#### Land Use

Currently the study area is being used for some cattle grazing and experimental forestry research. Fire has swept the area periodically over the years, the most recent being a prescribed burn in 1956 and a small wildfire within the last two years. In addition to grazing by cattle and occasional horses, the area is inhabited by deer, porcupine, squirrels, rabbits, turkey, and various birds.

## EXPERIMENTAL DESIGN, TREATMENTS, METHODS, AND PROCEDURES

### Experimental Design and Site Selection

The study was designed to evaluate the influence of "WATER-IN" on water infiltration rates. Three sites were selected and each received Treatment 1 and Treatment 2. In addition, Site 3 received Treatments 3 and 4. Each site had three treated plots and one control plot.

The selection of study sites was based on several criteria. One of the first requirements was to ensure that all sites would be accessible enough to bring in a pickup truck loaded with 200 gallons of water. Another criterion for site selection was to choose sites that were representative of the vegetation and soil conditions normally found in the ponderosa pine region of east central Arizona. The last criterion required that the site had a minimum slope of 5% and had not been disturbed by man (i.e., logging, thinning, control burning) within the five years preceding the study. The twelve plots were placed on slopes ranging from 7 to 11%. Sites 1 and 2 were established within 20 yards of each other under a stand of ponderosa pine. Site 3 was located about one-eighth mile away under a mature stand of ponderosa pine (Fig. 2).

### Field Procedures

A modified North Fork type sprinkling infiltrometer was chosen because of its reliability and adaptability to this study. Specifications for all the plot equipment are given by Rowe (1940).

The actual field installation of the plot equipment required extreme care to avoid any disturbance within the plot. The method of plot construction and field installation was the same as described by Zwolinski (1966). The constant head tank used was also described by Zwolinski (1966, 1969).

On each site, one of the four infiltration plots was designated as a control and the other three were treated after calibration with a 10 gallon per acre active ingredient concentration of "WATER-IN", the wetting agent used in this study. Treatment will be discussed in more detail in the section headed "Infiltration Runs and Treatments."

#### Measurements Made Before and After Treatment

Sites. Comparisons between sites were made by taking certain measurements and soil samples from each of the three sites.

1. Surface litter characteristics were determined by measuring litter bulk densities and depth at two locations within 2 feet of either side of each plot. The L (litter), F (fermentation), and H (humus) layers were separated for each sample. Litter bulk densities were determined using the same method and equipment as Zwolinski (1966, p.88):

A 4-inch diameter hole in the center of a CN-980 Soiltest Volumeasure density plate was used as a cutting guide. After selecting a litter sample site, the plate was placed on the litter and a sharp knife used to make a vertical cut around the hole to mineral soil. The litter was then removed from the hole by L, F, and H layers and placed in respective soil cans. After all litter was removed down to mineral soil, total litter depth and the depth of each layer was measured at five different locations within the hole. Bulk densities were then calculated for each layer, and for the entire depth by dividing the oven-dry<sup>1</sup> weight of the litter by the volume it occupied.

2. Duplicate soil bulk density samples were taken before and after each treatment to 0 to 1-inch and 5 to 7-inch depths from two locations within the wetted area outside each infiltration plot using a bulk density sampler described by Zwolinski and Rowe (1966). Bulk density samples were all taken when the soils were very near or at field capacity as suggested by Reinhart (1954). For each bulk density calculation, volume and weight of rock (soil particles greater than 2 mm in diameter) were subtracted from the original readings so that all measurements could be based on rock-free soil (Zwolinski, 1966; Smith, 1962). Volume of rock was determined by water displacement. The bulk density of the rock-free soil was calculated by:

$$\text{Bulk Density} = \frac{\text{weight of rock-free oven-dried soils (g)}}{\text{volume of soil minus volume of rock (cc)}}$$

- 
1. The oven temperature was 70 C. The length of drying time varied from 24 to 72 hours depending on the water content of the particular litter layer.

3. Duplicate soil samples were collected from the same locations and depths used for soil bulk density samples. Textural analyses were made on these samples in the laboratory.

Treatment Plots. Several samples were taken from the immediate area of the infiltration plots to determine the influence the wetting agent "WATER-IN" had on certain soil properties.

1. Samples of the surface one inch of soil were collected before and after treatment. These samples were analyzed for pH and texture.
2. Four bulk density samples of the surface one inch of soil were taken from within the infiltration plot to determine the effect the wetting agent had on soil bulk density.

#### Infiltration Runs and Treatments

Treatment 1 was used on all three sites and served to calibrate the infiltration plots. This treatment consisted of spraying 100 ml of distilled water on each of the three treated plots on each site and allowing to dry for 24 hours. Four consecutive infiltration runs were then made, one a day, on each of the treated plots and corresponding control. Four runs of about an hour duration were found to be sufficient to bring the soil up to field capacity as evidenced by very similar infiltration curves on the last two runs of each plot.

Treatment 2 consisted of spraying a solution of "WATER-IN", which had a concentration of 10 gallons of active ingredients per acre (2.28 ml of "WATER-IN" and 97.72 ml of distilled water), onto each of

the treated plots and allowing the plots to dry for 24 hours. As with Treatment 1, this second treatment was applied to a total of nine plots, three on each site. Four consecutive infiltration runs were made using the same procedure as for Treatment 1 above.

Treatments 3 and 4 were used only on site 3. Treatment 3 was removal of all litter from the three treated plots and the spraying of the bare mineral soil with 100 ml of distilled water, allowing 24 hours for drying (the control plot was left undisturbed). Two consecutive infiltration runs were made, one a day, on each of the plots including the control. Treatment 4 consisted of spraying "WATER-IN" directly onto the bare soil of the plots in the same concentration as Treatment 2. Two consecutive infiltration runs were made, one a day, after the 24-hour drying period.

An ordinary garden bug sprayer was used to apply the wetting agent and distilled water. A tent covering the plot prevented any wind disturbance. Before the start of each infiltration run, antecedent soil moisture was determined gravimetrically to a depth of six inches. The exact procedures for the infiltration runs were described by Zwolinski (1966, pp. 101,103):

The intensity of applied "rainfall" was...measured by placing a calibration pan over the infiltration plot. The trough cover was adjusted so that the rainfall collection area was 12 by 30 inches, horizontal distance. A piece of plastic protected the area surrounding the plot from being wetted during the calibration period.... During the actual infiltration run, this plastic was removed to allow a  $1\frac{1}{2}$  to 2 foot wetted buffer zone around the plot. A windbreaker tent was placed over the plot and surrounding areas during the run to minimize any wind disturbance to rainfall....

Water was pumped into the elevated constant head tank until overflow was obtained. The sprinkler assembly was then turned on and runoff from the calibration pan allowed to stabilize. Rainfall amounts were determined by collecting and measuring runoff from the pan for  $2\frac{1}{2}$  or 5 minute intervals depending on intensity. After calibration the sprinklers were shut off and the calibration pan and plastic sheet removed. The trough cover was replaced on the plot and adjusted to its correct position and the infiltration run started. Surface runoff was collected in cans and measured at 30-second intervals during the early stages of the run. As the runoff became constant the readings were extended to 1, 2, 3, and 5-minute periods. Water temperatures were taken during each run. After surface runoff had remained constant for at least 20 minutes, it was assumed that infiltration capacity had been reached, and the sprinklers were turned off.... Immediately after terminating the infiltration run, another rainfall calibration run was made and compared with the initial calibration....

The infiltrometer sprinkler assembly, windbreaker tent, and calibration pan were moved from plot to plot. Infiltration runs were made on all...infiltration plots on a site before the tank, pumping equipment, and water supply had to be moved to the next site.

To determine if there were any effects on the bulk density and water holding capacity of litter due to "WATER-IN", a 5-ft by 5-ft test plot was situated on each site. The test plot was divided into 25 sub-plots, one square foot each (Fig. 3). Quadrants I and III were each sprayed with 160 ml of distilled water and quadrants II and IV were each sprayed with 160 ml of "WATER-IN" solution<sup>2</sup> equivalent to 10 gallons of active ingredient per surface acre (3.65 ml of "WATER-IN" and 156.35 ml of distilled water). A buffer zone was left between the quadrants. After allowing 24 hours for the wetting agent to dry, the test

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2. An application rate of 10 gallons active ingredients per acre was used. On treated infiltration plots 100 ml was sprayed on 2.5 square feet of plot surface. Therefore, 4.0 square feet of test plot area required 160 ml.

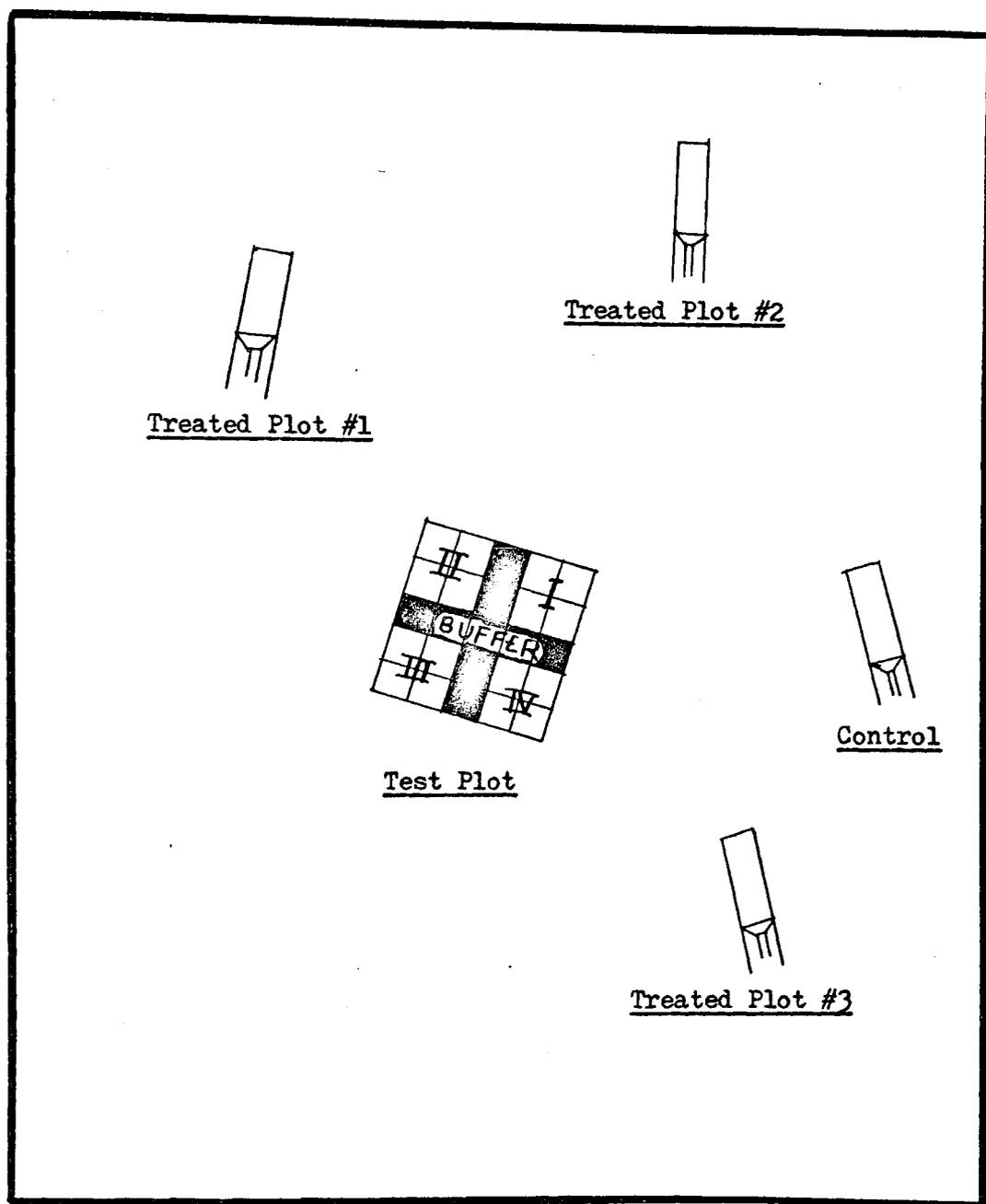


Fig. 3. Typical site showing the random locations of the three treated infiltration plots and control along with the 5 x 5 foot test plot for water holding capacity and bulk density of litter.

plot was sprayed using the infiltrometer rainfall applicator for two hours, moving the apparatus around 90 degrees counterclockwise every 15 minutes to insure even wetting of the litter. The litter was allowed to drain for 24 hours. Then the litter on each subplot was removed layer by layer (taking note first of the thickness of the layer) and placed in previously weighed plastic bags and sealed to hold in the moisture. The wet weight was determined by weighing, and the litter was allowed to oven-dry to a constant weight at 70 C. The moisture holding capacity and bulk density of the litter layers were determined.

#### Final Site Measurements

As the study of each site was completed, the infiltration plots were dismantled. Measurements were made on each plot to determine litter accumulation, litter depth of each layer, and the percentage of surface rock. The soil was examined for any unusual surface condition such as worm or ant holes or cracks, and for any subsurface characteristic such as root channels which may have influenced infiltration capacities and rates. No such unusual conditions were found. Bulk density samples of the surface inch of soil were taken along with soil samples for the same physical and chemical analyses made at the beginning of the study.

#### Laboratory Methods For Soil Analysis

Soil samples were air dried in the laboratory and passed through a 2 mm sieve before undergoing analysis. Laboratory procedures

used were as follows:

1. Gravimetric soil moisture percentages--weighing, drying to constant weight at 105 C, and reweighing.
2. Soil pH--Beckman Zeromatic pH meter on a 1:1, soil to water, paste.
3. Particle size distribution--Day's modification of the Bouyoucos hydrometer method. Soil samples were placed in a mixing cup with 50 ml of 20% "Calgon" (sodium metaphosphate) and 200 ml of distilled water. This mixture was then agitated by a standard mixer for five minutes to accomplish soil dispersion (Youngberg, 1957; Day, 1956, 1965).

## RESULTS AND DISCUSSION

Results will be presented and discussed in three sections: 1) changes in infiltration capacities following the application of "WATER-IN", 2) effects of "WATER-IN" on ponderosa pine litter, and 3) effects of "WATER-IN" on some soil properties.

### Changes in Infiltration Capacities Following Treatments

Data from each infiltration run were analysed by a CDC 6400 computer system, programmed to convert all "rainfall" and runoff readings to inches per hour and to determine infiltration rates (rainfall minus runoff) for each time interval. Curves of infiltration over time were plotted from the information computed by the program. All infiltration capacity curves stabilized and remained nearly constant during the final 20 to 30 minutes of the run. An infiltration capacity value was determined for each curve by extrapolating the constant portion of the curve back to the ordinate. Some runs were allowed to continue an additional hour to determine if these constant rates would vary over a longer period of time. No differences were observed in final infiltration capacities at the end of this extended period when compared with the rate after one hour.

The mean final infiltration capacity for the last two runs of each treatment are presented in Fig. 4. The conclusions stated on the following pages were reached primarily by the use of a three factor analysis of variance (Table 1) and Duncan's multiple-range test.

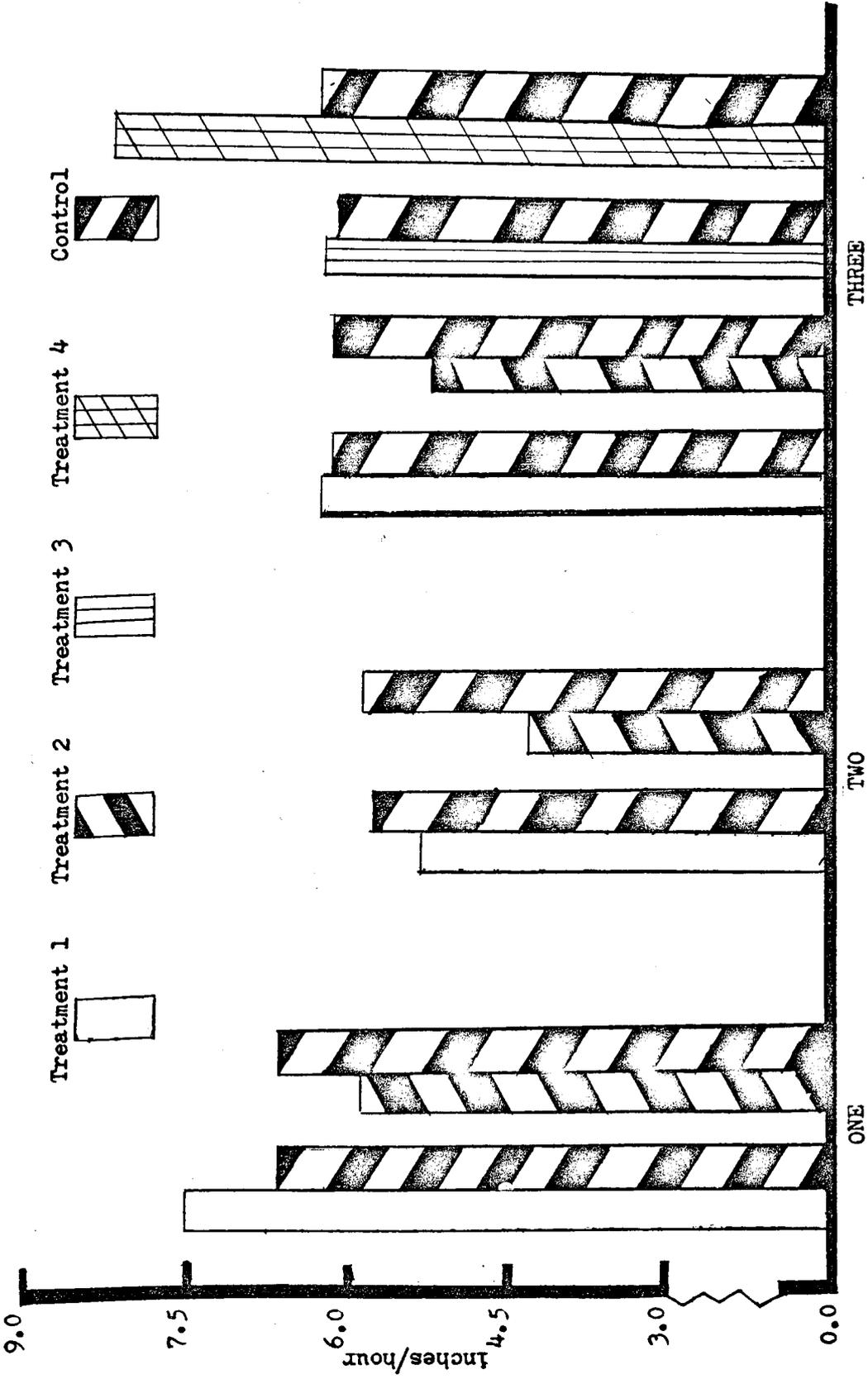


Fig. 4. Mean final infiltration rates for treatments and control plots for three sites.

TABLE 1. Three-factor analysis of variance for infiltration capacities.

Source of Variation	Degrees of Freedom	Mean Squares
Blocks (Sites) (B)	2	11.32*
Error A	6	1.22
Plots (P)	2	
PB	4	
Treatment (T)	1	13.87**
TB	2	0.27
Error B	6	0.23
PT	2	
PBT	4	
Error C	18	0.0005
Samples (S)	1	
(Last two runs of each treatment)		
BS	2	
PBS	4	
PS	2	
ST	1	
BST	2	
PBST	4	
PST	2	
Total	35	

\*Significant at the .025 level.

\*\*Significant at the .01 level.

Treatment 1, consisting of an application of 100 ml of distilled water to the three treatment plots on each site, served as a calibration for subsequent infiltration runs. Plots were undisturbed with litter and soil intact. Runs 3 and 4 on each plot showed consistent infiltration capacities. The mean infiltration rate for all sites with this treatment was 6.27 inches of water per hour.

The application of 100 ml of "WATER-IN" solution (rate of 10 gallons per acre active ingredients) on each treatment plot on each site, in a manner similar to and under the same litter and soil conditions as Treatment 1, comprised Treatment 2. This treatment caused a significant increase in the amount of runoff from each treated plot. The mean apparent infiltration rate after Treatment 2 over all three sites was 5.03 inches per hour.

Treatment 3 involved the removal of all litter from the three treatment plots on Site 3 and the spraying of 100 ml of distilled water on the exposed mineral soil within the treatment plots. This treatment resulted in a mean infiltration rate of 6.13 inches of water per hour. This value is not significantly different from the mean infiltration value of 6.16 inches per hour for the plots receiving Treatment 1 on Site 3.

Treatment 4 consisted of an application of 100 ml of "WATER-IN" solution in the same concentration as used for Treatment 2 to the bare soil of the three treatment plots on Site 3. This treatment increased the final infiltration rate to a mean of 8.09 inches of water per hour.

For a given site, the control plot infiltration rate was constant from one treatment to the next. Figure 4 illustrates this as well as showing the relative effects of each treatment on infiltration.

When comparing the final infiltration rates following Treatments 1 and 3, it appears that raindrop impact was negligible on bare mineral soil. Whether the negligibility of raindrop impact was due to the small size of the water droplets, the failure of the droplets to reach terminal velocity, or an effect of the wetting agent is not clear.

The increase in the final infiltration rate caused by "WATER-IN" applied to bare soil (Treatment 4) can be attributed to a decrease in the soil bulk density, an increase in the total soil porosity (Table 2) for the surface one-inch of soil, and possibly a reduction of the soil-water contact angle. It follows that a decrease in soil bulk density should result in an increase in total porosity, but how the bulk density is decreased is not known at this time.

Treatment 3 resulted in an increase in the final infiltration rate compared to Treatment 2 possibly because of the removal of the litter which seems to channel off a significant proportion of the "rainfall" before it can reach the soil.

There was no fungi mycelia growth to account for the reduction in infiltration rate with Treatment 2. Treatments 3 and 4 suggest that "WATER-IN" reacts upon the litter or is acted upon by the litter, probably in the H layer, creating a hydrophobic condition. How the hydrophobic condition is created is not known. Several possibilities exist:

TABLE 2. Summary of some physical properties of the surface inch of soil for each treatment and each site.

Site	Treatment	Field Capacity	Particle Size Distribution*			Bulk Density*	Total Porosity**
			Sand	Silt	Clay		
----- Per Cent -----							
1	1	38.07	26.35	56.52	17.13	1.124	57.57
	2	38.41	27.56	56.06	16.38	1.128	57.43
2	1	47.81	24.40	64.23	11.37	1.088	58.94
	2	47.94	23.83	65.87	10.30	1.087	58.98
3	1	45.53	39.77	51.92	8.31	1.167	55.96
	2	---	---	---	---	---	---
	3	---	---	---	---	---	---
	4	45.68	40.27	52.47	7.26	1.049***	60.42***

\*Average of all three treated plots.

\*\*Calculated from  $S_t = 100((d_p - d_b)/d_p)$  where  $d_p = 2.650$  gm/cc and  $d_b =$  bulk density of the soil in question.

\*\*\*Statistically significant difference at the .05 level between Treatment 1, Site 3 and Treatment 4, Site 3.

- 1) A chemical reaction in the wettable litter may destroy the effectiveness of the wetting agent. Since the litter material was initially wettable, it is possible that the wetting agent was adsorbed on the litter in such a fashion that it made the litter water repellent. Chemically, the nonionic wetting agents have a wettable (polar) group at one end and a hydrophobic (hydrocarbon) chain at the other. When added to a hydrophobic material, the hydrocarbon end of the wetting agent tends to be adsorbed onto the surface leaving the hydrophilic end in contact with water. Hence, good wetting properties are imparted to the water repellent substances. However, when the wetting agent is placed on a wettable surface, it is possible for the wettable end of the wetting agent to be adsorbed by the wettable surface leaving the hydrophobic end exposed to the water. This type of adsorption can leave a formerly wettable material water repellent.
- 2) The dissolution of hydrophobic resins from the top litter layers may be redeposited in the H layer with its finer texture and more chemically active surfaces.
- 3) The reduction by "WATER-IN" of the surface tension of the water passing through the litter makes it easier for the water to run off rather than infiltrate.

The interval between the start of rainfall application and the appearance of surface runoff is affected by the amount of surface litter. In general, the greater the amount of litter, the longer the

period before runoff occurs. This is due to the water storage capacity of litter which must be satisfied before surface runoff can occur. The importance of the water storage capacity of litter can be shown by a simple example. Using the average depth of litter as 2.81 inches, litter bulk density as .119 gm/cc, and a water holding capacity of 170% (Lowdermilk, 1930; Bodman, 1935) the amount of water needed to satisfy litter storage requirements is:

$$\frac{0.119 \text{ g/cc}}{1.000 \text{ g/cc}} \times 2.81 \text{ inches} \times 1.70 = 0.57 \text{ inches}$$

This indicates that surface runoff is delayed until more than half an inch of rain has been absorbed by the litter. Therefore many rainstorms fail to wet the surface soil. It would be beneficial if a wetting agent could be found that could reduce the storage capacity of the litter thus increasing substantially the amount of water entering the soil.

#### The Effects of "WATER-IN" on Ponderosa Pine Litter

From the 5-ft by 5-ft test plots, it was learned that the litter bulk density and water holding capacity were not affected by the application of "WATER-IN". However, there are significant differences within sites and between sites that are not attributable to "WATER-IN". These differences are in the litter bulk density, litter thickness, and water holding capacities of the L, F, and H litter layers, and are summarized in Table 3.

TABLE 3. Water holding capacity, thickness, and bulk density with respective standard deviations of litter on treated infiltration plots.

Site	Layer	Water Holding Capacity (Inches of Water x 10 <sup>-2</sup> per inch of litter)	Thickness (cm)	Bulk Density (g/cc)
1	L	0.389 ± .032	1.45 ± .04	0.0943 ± .0025
	F	1.118 ± .010	3.23 ± .04	0.1553 ± .0010
	H	7.881 ± .604	2.94 ± .04	0.1553 ± .0223
2	L	0.353 ± .009	0.83 ± .04	0.0907 ± .0021
	F	1.123 ± .001	3.07 ± .23	0.1137 ± .0006
	H	8.174 ± .898	2.84 ± .24	0.1650 ± .0290
3	L	0.329 ± .013	0.64 ± .02	0.0867 ± .0015
	F	1.083 ± .052	3.17 ± .24	0.1037 ± .0035
	H	8.340 ± .805	3.03 ± .18	0.1553 ± .0061
Over All Sites	L	0.357 ± .034	0.97 ± .37	0.0905 ± .0038
	F	1.108 ± .032	3.16 ± .21	0.1074 ± .0051
	H	8.131 ± .704	2.93 ± .68	0.1586 ± .0192

Effects of "WATER-IN" on Some Soil Properties

Results obtained on some moisture and physical properties of the surface inch of soil before and immediately after treatments are summarized in Table 2. Treatments 1, 2, and 3 had no significant effect on the antecedent moisture, the soil particle size distribution, the bulk density, or the total soil porosity in the surface inch and 5 to 7 inch depth of soil. Treatment 4 did not significantly change the antecedent moisture or the soil particle distribution but did significantly decrease the bulk density of the surface inch of soil and significantly increased the total porosity. Duncan's multiple range test (Steel and Torrie, 1960) was used to reach the above conclusions. Since soil bulk density samples were taken from outside each infiltration plot before and after each treatment, and there was no significant difference from the first samples to the last, it is indicated that Treatment 4 decreased the soil bulk density, and that the difference in bulk densities inside and outside the plot is not due to compaction when unavoidably stepping around the outside of the plots. The decrease in soil bulk density and hence the increase in total porosity due to Treatment 4 may be responsible for the increase in water intake observed on all plots having received Treatment 4. It is impossible at this time, due to lack of knowledge, to explain how "WATER-IN" decreased the soil bulk density.

## SUMMARY AND CONCLUSIONS

### Summary

An infiltration-wetting agent study conducted in the ponderosa pine forest type of east central Arizona gave the following results:

- 1) The application of "WATER-IN" at the rate of 10 gallons per surface acre to ponderosa pine litter significantly increased runoff.
- 2) The application of "WATER-IN" at the rate of 10 gallons per surface acre to bare mineral soil significantly increased the infiltration capacity from an average of 6.16 inches of water per hour to 8.09 inches of water per hour.
- 3) The application of "WATER-IN" to bare mineral soil significantly decreased the average bulk density of the surface inch of soil from 1.167 g/cc to 1.049 g/cc and increased the total porosity from 55.96% to 60.42%.
- 4) The average soil pH was about 5.8. The pH was not significantly affected by "WATER-IN".
- 5) Antecedent moisture and soil particle distribution were not affected significantly by "WATER-IN".
- 6) The water holding capacity and bulk density of ponderosa pine litter were not significantly affected by "WATER-IN".

### Conclusions

On the basis of the results obtained from this study, the following conclusions can be made:

- 1) "WATER-IN", at least in the concentration and method of application used, increases runoff when applied to the litter. If the management objective were to decrease runoff, hence increase the infiltration rate, it would be necessary to remove all or part of the litter. The method of removal could be mechanical or a prescribed burn.
- 2) Except for the decrease in soil bulk density when "WATER-IN" was applied directly to the soil, changes in the physical properties of this area were negligible.
- 3) It is not known whether "WATER-IN" caused any chemical changes to the soil or litter.
- 4) "WATER-IN" does not affect the bulk density or water holding capacity of ponderosa pine litter.
- 5) How "WATER-IN", when applied directly to bare mineral soil, decreases the soil bulk density of the surface inch is not known.
- 6) Why and how "WATER-In" causes increased runoff when applied to litter and an increased infiltration capacity when applied to bare soil is not known. Further study of this phenomenon is needed.

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