IMPROVING WATER PROPERTIES TO INCREASE INFILTRATION CHARACTERISTICS

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ABSTRACT

Water properties, such as the viscosity and surface tension, can be affected by temperature and surfactants to increase infiltration rates into soils. Specifically, they will change the hydraulic conductivity of the soil. A simple soap solution and the new material PAM (inexpensive polymer chemical) were evaluated as surfactants. Laboratory experiments and field tests on a site in Davis, California were done to quantify the effects of changing the water properties. Additional effects, like the improved soil structure during infiltration and less soil particles in tailwater (reduced erosion due to runoff) were observed and are described in this paper. The conclusions of this study are translated into suggestions for improved on-farm water use in furrows, sprinklers, and drip irrigation.

INTRODUCTION

Infiltration is an important factor in irrigated agriculture in California. It is an intriguing subject: Infiltration depends on the porous media characteristics and on the properties of the fluids that saturates the media. Soil structure, furrow spacing, compaction, surface sealing, tillage and water quality are some of the factors that modify the infiltration rate of soils. Many studies had been developed to determine the influence of some of these parameter on the infiltration rate. Most of the literature refers to soil characteristics and very few

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to the properties of the fluid used to irrigate. Grismer (1986) analyzed the effect of the pores size distribution of the soil over infiltration. Grismer (1994) also studied the effect of air compression and counterflow on infiltration into soils.

Fluid properties are not always studied in relation to infiltration, other than empirically (salt concentration effect on infiltration, adding surfactants). The studies on fluid properties focus on viscosity changes due to temperature effect (Dane and Hopmans, Duke, 1992) and the effect of surfactants on surface tension and density. Viscosity and density are both directly related to the hydraulic conductivity. The surface tension only has an effect on the infiltration as a result of air water interfaces.

This project intends to measure the impact of surfactants by evaluating the change in surface tension, density, and viscosity. In order to evaluate this effect, an optimum concentration of surfactants should be determined. This concentration should maximize the effect of adding a surfactant without reaching a point of diminishing return. We also present the effect of changing the temperature of irrigation water.

EQUATIONS (THEORY)

The following aspects make infiltration an intriguing subject:

- Infiltration rates vary during an irrigation.
- Many design strategies proposed for surface irrigation require knowledge of the precise mathematical constants in advance and infiltration equations.
- Each soil has different infiltration characteristics.
- Infiltration can vary with subsequent irrigations of the same field.
- Laboratory determinations of mathematical constants for the infiltration rates are not the same as unadjusted field results.

- Infiltration rates have traditionally been very difficult to evaluate in the field.

Field Measurement Equations. Several formulas have been developed to describe the advance and infiltration rates as a function of time. The most common form of the depth infiltrated equation is:

$$D = Kt^n \tag{1}$$

where,

D = the depth infiltrated (usually in. or cm.)
K = a constant
n = a constant
Both K and n are soil dependent
T = the opportunity time in minutes

If the constants (K and n) can be determined for a soil and irrigation configuration for a particular event, one can calculate the depth infiltrated at any point if the opportunity time at that point is known. By differentiating the cumulative intake, the equation for an instantaneous intake rate can be determined.

The basic form of the infiltration equation is:

$$I = nC\ T^{n-1} \tag{2}$$

where,

I = Instantaneous intake rate at a point
nC = constants
T = Opportunity time at the point

The constants "nC" in the equation must be determined for every irrigation. On the same soil with the same moisture content, the nC values for furrows will be different than for border strips. There is no reliable and transferable table of nC values available for different soils under furrow, border strip, etc. Figure 1 shows the general relationship of the intake rate for different soil types.

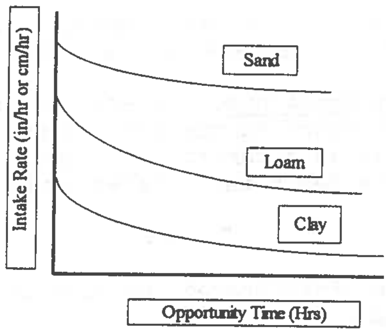

Fig. 1. Hypothetical Relation of Intake Rate to Time for Three Soils. Assumes the Same Percentage of Flooded Soil Surface Area for All Three Soils.

Laboratory Measurement Equations

The basic equation for flow through porous media is given by Darcy (19xx) as:

$$q = -K_{sat} * \frac{\partial H}{\partial L} \tag{3}$$

where,

- q = flux
- K_{sat} = saturated hydraulic conductivity
- H = hydrostatic and elevation potential
- L = length over which H occurs

Darcy showed this equation to be true for saturated flow, but it has also been shown that the relation is valid for unsaturated flow, when the unsaturated hydraulic conductvity is used.

The hydraulic conductivity is affected by fluid properties as well as the properties of the porous medium. Poiseuille (19xx) created the following relation:

$$K_{sat} = \frac{k * \rho * g}{\eta} \tag{4}$$

where,

- k = instrinsic hydraulic permeability
- ρ = density of the fluid

g = gravimetric constant
η = kinematic viscosity of the fluid

Using the properties of water, it can be seen that the hydraulic conductivity is also temperature dependent, since the kinematic viscosity of water changes significantly with temperature. Jaynes (1990) combined the temperature dependent kinematic viscosity with the Darcy equation for unsaturated flow, which resulted in:

$$q(T) = -\frac{\eta_r}{\eta_T} * K_r(h) * \frac{\partial H}{\partial L} \quad (5)$$

where,

η_r = kinematic visc. of the fluid at 21 degrees C
η_T = kinematic visc. of the fluid at temperature T
$K_r(h)$ = unsaturated hydraulic conductivity

Warm water has a lower viscosity than cold water. Equation 5 shows that the ratio of the kinematic viscosity will increase with temperature, resulting in a larger flux through a porous medium. Water with different concentrations of PAM have higher viscosities than water without PAM added. Equation 4 shows that the hydraulic conductivity for fluids with higher viscosities will be lower, hence resulting from equation 3 in a reduced flow through porous media. A surfactant like soap added to water will not change the viscosity significantly, nor the density of water. The only fluid property that changes is the surface tension. The surface tension of a fluid only affects the entry pressure, as shown in Equation 6:

$$h = \frac{2\sigma \cos\alpha}{g} \quad (6)$$

where,

h = air entry pressure
σ = surface tension of a fluid
α = angle of contact between fluid and solid, (cosα is normally assumed to be 0 in small capillary tubes)
g = gravimetric constant

In the soil water retention curve, the air entry pressure is the pressure when the soil will actually release water when the absolute hydraulic pressure is larger then air entry pressure (see Fig. 2).

Lowering the air entry pressure on a saturated soil with a small negative hydraulic head by adding a surfactant would result in the release of water, and the curve in Fig. 2 would shift down. For infiltration in a dry soil with a high soil matric potential this would not make much difference. However, on a molecular level, water with a low surface tension would be able to access smaller pores, hence wetting the soil more thoroughly and increasing the actual soil moisture content (θ), resulting in a hydraulic conductivity that more closely represents the saturated hydraulic conductivity. A higher hydraulic conductivity will result in a higher flux through the soil.

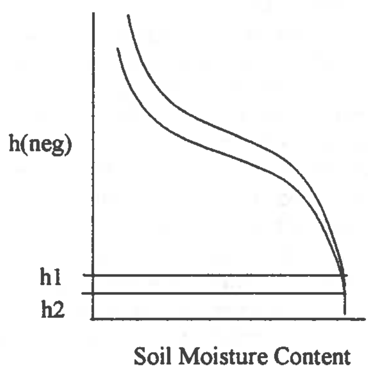

Fig. 2. Theoretical Soil Moisture Retention Curve (Upper Curve) and Lowered Air Entry Pressure (Lower Curve)

LABORATORY TESTING RESULTS

Constant Head Flow Hydraulic Conductivity

Several columns of 10 cm length by 5 cm of diameter were careful packed and filled with the experimental soil (fine sand) in such a way that the density of the soil is similar over the whole length of the experimental column. These columns of soils were setup to measure the hydraulic conductivity for a constant head. From this system the difference in distance between the bottom where water flows out and the top where water is open to the atmosphere is measure in order to determine the total head over the soil column.

Constant head flow experiments were performed for each one of the fluids chosen previously. For each different fluid we used a newly created soil column, so that residual PAM or soap did not influence the other measurements. The soil column was rinsed with each fluid several times to ensure a saturated flow. The volume of fluid over time was measured to calculate the saturated hydraulic conductivity. Four fluids were used: di-water at room temperature, PAM with a concentration of 10 mg/l, PAM with a concentration 1000 mg/l and a soap solution with a concentration of 4 ml/l.

Saturated Hydraulic Conductivity

Results from this experiment showed that the saturated hydraulic conductivity for soapy water was slightly lower than for distilled water. The low concentration PAM showed even a slightly lower saturated hydraulic conductivity. However, the variability of the measurements was high, and differences might not be significant. It is no surprise that there is not a large difference between distilled water and soapy water, since the surface tension is the main difference between the two types of water, and the surface tension does not have any effect on the flow of water through saturated soil. The high concentration PAM, of which the results are not shown, formed a gel-like layer on top of the soil column and did not allow for any water to infiltrate. This might explain why the low concentration PAM shows a slightly lower saturated hydraulic conductivity than the other two fluids. Since PAM keeps the structure of a soil in the field, it is not expected to have a large effect on the infiltration in a sifted soil without much structure.

Water	***Average K_{sat} [cm/hr]***
Distilled Water	5.46E-05
Soapy Water	3.81E-05
10 mg/l PAM	1.94E-05

Unsaturated Hydraulic Conductivity

A constant head device was connected to one side of a horizontal soil column according to the method described by Bruce and Klute (19xx). A positive head equal to half the diameter of the soil column was applied. The soil column was packed to a constant density using sifted soil (Yolo Sandy Loam). Two different fluids were allowed to infiltrate in the unsaturated soil column for three hours. The soil column was then divided into slices of 1 cm wide, and of each slice, the water content was determined. Using an empirical equation [add equation?] a regression line was created. Using this equation, the diffusivity was obtained according to the method described by Bruce and Klute(19xx). Results for a trial using tap water and a trial using soapy water are shown in Fig. 3.

The results indicate that, although the surface tension does not occur in the Darcy equation, that this is a parameter that affects the infiltration of water in a soil. With a reduced surface tension in the soapy water, advance of the water front is faster, but wetting is not as thorough as the tap water trial showed. The faster advance of the soapy water is explained by a lower surface tension (lower adhesive forces between the water molecules) which allows water to move more easy through the soil/air medium.

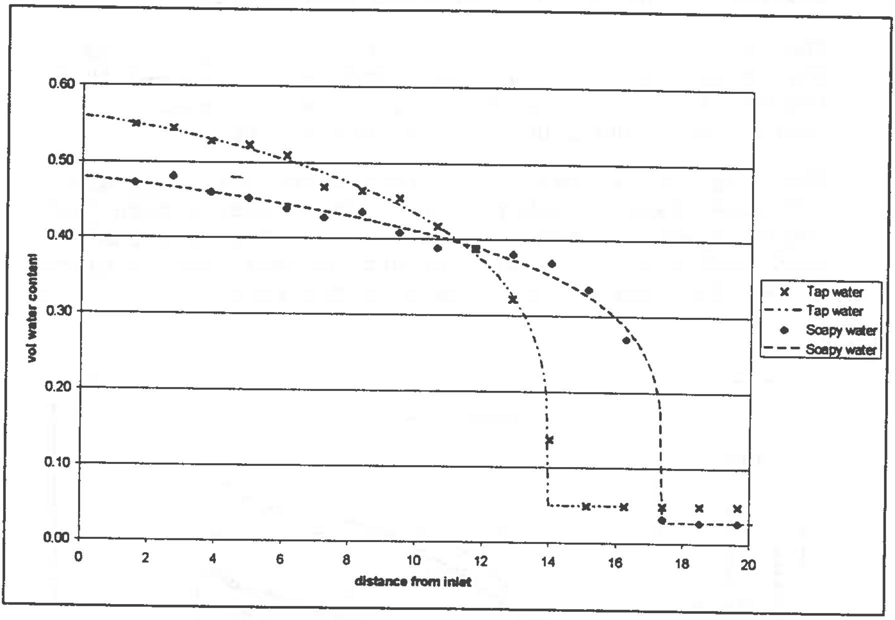

Fig. 3. Results for the Tap Water and Soapy Water Unsaturated Flow

FIELD TESTING RESULTS

The objectives of setting up an evaluation of measuring intake rates was to become familiar with the process of infiltration in the field and the basic concepts of multiphase flow. It was performed to find different infiltration characteristics for the five setups previously selected.

The infiltration was determined in the field using a double ring infiltrometer. This is a widely used method of determining an intake equation. The installation and measurement procedure is well documented in NRCS literature. From the infiltrometer ring experiment we obtained the infiltration rates. Figure 4 shows the results of the infiltrometers by plotting the cumulative intake rate versus time. The results indicate that the warmed water and the surfactant had the highest cumulative intake.

The last plot of the infiltration data (fig. 5), is the intake rate versus time. The results showed that the PAM (1000 mg/l concentration) and the soap (surfactant) had high initial intake rates.

The ring infiltrometer show that water with soap and hot water have a higher rate of infiltration than just the well water. Reservoir water and water with PAM at 1000 mg/l and at 10 mg/l present a very similar plots of depth of infiltration rate versus time.

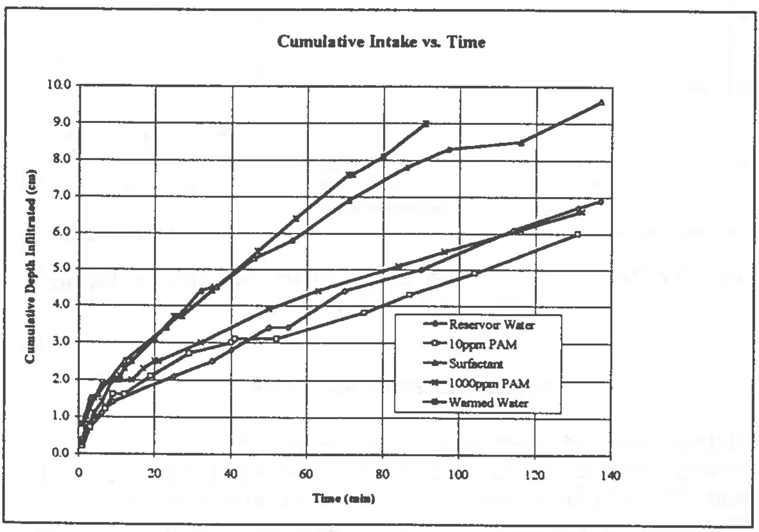

Fig. 4. Plot of the Cumulative Depth of Infiltration Versus Time

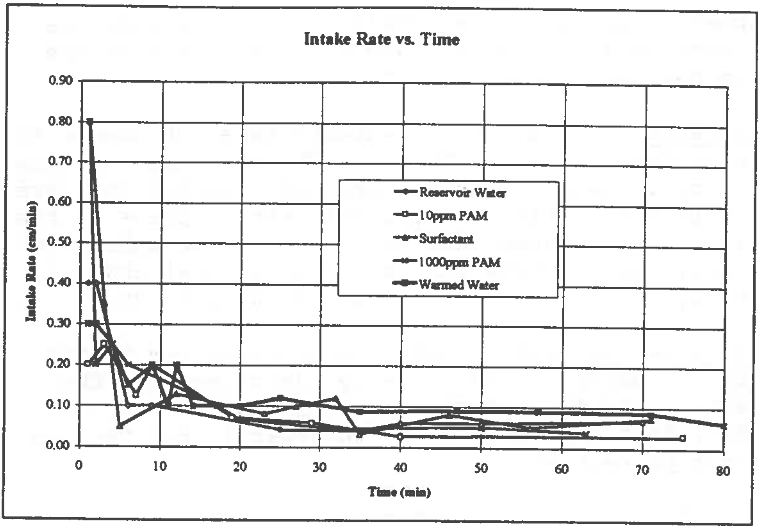

Fig. 5. Plot of the Intake Rate Versus Time

FARMER EXPERIENCES WITH ADDITIVES

Chemical additives for agriculture have been sold to growers with a variety of claims. The use of the dreaded "snake oil" label is readily applied if the product fails to perform as promised. There are several products on the market that seemed to have survived the initial "snake oil" label and farmers are slowly adopting practices that incorporate the chemicals into regular irrigation practices.

Gypsum. For infiltration modification, gypsum additives have been utilize for a number of years. The gypsum provides a rich source of available calcium which is beneficial for soil structure. Gypsum also can be used for water with low salt concentrations. Low salt waters tend to have poor infiltration characteristics due to sealing of the soil surface.

Growers have added gypsum to increase the calcium concentration of the water with commercially available equipment since the late 1980's. There are numerous applications in California where the addition of the gypsum has been shown to be beneficial (Burt 1994).

Surfactants. The use of surfactants have not proven to be as successful in California. The basic idea of how they work is generally misunderstood. Surfactants are only effective during the initial wetting phase of the infiltration. Growers who have used surfactants have seen only limited benefits from the chemical and generally do not endorse the use of surfactants.

Polyacrylamides (PAM). PAM is relatively new to the California market. PAM is being advertised for the settling properties of the material and not entirely the infiltration properties. In general, PAM has two distinct properties:

1) holding soil structure by coating the soil (improves infiltration characteristics)
2) dropping sediments out of suspension

Growers on the west side of the San Joaquin Valley of California have been adopting the use of PAM due to the second property. Tailwater that leaves the field is typically high in sediment load from erosion along the furrow irrigated fields. PAM appears to be quite effective in reducing the sediment load. Typical recommended rates by the manufactures are up to 10 ppm PAM in the irrigation water. Most growers have reduced this value to about 1-2 ppm PAM and only at the beginning of the irrigation event. This is readily done by placing a teaspoon of dry PAM at the head of each furrow at the beginning of the irrigation set.

Table 1 includes the results of a field study completed in 1997 that evaluated the use of PAM. The data support the effectiveness of PAM but also illustrate that water management can be a major part of addressing infiltration and erosion problems.

PAM is not effective in low salt water. In fact, it seems to increase the ability for the water to hold the particles in suspension. Adding gypsum

Table 1. Field Evaluation of PAM

Reference: Irrigation Water Conservation and Sediment Reduction Study. West Stanislaus RCD. 1997.

	Single Event (control)						Single Event (treated)				
Grower	Field Size, ac	Crop	Applied ft	Runoff ft	% Runoff %	TSS	Treatment	Applied ft	Runoff ft	% Runoff %	TSS
D	17	Walnuts	1.10	0.50	45.5	351	dry PAM	1.1	0.33	30.0	274
E	25	Beans	0.16	0.06	37.5	1,212	liquid PAM	0.37	0.1	27.0	27
F	26	Beans	0.34	0.20	58.8	904	dry PAM	0.36	0.17	47.2	393
H	28	Beans	0.29	0.19	65.5	5,610	dry PAM	0.31	0.21	67.7	4,250
I	28	Beans	0.28	0.17	60.7	5,790	dry PAM	0.26	0.05	19.2	1,148
M	50	Asparagus	0.26	0.05	19.2	3,591	dry PAM	0.37	0.08	21.6	2,604
N	25	Spinach	0.26	0.18	69.2	1,124	dry PAM	0.26	0.11	42.3	790
O	34	Broccoli	0.42	0.15	35.7	1,018	dry PAM	0.3	0.08	26.7	732
O'	34	Broccoli	0.42	0.15	35.7	1,018	dry PAM (fish feeder)	0.36	0.09	25.0	62
P	66	Tomatoes	0.52	0.01	1.9	2,250	dry PAM	0.56	0.01	1.8	182
Q	66	Tomatoes	0.64	0.06	9.4	2,140	dry PAM	0.68	0.05	7.4	186
R	34	Broccoli	0.40	0.15	37.5	1,456	dry PAM (fish feeder)	0.38	0.11	28.9	47
Average						**2,205**					**891**

NOTES:

D Small siphon pipes were clogging due to the PAM

E Large reduction in TSS due to liquid PAM.

F Used 1ounce per furrow in small measuring cup. By far the easiest application method.

H Large reduction in TSS due to dry PAM. But the TSS is high. Problem with high furrow inflow rate.

I Same field as H except the furrow flow rate was reduced on the dry PAM furrows.

M Flow rates in the furrow were too great to make the PAM effective. Management needs to reduce the furrow flow rates.

N Flow rates again were the primary problem.

O Applied 1 ounce of dry PAM into head of furrows.

O' Same as O, except dry PAM added to head ditch through fish feeder (1ppm). Very effective.

P Large decrease in the TSS. Very low runoff amount.

Q Large decrease in the TSS. Very low runoff amount.

R Used 2 pounds of Superfloc duri ; first 6 hours of irrigation. Large decrease in TSS.

General Conclusions from Study:

- The most significant problem seems to be associated with the furrow flow rates.
  High flow rates cause erosion and high TSS.
  Using PAM requires higher flow rates because there is more infiltration and the water will not 'get out'.
  High tailwater amounts are associated with high TSS.
  -->>> Need to modify management (reduce tailwater) along with adding PAM to reduce TSS.

- Dry PAM works best if applied in the head ditch with a fish feeder at low rates (1ppm)
- Best way to apply PAM is to inspect tailwater and add an ounce (teaspoon?) to furrows that have high erosion.
- Large siphon tubes (>1 1/4") do not clog with PAM added to head ditch. Small tubes (3/4") have a trendancy to clog.

- There is general confusion on whether the PAM changes infiltration or drops out sediment.
  PAM drops out sediment during the season reducing TSS of tailwater. Not effective with too high flow rates.
  PAM improves infiltration by maintaining structure. Increases infiltration early in the season.
  Keeps furrows from melting later in the season.

dramatically changes the chemistry and improve the capability for the water to drop sediments.

MEASURING INFILTRATION IN THE FIELD

The use of a soil probe to determine the depth of penetration during and after an irrigation is a useful irrigation management tool. There is one probe that is simple to use and make that is increasing in popularity among farmers and field researchers. The tool is a "tile probe" that was historically developed to find tile lines in a field.

Once the soil has reached field capacity, it was found a steel rod with a rounded tip could easily be "pushed" into the soil. This idea was then adapted and promoted by Mr. John Merriam (Professor Emeritus in BioResource and Agricultural Engineering at California Polytechnic State University in San Luis Obispo, California, USA) to be used for irrigation management (Merriam 19xx).

There are several ways to use the probe for irrigation management. It can be used to determine when to shut off an irrigation. It can be used to determine the uniformity of irrigations. An area of increasing use is the use of the probe to evaluate the adequacy of water applied during pre-irrigation.

DISCUSSION AND CONCLUSIONS

Kinematic viscosity and surface tension appear to be two major fluid properties that affect flow through porous media. Infiltration experiments on dry soil created a two-phase flow (air/water), resulting in different infiltration rates for water with and water without surfactants. Saturated column experiments resulted in a one phase flow through porous media. Unsaturated hydraulic conductivity measurements provided a method in the laboratory to study the two-phase flow in a non-structured soil.

The saturated hydraulic conductivity experiment showed that there was no effect of the surface tension under saturated conditions. The surface tension will only be important in a medium where interfaces between two phases occurs (such as between air and water). This was shown clearly in the unsaturated flow experiment.

The infiltration experiments showed a fast infiltration rate for warm water and soapy water. Water with PAM and water at room temperature showed lower infiltration rates. The high infiltration rate for warm water is a result of a lower kinematic viscosity, resulting in a higher hydraulic conductivity. The higher infiltration rate for water with soap cannot be explained with the Pouseuille equation, nor has it been described in equations in the reviewed literature. However, it is believed that the higher rate is a result of a lower surface tension. Not only do the infiltration rates support this idea, but a visual experiment of putting two drops of water with and without soap on a dry soil and a plastic surface showed a difference in behavior between the two fluids. The drop with soap infiltrated faster in the soil and spread out more, while the water without soap formed a curved shape that remained on top of the soil for a longer time.

Possible explanations for this could be that a reduced surface tension allows for a flatter film of water on the soil particles that is interconnected, instead of a situation as in Fig. 2.3 in Corey (1994). When the water is interconnected, it will create a path of less resistance for water to travel through, thus increasing the unsaturated hydraulic conductivity.

Another possible explanation is that the reduced surface tension will allow smaller soil pores to be filled, resulting in an unsaturated hydraulic conductivity closer to the saturated hydraulic conductivity. The column study did not result in a significant difference of the flux rate, which suggests that the surface tension only makes a difference in a two phase flow, when there is a surface interface.

During the infiltration experiment, a high initial water intake was observed during the first few minutes for the high concentration PAM and the water with soap setup. The high initial intake of the PAM can be explained by the immediate stabilization of the soil aggregates, resulting in a large initial intake in the macro pores of the soil. However, after the macro pores are filled, the infiltration rate is slower than that of regular water.

The large initial intake of water with soap supports the explanation above. During infiltration, a larger hydraulic conductivity occurs due to a more continuous path of water in the pores. When the infiltration reaches a steady state (saturated flow), the lower surface tension does not make a difference in the flux rate any more and the infiltration rate becomes similar to the one of regular water.

Overall, the following was concluded from this study:

- Temperature has a high effect on the viscosity of the water resulting in higher intake rates. However, in laboratory and field measurements, the temperature is often not measured.

- Surfactants affecting the surface tension of a fluid will increase the initial intake of the water. Its affect will decrease with increasing volumetric water content due to less air/water interfaces in the soil.

- PAM does not affect any of the water properties we evaluated. It is very effective for erosion control and might be effective in increasing infiltration characteristics of a highly structured soil.

- Any attempt to increase infiltration should be evaluated based on the irrigation efficiency and distribution uniformity effects. Increasing the infiltration rates can be detrimental in some cases causing decreases in the irrigation efficiency and distribution uniformity.

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