THESIS

SOIL PUDDLING FOR REDUCING SEEPAGE

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ABSTRACT OF THESIS

SOIL PUDDLING FOR REDUCING SEEPAGE

This thesis is a report of laboratory and field studies designed to determine the potential of soil puddling for reducing seepage in irrigation distribution systems.

Laboratory studies were conducted under ideal conditions of thorough puddling, a screened soil, constant head, and nearly constant temperature. Field studies were conducted under less controlled but more realistic conditions. A 26-foot, polyethylene covered, rectangular channel was constructed at three field sites, and seepage was monitored before and after puddling the channel invert. Hand and mechanical puddling methods were employed. Labor input is less and the effectiveness of the puddled layer greater with mechanical puddling.

Results indicate that soil puddling has potential for reducing seepage, particularly when the entire channel perimeter can be puddled. This method can be labor intensive and adaptable to the situation found in many developing countries.

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Symbol	Description
A	Cross-sectional area of water in the channel
D_i	Vertical distance between the impermeable layer and the channel invert
D_p	Vertical distance between the permeable layer and the channel invert
H_w	Water depth in the center of the channel
$\overline{I}_s$	Rate of fall of the water level due to seepage as if the channel were ponded (dimension length/time)
K_a	Hydraulic conductivity of the puddled layer (dimension length-time)
K_s	Hydraulic conductivity of the soil at zero or positive soil-water pressure (dimension length-time)
L_a	Thickness of the puddled layer
P	Soil-water pressure head below the puddled layer
P_b	Bubbling pressure head
P_c	Critical pressure head of the soil
q_s	Volume rate of seepage per unit length of channel
R	Hydraulic radius of a channel
R_a	Hydraulic impedance L_a/K_a of the puddled layer
V	Flow rate through the puddled layer
W_b	Width of the channel bottom
W_s	Width of the water surface in the channel

Chapter 1

INTRODUCTION

Problem Statement

Technological advances commonly accepted in the developed countries of the world have not yet generally reached the agriculturalist of the developing country. Often, when these advances do reach this farmer they are not easily implemented because of a lack of materials, tools, capital, or engineering knowledge. Some technological advances simply are not practical in certain economic, social, or governmental situations. The farmer of the developing country might be greatly aided by changes in established techniques or new methods if they could easily be understood and implemented using available tools, labor, and materials (Collinson, 1972).

In most countries of the world, earth channels are extensively used for water delivery and seepage from them is often substantial. Seepage is that water which infiltrates from the channel cross section down into the soil profile and eventually to the water table. The minimization of seepage, in some cases, might mean the difference between a shortage or a surplus of available irrigation water.

In Pakistan, water losses from earth channels due to seepage, wastage through channel breaks, and evapotranspiration by non-beneficial plants frequently range from 30 to 50 percent of the available flow from the main canal turnout (Corey and Clyma, 1974). Water supplies in Pakistan are often insufficient for maximum agricultural output.

For some locations, the loss of water due to seepage merely means that the lost water must be returned to the surface by additional pumping, thus increasing pumping costs. The problem is not simply a monetary one for the Grand Valley of Colorado where salinity problems and rising groundwater tables often result from excessive seepage out of irrigation channels (Skogerboe and Walker, 1972).

Various channel lining methods have been under study for many years to reduce seepage and to prevent undesirable recharge of the groundwater (U.S.B.R., 1963). But few of the studies conducted have resulted in techniques which could be employed by the small farmer of the developing country. Plastic sheeting, concrete lining, and asphalt lining all provide a virtually impermeable layer which effectively reduces seepage. However, all of these methods require materials, machinery, and substantial capital investment which often puts these methods out of reach for the small farmer.

The use of colloidal clays in sealing irrigation channels would appear to have some applicability to developing countries. Unfortunately, this method requires a high-swell bentonite, and this sealing agent would often have to be transported to the channel site, thereby increasing project expense (Dirmeyer, 1957).

The use of thick, compacted earth lining for canal sealing would require heavy earth moving and compaction equipment to be effective (Holtz, 1957). This type of equipment is not generally available to the small farmer of the developing country, and even when it is available, the cost is prohibitive. This method, to be effective, also requires in addition certain soil types.

One means of minimizing seepage from earth channels, which could be utilized by the agriculturalist of the developing countries, is thorough sealing of the channel by "puddling" the soil. When a surface soil in a wet and plastic condition has been worked (by stirring or applying pressure) until its pore space is much reduced, it becomes highly impervious to air and water and is said to be puddled (Buckman and Brady, 1969). Even sandy soils with a small amount of clay particles can be puddled, and management practices, using existing knowledge that would promote sedimentation in the channel to provide more fine materials, mightly greatly enhance the soil's ability to puddle. Methods such as designing turnouts to effectively transfer sediment load from a main channel to a branch channel could potentially be employed (Rakha, 1971).

If the puddling of soil does prove to be a reasonable method for reducing seepage in delivery channels, it is a method that could be readily utilized by a developing country with a labor intensive economy. This channel lining method should require only minimal tools (potentially only hand tools already available to the farmer), very little capital, and little technical expertise on the part of the farmer.

Objectives

The objectives of this study were to determine: (1) how much the seepage is reduced by soil puddling under both laboratory and field conditions; (2) by what means the soil can best be puddled; and (3) the development of a method for anticipating puddling effectiveness.

Study Scope

A laboratory study was designed to determine the effect soil puddling would have on the seepage through soils under the ideal conditions of thorough puddling, a screened soil, constant head, and nearly constant temperature. Subsequently, a field study was undertaken to look at the effect of puddling three small, ponded channels under less controlled but more realistic circumstances. Additional laboratory studies were then conducted on the field site soils using the same puddled thicknesses that occurred in the field. No attempt has been made to directly relate laboratory results to those obtained in the field, or to match theoretical results to those obtained in the laboratory or field.

Chapter 2

SEEPAGE FROM EARTH CHANNELS

Channel Seepage (General Case)

Seepage, being a dynamic process, is complicated by nonuniformity of the soil, water quality, erosion, sedimentation, soil hydraulic conductivity, water level fluctuation in the channel and in the ground, and by periodic drying of the channel (Bouwer, 1965). In most theoretical solutions for steady-state seepage from open channels, the results generally apply only to a specific set of assumed conditions. For example, water depth and channel shape are not usually considered. Bouwer (1965) presented solutions for seepage from open channels for a rather broad spectrum of depths and channel shapes and for various positions of the underground water table.

Examples of four commonly encountered flow systems for trapezoidal channels are shown in Figs. 1, 2, 3, and 4 after Bouwer (1975). Figure 1 illustrates seepage into a deep, uniform soil with a shallow water table.

Seepage into a uniform soil underlain by a material of much greater hydraulic conductivity can be divided into two classes. Condition A, when the groundwater table is above the more permeable bottom layer, is shown in Fig. 2. For this condition, the water table slope will decrease with increasing distance from the channel and reach zero at infinity. But the water table slope can be considered to be zero at some finite distance for practical purposes. Bouwer (1965) arbitrarily selected this distance to be $10W_b$, where W_b is the width of the channel invert, as measured from the channel center.

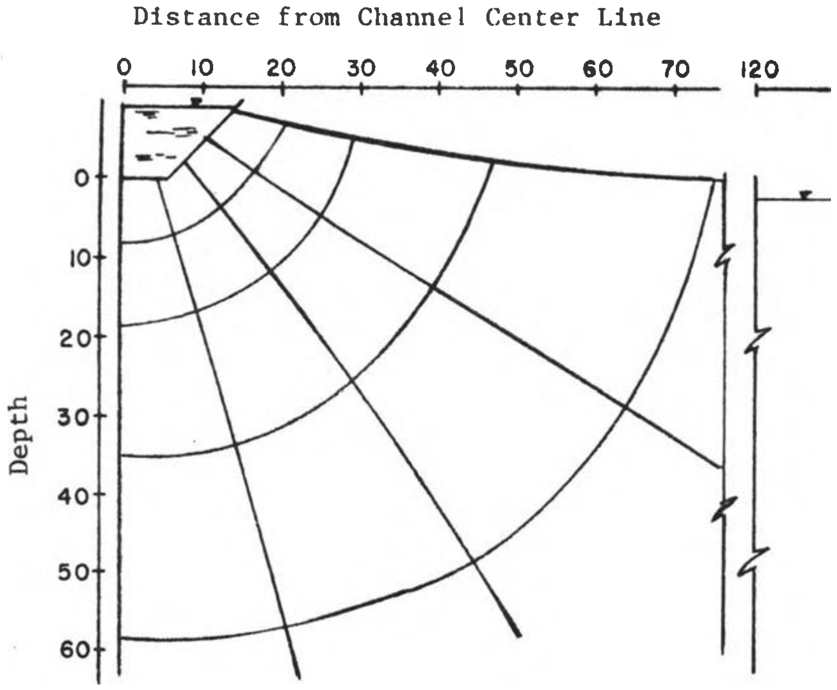

Fig. 1. Flow system in deep, uniform soil with a shallow water table (after Bouwer, 1965).

Condition A', when the groundwater table is at or below the top of the more permeable layer, is shown in Fig. 3. If for Condition A', the distance from the channel invert to the permeable layer becomes relatively small, the seepage distribution shows a marked increase in bottom seepage (Bouwer, 1965).

Seepage into a uniform soil underlain by a material of much lower hydraulic conductivity is shown in Fig. 4 and is designated Condition B. Under this condition, the water table slope at sufficient distance from the channel becomes constant as the flow approaches uniform flow. The lateral flow boundary can then be represented by a vertical equipotential, also taken at a distance of $10W_b$ from the channel center. The position of the water table at that point can be

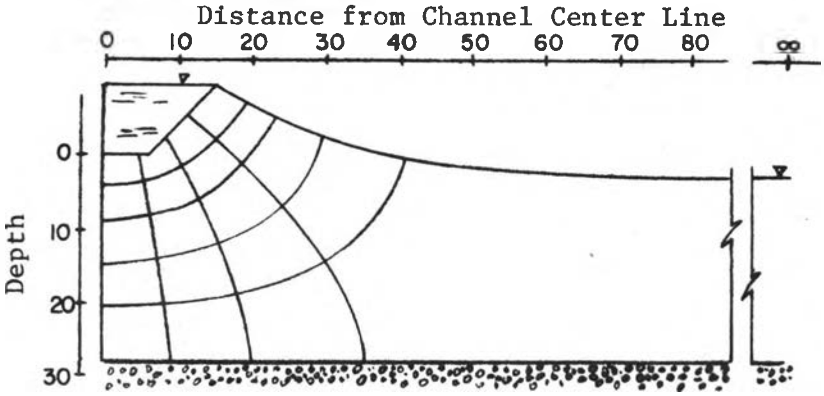

Fig. 2. Seepage into a uniform soil underlain by material of much greater hydraulic conductivity with water table above the top of the underlying layer (Condition A after Bouwer, 1965).

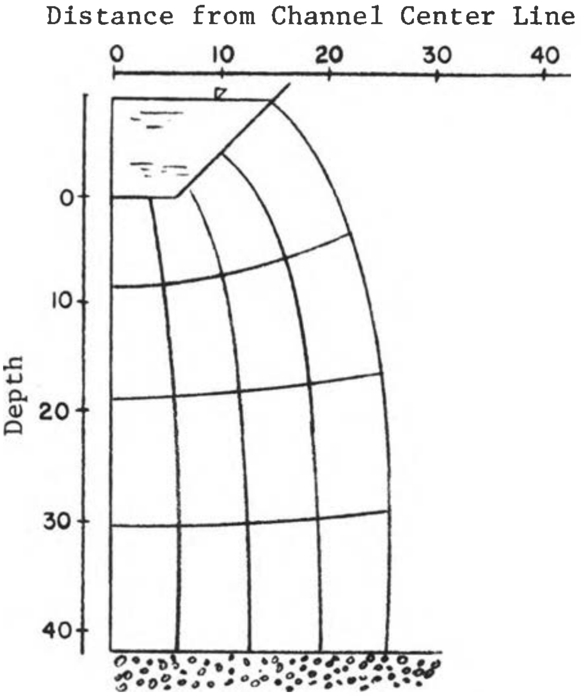

Fig. 3. Seepage into a uniform soil underlain by material of much greater hydraulic conductivity with the water table below the top of the underlying layer (Condition A' after Bouwer, 1965).

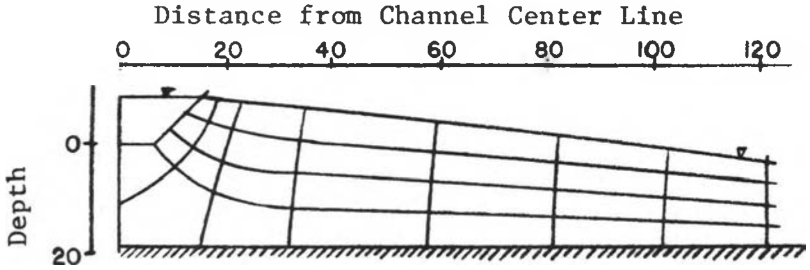

Fig. 4. Seepage into a uniform soil underlain by material of much lower hydraulic conductivity (Condition B after Bouwer, 1965).

considered as indicative of the "original" water table position controlling the flow system adjacent to the channel. If for Condition B, the distance from the channel invert to the impermeable layer becomes relatively small, reductions in bottom seepage occur (Bouwer, 1965).

In practice, channel seepage is seldom steady because of changing water levels in the channel and soil and other factors. So, the steady-state conditions covered by Bouwer's (1965) analyses are individual pictures of a system that tends to be continuously transient.

Bouwer's solutions were obtained with a resistance network analog. Thus, the unit lengths expressed in Figs. 1, 2, 3, and 4 are in terms of the unit node distance in the dense part of the resistance network analog. Solutions to these flow systems are presented by Bouwer (1965) in chart form and are readily adaptable to many channel shapes and flow depths. The seepage rates, measured as electrical current, were converted to a volume rate of seepage, q_s, per unit length of channel. These rates were then divided by W_s, the channel's water surface width, to give the rate of fall, $\overline{I}_s$, of the water surface due to seepage as if the channel were ponded.

Channel Seepage (Entire Perimeter Puddled Case)

Bouwer (1965) also discusses channel seepage through a thin, slowly permeable layer at the wetted perimeter such as would be the case with a layer of puddled soil (Fig. 5). This situation is designated Condition C, and it was treated analytically by Bouwer (1964).

Several hydraulic conductivities are relevant to Bouwer's (1964) analyses. The hydraulic conductivity of the puddled layer is K_a, and K_s is the hydraulic conductivity of the soil at zero or positive soil-water pressure.

The ratio L_a/K_a of the puddled layer is called the hydraulic impedance, R_a. The material underlying the puddled layer will be unsaturated and at unit hydraulic gradient if: (1) the hydraulic impedance is large enough for the downward flow rate, V, to be numerically less than K_s of the underlying, relatively permeable material, (2) if the underlying material is sufficiently well drained to keep the water table well below the slowly permeable layer, and (3) if air can enter or is present.

The pressure head, P, of the soil in the underlying material is approximately equal to the critical pressure head, P_c, of that material. The critical pressure head, P_c, is defined by Bouwer (1964) to be the negative pressure head where the reduction in hydraulic conductivity takes place if the sigmoid curve relating hydraulic conductivity and negative pressure is replaced by a step function.

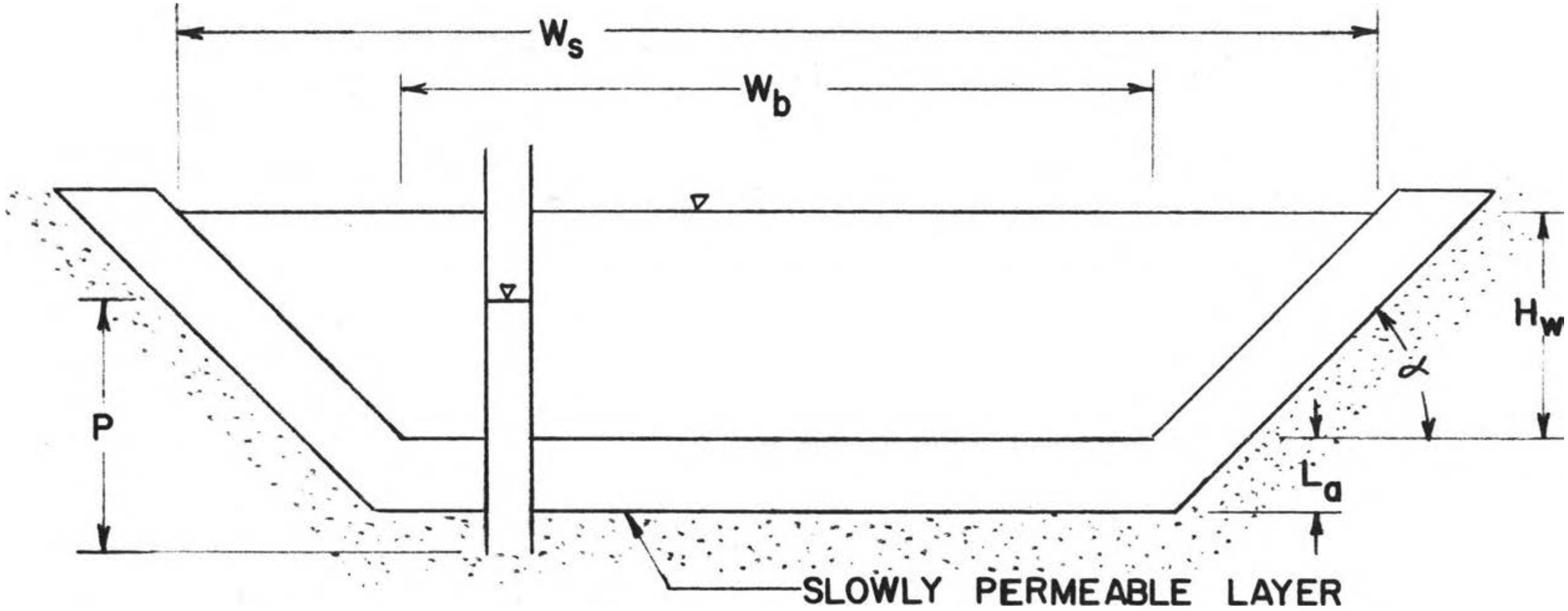

Fig. 5. Cross section through a trapezoidal channel with definitions for flow through a slowly permeable layer to an unsaturated, permeable material (Condition C after Bouwer, 1965).

Bouwer's (1964) critical pressure head would always have a value greater than the "bubbling pressure head", P_b. Bubbling pressure head, defined by Brooks and Corey (1966), could be used to approximate P_c, however. Sands may have a P_c value of -15 centimeters of water or less.

From Darcy's equation, the flow rate, V, through the puddled layer of an infinitely wide channel can be represented by

$$V = \frac{H_w + L_a - P_c}{R_a} \tag{1}$$

where H_w is the channel flow depth, L_a is the thickness of the puddled layer, and R_a is the hydraulic impedance, L_a/K_a, of the puddled layer (Bouwer, 1965).

If the puddled layer has a uniform R_a for the entire wetted perimeter, if the flow through the layer is normal to the wetted perimeter at all points, and if L_a is negligibly small as compared to H_w, Eq. 1 can be applied to the entire wetted perimeter of a channel of finite geometry (rectangular, trapezoidal, or triangular) to give the following equation.

$$\bar{I}_s = \frac{1}{W_s R_a} \left[(H_w - P_c)\, W_b + (H_w - 2P_c)\, \frac{H_w}{\sin\alpha} \right] \tag{2}$$

W_b is the channel bottom width, and W_s is the water surface width in the channel.

The seepage is expressed as the rate of fall, $\bar{I}_s$, of the channel's water surface as if the channel were ponded. Equation 2 has applicability to puddled channels with rectangular (α = 90 degrees, $W_b = W_s$), trapezoidal, and triangular ($W_b = 0$) cross sections.

If P_c is numerically small compared to H_w, Eq. 2 can be simplified to

$$\bar{I}_s = \frac{H_w - P_c}{W_s \quad R_a} \left(\frac{H_w}{\sin\alpha} + W_b \right) \tag{3}$$

Channel geometry and the hydraulic impedance of the puddled layer essentially control seepage under Condition C. If the groundwater table is sufficiently below the channel invert, it will have no effect at all, and the subsoil only affects the seepage through P_c (Bouwer, 1965).

Channel Seepage (Invert Puddled Case)

Figure 6 illustrates the flow system for Condition A' when only the channel invert is puddled. Under these circumstances, Eq. 1 could be used to determine the seepage through the puddled layer, but the seepage through the channel sides must also be accounted for.

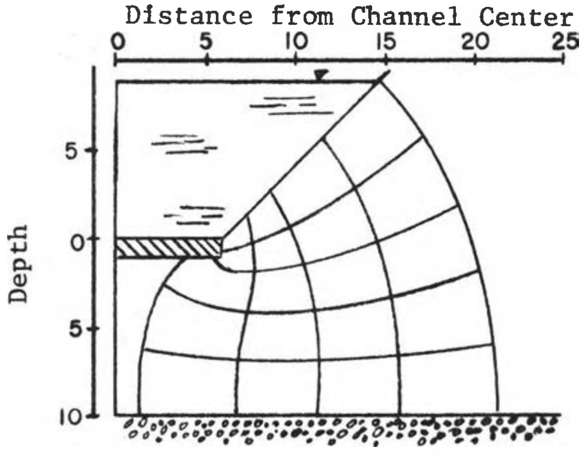

Fig. 6. Flow system for a channel with an impermeable bottom layer (Condition A' after Bouwer, 1965).

Using a resistance network analog, Bouwer (1965) evaluated the reduction in seepage caused by puddling the bottom of trapezoidal channels in relation to water depth. For simplicity, the puddled layer was considered as impermeable, and L_a was taken as one node distance or as $W_b/12$. Analyses were made for Conditions A and A' with three H_w values. Under Condition A, the depth to the permeable layer from the channel bottom, D_p, was $7.5W_b$. The vertical distance from the channel water level to the groundwater table was $1.5W_b$. For Condition A', D_p was $0.83W_b$.

The results of the analyses were expressed as a percentage of the seepage prior to sealing the channel invert and plotted against H_w/W_b for the two conditions (Fig. 7). A curve for Condition A with $D_p < \infty$ would be below the curve for $D_p = 7.5W_b$. Curves lower than the curve for Condition A' can be expected only if $D_p << 0.8W_b$. Thus, according to Bouwer (1965), little seepage reduction can be expected from sealing the channel bottom only unless: (1) the channel is shallow or (2) the permeable layer is at small depth and already causing considerable bottom seepage.

Effect of Water Depth on Seepage

Bouwer (1965) evaluated the effect of water depth on seepage. He found that, in general, the channel water depth has the most effect on seepage under Condition A'. But for all conditions (Conditions A, A', B, and C), he found that the discharge capacity of the channel increases much faster with water depth than the seepage. So, with uniform flow, the overall water conveyance efficiency increases with increasing channel water depth.

Effect of Channel Shape on Seepage

To determine the effect of channel shape on seepage, Bouwer (1965) performed analyses with the resistance network for rectangular,

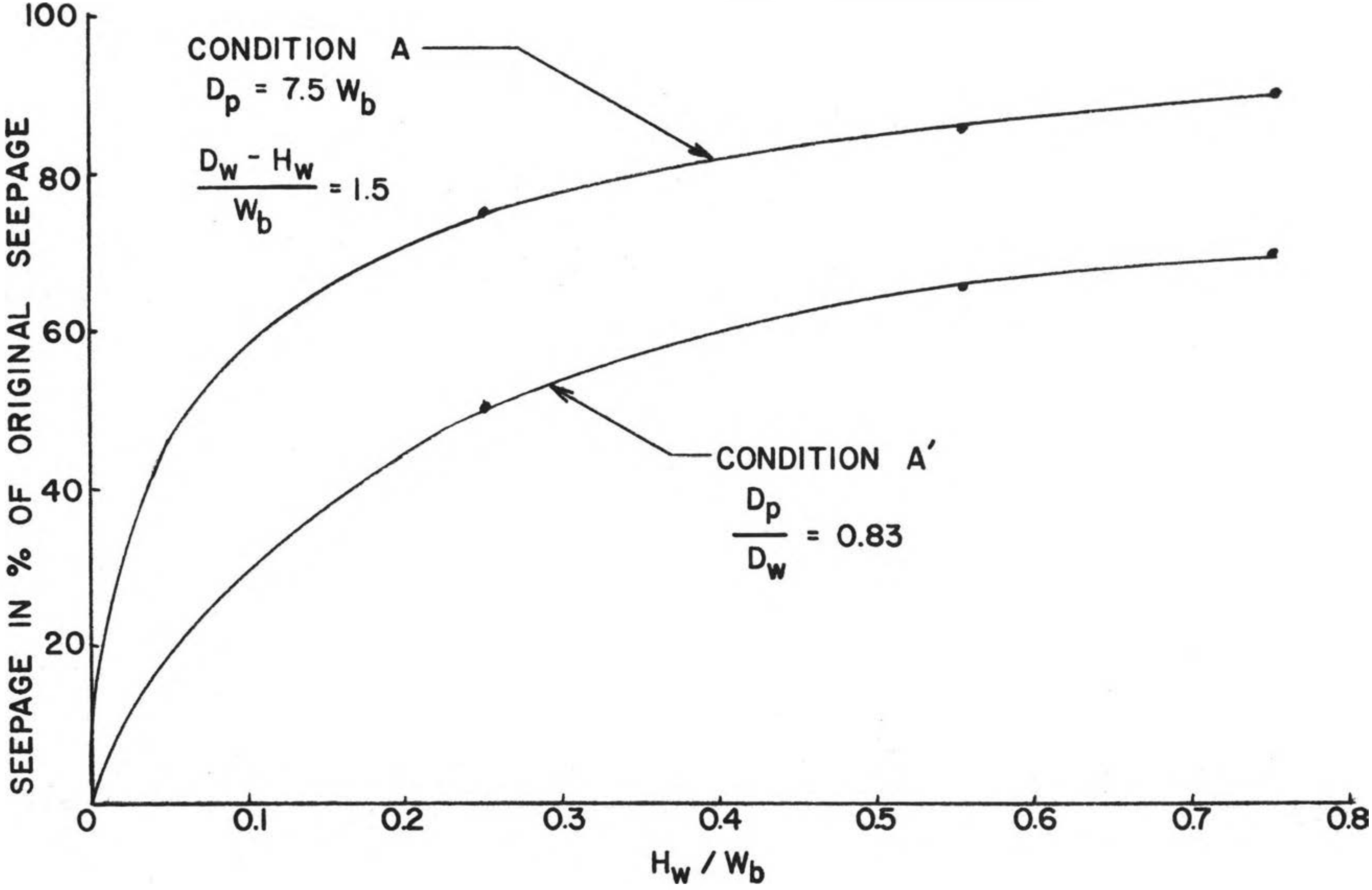

Fig. 7. Effect of sealing a channel bottom on seepage for two seepage conditions (after Bouwer, 1965).

trapezoidal, and triangular cross sections with constant W_s and H_w. The results of these analyses are presented in Table 1 with length dimensions expressed as ratios to W_s rather than to W_b, because W_b was not constant for the different channel shapes. The ratio of H_w to W_s was 0.3 for all shapes. Seepage was calculated with Eq. 2, assuming $P_c = 0$, for Condition C, and seepage for this condition was expressed in terms of the dimensionless ratio $\bar{I}_s W_s R_a / H_w^2$.

The effect of channel shape on seepage should also be considered in relation to the effect of shape on channel discharge capacity. The dimensionless discharge factor according to the Manning formula is $AR^{2/3}/W_s^{8/3}$ where A is the cross sectional area of water in the channel and R is the channel's hydraulic radius. This factor was divided into the seepage terms of Table 1, and the resulting values were arbitrarily set at 100 for the trapezoidal shape. The various channel shapes could then be compared using this "index of relative flow reduction." Results show that, for a given W_s and H_w, rectangular channels are more efficient water conveyors than trapezoidal or triangular channels with a possible exception of seepage under Condition A' with a very small D_p.

Effect of Channel Velocity on Seepage

Velocity can indirectly modify seepage through its effect on erosion, sedimentation, and wetted perimeter. However, velocity apparently has no direct effect on seepage according to Bouwer, Meyers, and Rice (1962), and measuring channel seepage by means of ponding is correct in principle. Velocities from zero feet per second to seven feet per second did not affect the seepage in a flume with a sand and gravel bottom. For this reason, it was decided that ponding would be the best method for studying the effect of puddling on seepage under field conditions.

Table 1. Effect of Channel Shape on Seepage and on Relative Discharge Reduction, H_w/W_s = 0.3 (after Bouwer, 1965).

Cross section (1)	Seepage condition (2)	D_w/W_s (3)	D_p/W_s (4)	D_i/W_s (5)	$\bar{I}_s/K$ (6)	Index of relative flow reduction (7)
Triangular	A	0.9	3	-	0.93	156
Trapezoidal	A	0.9	3	-	1.00	100
Rectangular	A	0.9	3	-	1.13	73
Triangular	A'	∞	∞	-	1.56	145
Trapezoidal	A'	∞	∞	-	1.81	100
Rectangular	A'	∞	∞	-	2.31	83
Triangular	A'	0.63	0.33	-	1.68	140
Trapezoidal	A'	0.63	0.33	-	2.03	100
Rectangular	A'	0.63	0.33	-	2.83	91
Triangular	B	0.37	-	0.2	0.004	171
Trapezoidal	B	0.37	-	0.2	0.063	100
Rectangular	B	0.37	-	0.2	0.066	68
Triangular	C				$\bar{I}_s W_s R_a/H_w^2 = 1.94$	119
Trapezoidal	C				$= 2.74$	100
Rectangular	C				$= 4.33$	103

Chapter 3

LABORATORY EQUIPMENT AND PROCEDURE

A laboratory apparatus was constructed to obtain data on the potential effectiveness of soil puddling for reducing seepage. Inverted, quart-size, soft drink bottles with the bottoms cut off were used as laboratory seepage flasks as shown in Fig. 8 and Plate 1. Glass beads were used to fill the neck of the bottle and to provide a medium through which the seepage could flow. Six flasks of the type shown in Fig. 8 were manufactured and arranged on a laboratory stand as shown in Plate 2. Seepage was collected in a laboratory beaker situated below each flask.

A 500-gram (1.03 pound) soil sample was screened through a number five mesh (3.962 millimeter) screen and placed on the glass beads. A bulk density of approximately the same bulk density that could be found in the field for that particular soil was obtained by tapping and shaking the flask. This resulted in a soil column eight to ten centimeters (three to four inches) high. The interior cross sectional area of the cylindrical portion of the flask was 50 square centimeters (0.054 square feet).

A Mariotte syphon and manifold arrangement (Plate 3) was used to maintain a constant head on each soil sample. Tap water was used in all of the laboratory tests. Before taking any seepage data and before any puddling was done, a constant head of approximately 1.5 centimeters (0.6 inch) was maintained. The seepage rate through each flask was observed but not recorded for about one hour or until the seepage rate stabilized.

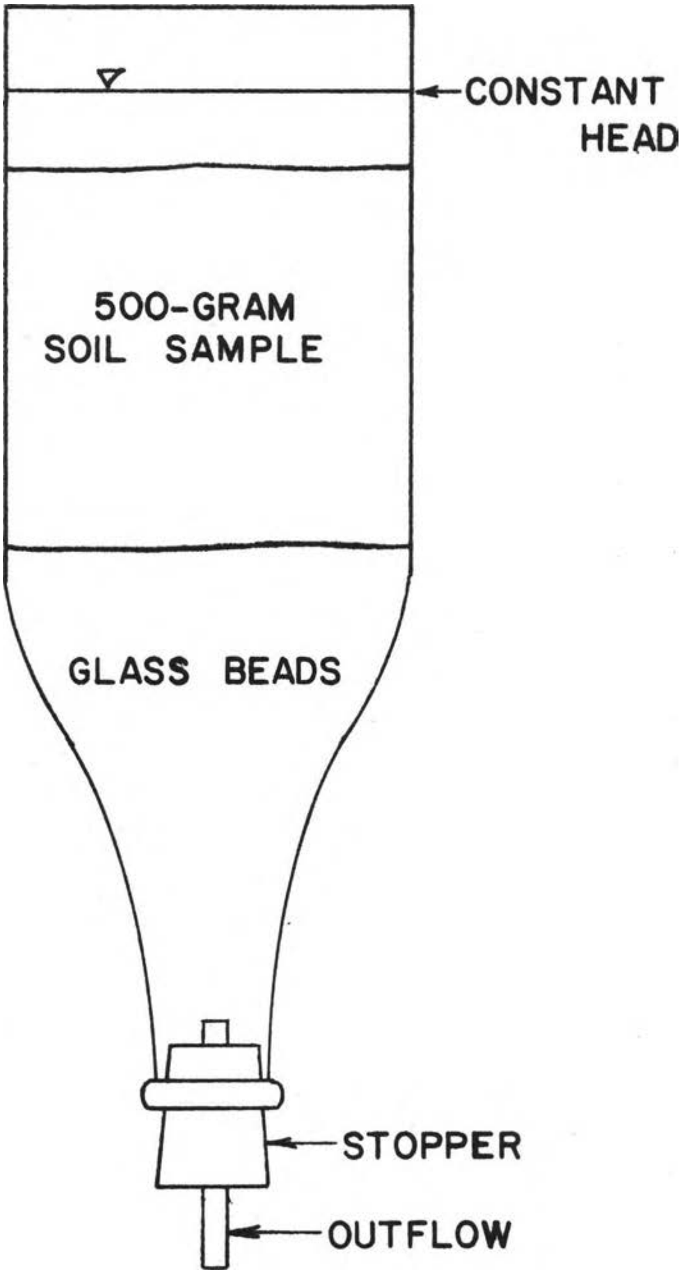

Fig. 8. Laboratory seepage flask.

The soil sample in four of the six flasks was then puddled by stirring the sample with a glass rod, taking care not to mix glass beads with the sample. This resulted in a breakdown of the soil structure and completely eliminated visible pore space within the puddled layer as seen through the glass sides of the flask. The entire soil sample was puddled for the laboratory tests conducted before the field tests. Because a hand puddled depth of approximately four centimeters (1.6 inches) was obtained in the field tests, the same puddled depth was used in laboratory tests conducted on field site soils. Results of the laboratory tests with different puddled depths will be presented separately in Chapter 4.

After a period of time to allow the seepage rates to stabilize, the rate through each of the six flasks was observed and recorded. Data were collected over time intervals varying from 15 minutes to several hours depending on the flow rate through the soil samples. The collection beakers were covered with plastic to inhibit evaporation.

It should be noted that because the pore space within the puddled layer was eliminated, the height of the soil column after puddling was reduced by approximately one centimeter (0.4-inch). This means that the actual head above the four puddled soil columns became about 2.5 centimeters (one inch) after the puddling operation.

Because some fine materials were temporarily suspended in the water above each puddled sample, a thin layer of fine materials was deposited on the top of the column as these materials settled. More will be mentioned about the possible effect of this thin layer in Chapter 7.

If this laboratory apparatus were to be duplicated, it would be helpful to have a tap in the seepage flask to measure the soil-water pressure at the bottom of the puddled layer or at the bottom of the unpuddled sample. With this information, the K_a of the puddled layer could be calculated from Eq. 1. It would also be advantageous to have a taller cylinder so that the H_w expected in a particular field situation might be duplicated.

Chapter 4

LABORATORY DATA ANALYSIS

Five soil samples were subjected to the laboratory investigation including three from the three field sites described in Chapter 6. A mechanical analysis of each soil sample was conducted. Two of the soils were loams, and the others were a loamy sand, a clay loam, and a silty clay loam. Tables 2 and 3 show the average seepage through a particular soil before and after puddling, expressed in units of centimeters per hour. The puddled depth for the two soils in Table 2 was the full depth of the 500-gram sample or eight to ten centimeters (three to four inches). For the soils in Table 3, the puddled depth was four centimeters (1.6 inches).

Table 2

Laboratory Data Summary for Soils
with Entire Soil Sample Puddled

Soil textural name	loam	loamy sand
Percent sand	40	82
Percent silt	33	13
Percent clay	27	5
Average initial seepage before puddling, S_b, cm/hr	8.70	9.96
Average seepage after puddling, S_a, cm/hr	0.15	0.15
S_a expressed as a percentage of S_b, $S_a(100)/S_b$	1.8	1.5

As one might expect, the seepage rate before puddling increases with an increasing percentage of sand in the soil with the exception of the clay loam soil in Table 3. The reason for the relatively high initial seepage of 18.75 centimeters per hour for the clay loam soil is not evident, but it may be due to organic matter in the soil. However, note that regardless of the textural classification or initial seepage, the average seepage after puddling for each sample is almost identical. The range in these values is only 0.03 centimeters per hour (0.01 inch per hour). Apparently, the difference in the depth of the puddled layers has very little effect on the seepage rate through the layer when the layer is puddled so thoroughly.

Table 3

Laboratory Data Summary for Field Site Soils with a Four Centimeter Puddled Layer

SOIL SAMPLE LOCATION	RIGDEN FARM	UNIVERSITY VILLAGE GARDEN	BAILEY FARM
Soil textural name	clay loam	loam	silty clay loam
Percent sand	40	44	13
Percent silt	23	30	59
Percent clay	37	26	28
Average initial seepage before puddling, S_b, cm/hr	18.75	9.66	6.43
Average seepage after puddling, S_a, cm/hr	0.17	0.15	0.18
S_a expressed as a percentage of S_b, $S_a(100)/S_b$	0.9	1.6	2.8

The seepage rate after puddling, expressed as a percentage of the rate before puddling is most indicative of the potential of soil puddling as a method of reducing seepage. Even considering that this was a laboratory situation involving a soil column subjected to complete breakdown of the soil structure, the results are dramatic. Under these idealized conditions, the flow rate, V, through the puddled layer can be reduced by 97 to 99 percent for the soils studied. This means that if the entire wetted area of a channel or reservoir were puddled and if the puddling was thorough, water losses due to seepage could be considerably reduced. Naturally, because of limits to the amount of energy which might be put into a unit area of puddled surface, one could not expect a 97 to 99 percent reduction in seepage for comparable soil types in the field. But even a 50 percent reduction in seepage with only labor input might be worthwhile in countries with a labor intensive economy and a surplus of available labor.

Table 4 shows a sample of representative laboratory seepage data upon which the averages of Tables 2 and 3 are based.

Table 4

Representative Laboratory Seepage Data[1]
from Puddled Soil Sample

RUN NUMBER	LAPSED TIME (min)	SEEPAGE VOLUME (ml)	SEEPAGE RATE (ml/min)	SEEPAGE RATE (cm/hr)
1	24	2.0	0.083	0.100
2	29	2.4	0.083	0.100
3	31	2.7	0.087	0.104
4	25	2.0	0.080	0.096
5	26	2.3	0.088	0.106
			AVERAGE =	0.101

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[1] Seepage flask no. 1, University Village Garden soil, and puddled depth of four centimeters

Chapter 5

FIELD EQUIPMENT AND PROCEDURE

In order to study the effect of soil puddling on channel seepage under field conditions, three sites with differing soil textures were chosen on which test channels could be established. Two of these sites were in or near Fort Collins, Colorado, and one was near Grand Junction, Colorado.

In outline, the procedure followed at each field site was to:

1. Layout the channel.
2. Excavate the channel and line the inflow and outflow basins with polyethylene.
3. Cause particle orientation by recirculating water within the channel.
4. Cover the channel with polyethylene and install the hook gauge and float valve.
5. Determine initial seepage.
6. Puddle the channel test section with hand tools.
7. Determine seepage after hand tool puddling.
8. Puddle the channel test section with a rototiller.
9. Determine seepage after rototiller puddling.

Channel Construction

At each field site a 7.9 meter (26-foot) length of rectangular channel was excavated on a level grade. The channels were 0.61 meter (two feet) wide and approximately 20 centimeters (eight inches) deep (Figs. 9 and 10). Basins, 0.91 meter (three feet) in length, at either end of the channel were lined with 0.006 millimeter (0.0015 inch) polyethylene sheeting to prevent seepage from occurring in these areas.

Excavation of the channel was done by hand with a shovel and hoe after the channel was laid out with stakes and string. One of the channel basins under construction may be seen in Plate 4. The trough seen in this photograph was constructed with a hoe, one end of the polyethylene sheeting was placed in the trough, and the soil removed from the trough was replaced completely to form as tight a seal as possible between the basin and the channel test section.

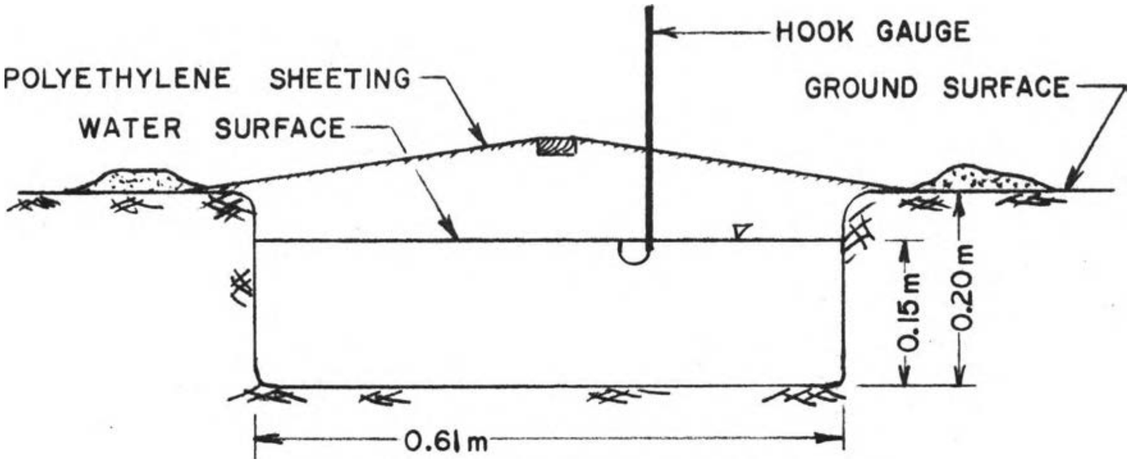

Fig. 9 Cross section through channel test section.

The basins were utilized in recirculating water within the channel so that proper particle orientation could occur before seepage data were taken. A gasoline-powered pump was used to recirculate water, and a velocity of approximately 15 centimeters per second (0.5 feet per second) was maintained for four to six hours as shown in Plate 5.

A conventional float type valve (Plate 5, foreground) maintained the desired water level of 15 to 18 centimeters (six to seven inches) in the channel during periods of time when data were not being collected. Tap water was used at all field sites to fill the channel. The entire channel was covered with polyethylene sheeting to minimize

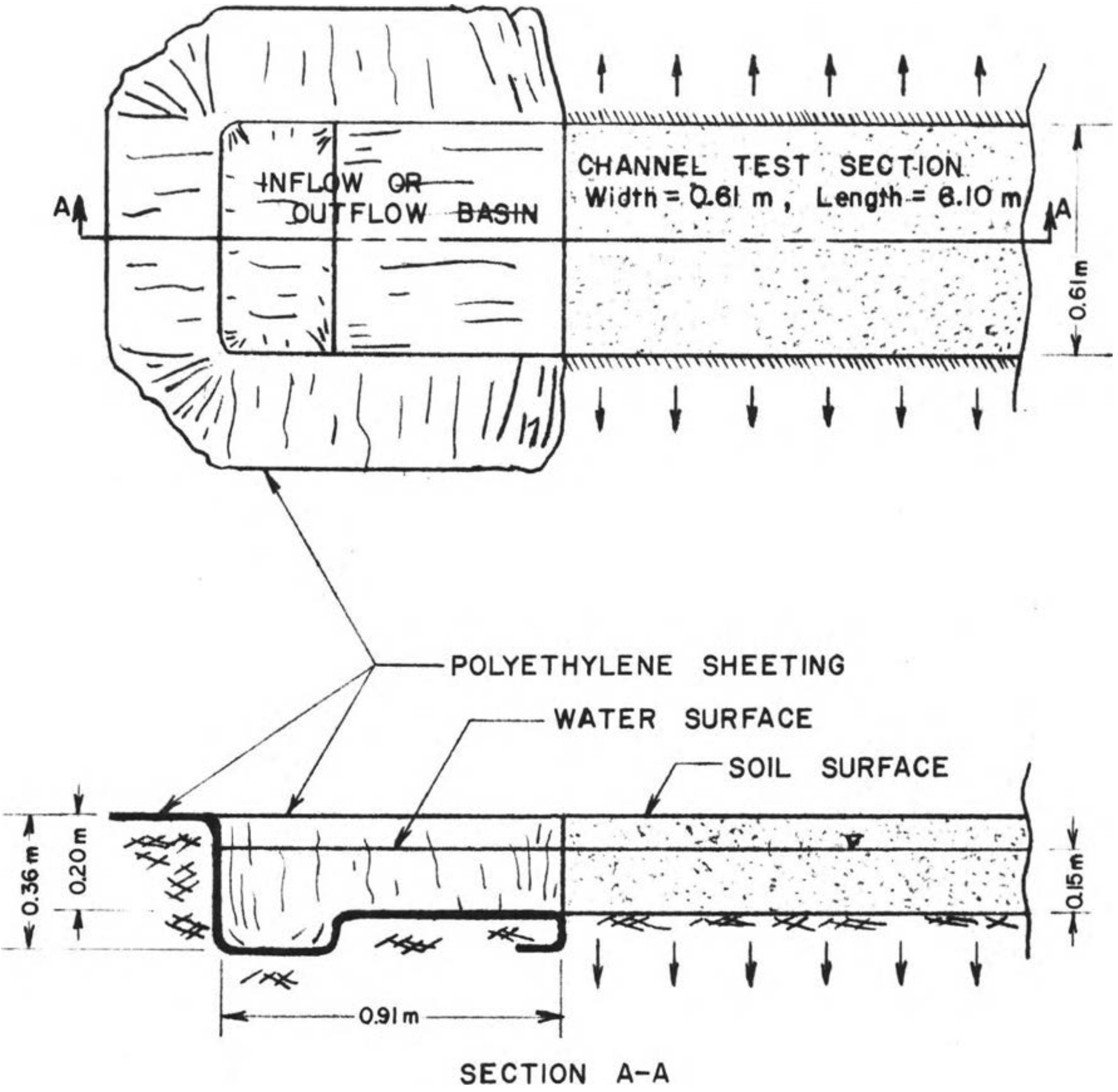

Fig. 10 Field site channel installation.

evaporation and to prevent precipitation from entering the channel (Fig. 9 and Plate 6). Therefore, water losses from the channel were due to seepage occurring only in the 6.1 meter (20-foot) test section of the channel.

A comparison of before and after puddling seepage rates was considered to be the primary thrust of this field work. The actual factors controlling seepage at the individual field sites such as soil hydraulic conductivity, location of the groundwater table, and stratification within the soil profile were considered to be of small importance as opposed to analysis of comparative seepage rates. In any case, the afore mentioned factors are of no consequence after puddling when the unsaturated flow condition is prevalent beneath the channel as discussed in Chapter 2. Mainly because of a time limit, not all parameters influencing seepage were measured in the field situation.

Obtaining Seepage Rates

Seepage was determined by using a conventional hook gauge to measure the drop in the water surface elevation with time. Plate 6 shows the hook gauge and its stand situated over the channel test section, and Plate 7 shows a close-up of the hook gauge itself. Hook gauge measurements were made in hundredths of a centimeter and corrected for the lined basins on each end of the channel. In other words, the hook gauge measured a water surface elevation drop over the entire channel length, but the volume of water represented by a drop in the water surface elevation within the basins was lost to seepage in the channel test section. Therefore, this volume of water must also be accounted for in the seepage calculation.

After the particle orientation period and after maintaining the channel water level for 12 to 16 hours, data to determine the initial seepage rate were taken. The incoming water supply was turned off, and the drop in water surface elevation was monitored for 20 minutes to one hour, depending on the seepage rate. After this initial data point was taken, one or more subsequent data points were taken before resupplying the channel with water. The incoming water supply valve was then opened to obtain the original channel water level, and a period of approximately one hour was allowed before extracting additional data.

This same procedure, as described, was followed in securing seepage data after puddling.

Soil Puddling Operations

The soil in the bottom of the channel was puddled under saturated conditions with hand tools or with a gasoline-powered rototiller. Only the channel bottom was puddled because the sides could not be puddled without causing erosion. Water depth in the channel was about 15 centimeters (six inches) during the time puddling was taking place.

Two tools were used in the hand puddling operation (Plate 8 and 9). Both of these tools are readily available in the United States, and the same or similar tools are available in most developing countries. Each tool was used for 20 minutes in the 40-minute puddling operation, resulting in 10.8 minutes of puddling per square meter (one minute per square foot) of puddled area.

The tool shown in Plate 8 known as a three-pronged, hand tillage tool, was used first and was good for loosening large clumps of saturated soil. Naturally, this tool could, and probably should, have a longer handle for the purpose of soil puddling. The full length of the test section was "worked up" with this tool before following with the second tool.

Plate 9 shows a tool which is called herein a heavy-tined garden rake. After a time lapse of 20 minutes for a particular area of soil (because the starting point was the same for both tools), this tool was able to stir the clumps produced by the first tool and cause them to break down further. It is believed that the 20-minute time lag between tool operations allowed the larger clumps to become softened by more direct exposure to the water in the channel.

The resulting, hand puddled soil layer varied from two to four centimeters (0.75 to 1.5 inches) in depth and contained little pore space. The puddled layer felt like a very viscous fluid immediately after puddling.

In some developing countries the social implications of doing strictly manual labor, such as would be required for hand puddling, are rather strong and negative. For this reason, a mechanical puddling method was considered. A five-horsepower rototiller, such as is used by home gardeners in the United States, was employed for mechanical puddling. This machine (Plate 10) was used without modification at both Fort Collins sites.

The machine is not self-propelled, but the rotation of the rotor makes forward movement easy. Plate 11 shows the machine in operation. The width of the rotor is 0.56 meters (22 inches), so the sides of the test channel were disturbed very little. Rotor diameter is 20 centimeters (eight inches).

The time required for the mechanical puddling operation was 4.3 minutes per square meter (0.4-minute per square foot) of puddled area, and this resulted in a puddled depth of from 12 to 18 centimeters (five to seven inches). The shallow layer of hand puddled soil was essentially broken up and incorporated into the mechanically puddled layer.

Unfortunately, some situations do not allow mechanical puddling with a rototiller of the type described. Attempts to mechanically puddle the soil at the Grand Junction site were unsuccessful. It is unclear whether this can be attributed to the soil condition and texture or to a somewhat different rotor on the rototiller available (Plate 12). A comparison of Plates 10 and 12 will show the differences in rotor design and width. Probably several factors entered into the failure of mechanical puddling at that site. In any case, the machine dug itself into the soil, water splashed onto the spark plug, and the machine drowned out repeatedly.

Chapter 6

FIELD DATA ANALYSIS

As described previously, seepage data were taken in units of centimeters per hour. To be in keeping with the work reported by others, these data will be reported as a volume of water lost to seepage per unit of wetted area per time. Obviously, volume/area/time is simply length/time, but the former manner of expressing seepage is used to avoid confusion with a measurement of the literal drop in water surface elevation over time, which does not account for the channel's wetted perimeter. Units used will be cubic centimeters per square centimeter per hour.

The general procedure followed in collecting field data was to:

1. Measure the drop in the water surface elevation over some time interval and compute the rate in centimeters per hour.
2. Correct the rate computed above for the lined channel basins by multiplying by 1.3 (the ratio of total channel length to test channel length is 26 feet/20 feet or 1.3).
3. Knowing the relationship between the hook gauge reading and the channel water depth, compute the average channel water depth for the time interval during which measurements were made for Step 1.
4. Multiply the average channel water depth by two and add the channel bottom width (61 centimeters) to obtain the average wetted perimeter.
5. Thinking in terms of the unit length of the channel, multiply the rate computed in Step 2 by the channel width and divide by the wetted perimeter to obtain a volume per unit wetted area per time.

Fort Collins Site Number One

The first channel was constructed near the Agricultural Engineering Shop facility at the old Rigden farm, five miles southeast

Table 5

Field Data Summary

CHANNEL LOCATION	RIGDEN FARM	UNIVERSITY VILLAGE GARDEN	BAILEY FARM
Soil testural name	clay loam	loam	silty clay loam
Percent sand	40	44	13
Percent silt	23	30	59
Percent clay	37	26	28
Average initial seepage before puddling, S_i, $cm^3/cm^2/hr$	1.52	3.67	2.72
Average seepage after puddling with hand tools, S_h, $cm^3/cm^2/hr$	0.64	1.40	0.59
S_h expressed as a percentage of S_i, $S_h(100)/S_i$	42	38	22
Average seepage after puddling with rototiller, S_r, $cm^3/cm^2/hr$	0.26	0.48	----
S_r expressed as a percentage of S_i, $S_r(100)/S_i$	17	13	----

of Fort Collins, Colorado. A site adjacent to, but not in, a pasture was chosen. This site was bounded on two sides by pasture and on two sides by fallow land. There was no evidence of pasture roots contributing to channel water loss.

Results of a mechanical analysis of the soil showed the soil was a clay loam. A 1.2-meter (four-foot) observation well did not locate a water table within that region before the channel was filled.

The average initial seepage rate before puddling was found to be 1.52 cubic centimeters per square centimeter per hour (1.2 cubic feet per square foot per day). The average seepage rate after puddling with hand tools was 0.64 cubic centimeters per square centimeter per hour (0.50 cubic feet per square foot per day). This implies a 58 percent reduction in seepage after puddling with hand tools.

An average seepage rate of 0.26 cubic centimeters per square centimeter per hour (0.20 cubic feet per square foot per day) was found after puddling with a rototiller, and this would indicate an 83 percent reduction in the average initial seepage rate (Table 5).

Fort Collins Site Number Two

This site was located west of a Colorado State University married student housing complex, University Village, on an area used as a community garden for students. The channel installation was surrounded by grass, and a large cottonwood tree and other smaller trees were growing close to the installation. Roots from these trees were evident during channel excavation and may have contributed to water losses from the channel test section. The depth to the water table from the soil surface was 0.9-meter (three feet). Seepage from a large irrigation channel was causing the water table to be excessively high.

A mechanical analysis indicated the soil was a loam. This soil was underlain with a clay soil at a depth of 0.9-meter to 1.2 meters (three to four feet).

The average initial seepage rate before puddling at this site was found to be 3.67 cubic centimeters per square centimeter per hour (2.89 cubic feet per square foot per day). After puddling with hand tools, the average seepage rate dropped to 1.40 cubic centimeters per square centimeter per hour (1.10 cubic feet per square foot per day) for a 62 percent reduction in seepage.

With rototiller puddling, the average seepage rate dropped to 0.48 cubic centimeters per square centimeter per hour (0.38 cubic feet per square foot per day), giving an 87 percent reduction in seepage compared with the initial losses (Table 5).

Grand Junction Site

This site was located on the Bailey Farm, southeast of Grand Junction, Colorado. The installation was constructed parallel to, and approximately seven meters (24 feet) from, a small irrigation channel used for water delivery on the farm.

The soil was a silty clay loam. The soil profile in the area contained cavities of unknown origin with a diameter of seven to ten centimeters (three to four inches) and a length of approximately one meter (three to four feet). A hoe handle could be pushed into one cavity with very little effort. Cavities of the type described were evident in the existing irrigation channels on the farm.

Seepage rates as determined by other Colorado State University researchers in the area were found to be highly variable. These rates varied from 0.2 to 3.2 cubic centimeters per square centimeter per hour (0.15 to 2.55 cubic feet per square foot per day) for channels in the immediate area of the Bailey farm. These higher seepage rates may be due to the soil cavities evident in the distribution channels of the area and are probably the cause of the high water table on the farm. The water table was 0.76 meter (2.5 feet) below the soil surface at the installation site.

Several soil cavities materialized during excavation of the channel test section, and these were allowed to remain as they appeared very similar to the cavities found in the existing channels. Hand puddling tended to close up the cavities and reduce seepage through them.

The average initial seepage rate before puddling was 2.72 cubic centimeters per square centimeter per hour (2.14 cubic feet per square foot per day), a rate within the range found by other researchers. The average seepage rate after puddling with hand tools was 0.59 cubic centimeters per square centimeter per hour (0.46 cubic feet per square foot per day), resulting in a seepage reduction of 87 percent (Table 5).

As mentioned earlier, rototiller puddling of the channel test section was not possible.

Table 6 presents representative field data from the Bailey farm field site and illustrates the way in which the seepage rates were computed.

Table 6

Representative Field Seepage Data from Bailey Farm--Hand Puddled Condition

DATE	TIME LAPSE (min)	CHANGE IN WATER SURFACE ELEVATION (cm)	UNCORRECTED[1] SEEPAGE RATE (cm/hr)	CORRECTED SEEPAGE RATE (cm/hr)	AVERAGE WATER DEPTH (cm)	WETTED PERIMETER (cm)	SEEPAGE EXPRESSED AS VOLUME PER WETTED AREA PER TIME (cm^3/cm^2/hr)
Sept. 6	23	0.25	0.652	0.85	16.9	94.8	0.55
Sept. 6	18	0.20	0.666	0.87	15.8	92.6	0.57
Sept. 6	23	0.26	0.678	0.88	16.2	93.4	0.57
Sept. 7	22	0.26	0.709	0.92	15.4	91.8	0.61
Sept. 7	23	0.35	0.913	1.19	16.6	94.2	0.77
Sept. 7	19	0.22	0.695	0.90	15.6	92.2	0.60
Sept. 7	25	0.24	0.576	0.75	17.9	96.8	0.47
						AVERAGE[2] =	0.59

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[1] Uncorrected for lined channel basins

[2] This average is utilized in Table 3

Chapter 7

DISCUSSION OF METHODS AND RESULTS

Natural Puddling

A certain amount of natural soil puddling probably occurs in most unlined irrigation channels over time. When the channel is in use, the soil in the bottom of the channel would, in most cases, be saturated, and the weight of the water in the channel would tend to puddle the soil. Also, animals might walk along the channel bottom, thereby causing some puddling due to compaction.

Figure 20 shows a trench dug through the cross section of a seven year old irrigation channel in southeastern New Mexico. A layer approximately ten centimeters (four inches) in depth was found to be more dense as compared to the soil underneath and in the field. Each time a soil probe was pushed through this layer, an eight- to ten-centimeter (three- to four-inch) soil column could be found in the top of the probe, and the rest of the soil in the probe would crumble away easily. This indicated some amount of natural puddling in this channel.

It should be noted that the test channels constructed in the field were not given time to develop the characteristics of a channel in use for a great deal of time. In all probability, the seepage losses found are representative of the losses which would be found in a newly constructed channel, under those conditions given, and for that soil type. However, the seepage losses in most newly constructed channels would gradually decrease over time depending on the amount of use and other conditions. This factor could not be accounted for in this research. However, as pointed out in Chapter 5, a particle orientation period was allowed to more nearly simulate actual conditions.

Purposely puddling a channel may be thought of as a means of speeding up and magnifying the natural aging process. Under conditions of shifting agriculture when field and home sites are changed every two to five years, puddling would be a particularly useful channel lining method.

Stratification within the Puddled Layer

Stirring the soil by hand puddling or by rototiller puddling is much more effective as compared to natural puddling because of much more complete puddling and because of a stratification which occurs within the puddled layer. After the test channel was puddled, either by hand or by rototiller, it took as much as 30 hours for the suspended sediments to settle out. The first particles to settle were the more coarse materials followed by finer and finer materials. This caused the topmost layers within the puddled layer to be composed entirely of fine materials. Possibly this stratification effect is the primary reason why puddling reduced seepage in the test channels by as much as 87 percent.

Plate 14 shows a cross section through a hand puddled layer at Rigden farm field site. The lighter colored strip in the cross section is a layer of coarse materials which settled out first.

Puddling may also be accomplished by compacting the soil in a saturated state. However, it would not be possible to obtain the stratification within the puddled layer with compaction, and this is an apparent advantage to puddling the soil by stirring in some way. Rice cultivators have for many years puddled rice paddy soils to prevent excessive seepage from the paddy. One means of accomplishing this is to pull a large stone wrapped inside a straw mat around through the paddy, generally by animal power (Matsushima, 1961).

The depth of water in the channel at the time of puddling would also have an effect on stratification. Puddling could be done with only a small amount of water as long as the soil is saturated, but the stratification effect would be minimal without enough water to hold a lot of fine materials in temporary suspension.

Intermittent Channel Use

If a puddled layer of soil is allowed to dry, it will contract and crack as shown in Plate 15. However, when the channel is again filled with water, the cracks start closing up, and the seepage, which may be high initially, begins to reduce. The photograph shown in Plate 16 was taken just five minutes after water began to fill the dry channel.

It is not known if a puddled layer can regain its full effectiveness after drying and cracking. This would be at least partially dependent on soil type, and this aspect of soil puddling was not fully studied. More clay particles in the soil would cause more expansion upon wetting and probably tend to more fully restore the effectiveness of the layer.

Tools for Puddling

The tools described worked well for puddling, but they are certainly not the only possibilities. Tools available in the developing countries may be much more suited for the purpose. For example, one intriguing hoe called a katsina (Fig. 11), used by certain tribes in Nigeria, might be very useful for soil puddling (Meek, 1925). The actual blade could be used for loosening chunks of saturated soil, then the tool could be inverted and used as a rake for stirring.

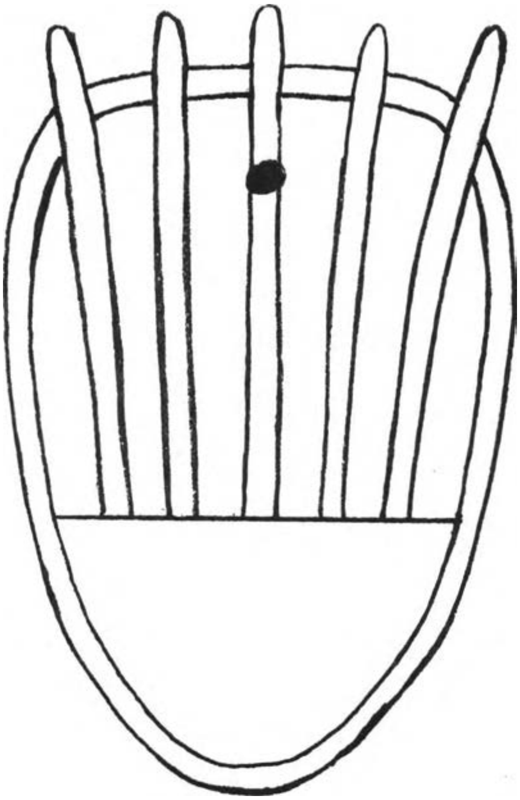

Fig. 11. Sketch of a Nigerian hoe called a katsina made of wood and metal (after Meek, 1925).

Also, some type of animal drawn tool similar to a spike-toothed harrow could be employed. Such a device could be pulled along the channel bottom by animals on either side of the channel, or by one animal walking in the channel.

Rototillers with special rotors developed for puddling specifically and with better "floatation" on saturated soil would hold promise too. "Squirrel cage" type wheels such as those used on rice paddy tractors might be utilized.

Puddling in Practice

Ideally, a channel which is to be puddled should be dammed up in sections short enough to allow water to be ponded. The length of these sections would depend on the channel slope and on the water depth desired. Twelve to 15 centimeters (five or six inches) of ponded water would seem to be adequate.

Unfortunately, the channel must be taken out of service for the puddling operation suggested, or flow in the channel would tend to carry the fine materials downstream to be deposited elsewhere. Also, the potential for channel scour would be higher. Most on-farm, water distribution channels can be taken out of service between irrigations or during non-cropping seasons of the year.

The entire wetted perimeter of trapezoidal, parabolic, or triangular channels with small gradient sides should be puddled whenever possible. More substantial seepage reduction can be anticipated for the reasons discussed in Chapter 2.

Soil puddling would be particularly well suited for reducing seepage from on-farm reservoirs used in water storage. Scour of the puddled layer and cracking due to intermittent use would not be a problem in most cases, and sedimentation over time would contribute to further reductions in seepage. Also, the entire wetted area could be puddled for reservoirs with small gradient sides.

Maximum Permissible Velocity for the Puddled Layer

The maximum permissible velocity is the greatest mean velocity that will not cause erosion (scour) of channel bottom or sides. This velocity is uncertain and variable, and an estimate requires judgment based on experience.

Puddling of the channel would tend to lower the maximum permissible velocity especially when the stratification effect causes the fine materials within the soil to accumulate on the top of the puddled layer.

This would be a distinct disadvantage in puddling an existing channel for which the mean velocity was greater than the expected maximum permissible velocity of the puddled layer.

Fortier and Scobey have reported maximum permissible velocities for various materials as shown in Table 7 (Fortier and Scobey, 1926), and it is recommended that these velocities be used when possible. A gravel blanket over a puddled layer could be used to substantially increase the maximum permissible velocity of a channel. The design criteria for such a blanket are discussed by Skogerboe, Somoray, and Walker (1971).

Table 7

Maximum Permissible Velocities Recommended by Fortier and Scobey (1926)

MATERIAL	VELOCITY, fps, for clear water
Fine sand, colloidal	1.50
Sandy loam, noncolloidal	1.75
Silt loam, noncolloidal	2.00
Alluvial silts, noncolloidal	2.00
Ordinary firm loam	2.50
Volcanic ash	2.50
Stiff clay, very colloidal	3.75
Alluvial silts, colloidal	3.75
Shales and hardpans	6.00
Fine gravel	2.50
Graded loam to cobbles, noncolloidal	3.75
Graded silts to cobbles, colloidal	4.00
Coarse gravel, noncolloidal	4.00
Cobbles and shingles	5.00

Depth of Flow

When only the channel invert is sealed against excessive seepage, the flow depth becomes important. A greater flow depth increases seepage, as more water can be lost through the channel sides. Thinking in terms of the rectangular test channels described, this means that the ratio of bottom width to flow depth has an effect on seepage. The ratio of bottom width to flow depth for the test channels was approximately four. Seepage in the test channels could be expected to increase with a ratio smaller than four and decrease with a ratio greater than four, assuming total flow and other variables remain constant. So, channels which are to be puddled should be as wide as practical under the circumstances to get maximum reduction in seepage.

Anticipating Puddling Effectiveness

It is recommended that, if possible, the entire wetted perimeter of a channel should be puddled. In this case, Eq. 1 may be used to calculate a flow rate, V, which could be expected through the puddled layer. Laboratory results indicate that, for the soil textures studied, this flow rate through a thoroughly puddled layer of soil can be expected to be between 0.15 and 0.18 centimeters per hour (0.06 and 0.07 inches per hour) with an H_w of approximately one centimeter (0.4-inch) and an L_a of four to ten centimeters (1.5 to four inches). So, under most conditions, substantial reduction in seepage could be expected when the entire wetted perimeter is to be puddled.

Equations 2 and 3 may also be used when the entire wetted perimeter is puddled to compute the rate of fall, $\bar{I}_s$, of the water surface in the channel as if the channel were ponded.

If only the channel invert is to be puddled, it is recommended that:

1. Initial seepage should be calculated using Bouwer's (1965) charts for the channel and conditions anticipated, or in the case of an existing channel, the initial seepage could be measured in the field.
2. An estimate of the effect of completely sealing the channel bottom should be made from Fig. 7 or from a judgmental evaluation. The seepage after completely sealing the channel invert should then be calculated.
3. The seepage rate, V, through the puddled layer should be calculated using Eq. 1.
4. The after puddling seepage rate, based on the necessary estimates, should then be calculated as the sum of the seepage rates calculated in Steps 2 and 3.

Chapter 8

SUMMARY AND RECOMMENDATIONS

Results of the research reported herein indicate that soil puddling does have potential as a method of reducing seepage from irrigation distribution channels. Laboratory tests conducted under idealized conditions and intensive puddling show that the flow rate through a thoroughly puddled layer can be drastically reduced as compared to the flow rate through an unpuddled sample.

Field tests conducted under more realistic circumstances with only the channel invert puddled also indicate significant seepage reductions are possible. Mechanical puddling produces greater seepage reductions with less labor input than hand puddling methods, but hand puddling can be accomplished with tools already available to most agriculturalists of the developing countries. Animal powered puddling would also be feasible.

It was not possible to examine all the different aspects associated with soil puddling because of a lack of time. In order to fully understand the potential of soil puddling for reducing seepage, it is suggested that the following be investigated:

1. The effect of varying velocities on the puddled layer of differing soil types should be investigated.

2. The effect of soil or water salinity on seepage through the puddled layer should be studied.

3. The possibility of puddling the entire wetted perimeter of trapezoidal or parabolic channels should be researched.

4. The effect of various puddled depths on seepage rates should be examined for various soil types. A point of diminishing returns could be found for a particular soil type.

5. An animal drawn device could be employed for puddling, and this possibility should be investigated, as should the development of a rototiller-like machine specifically for puddling.

6. The effect on the puddled layer of alternate wetting and drying under intermittent use should be studied.

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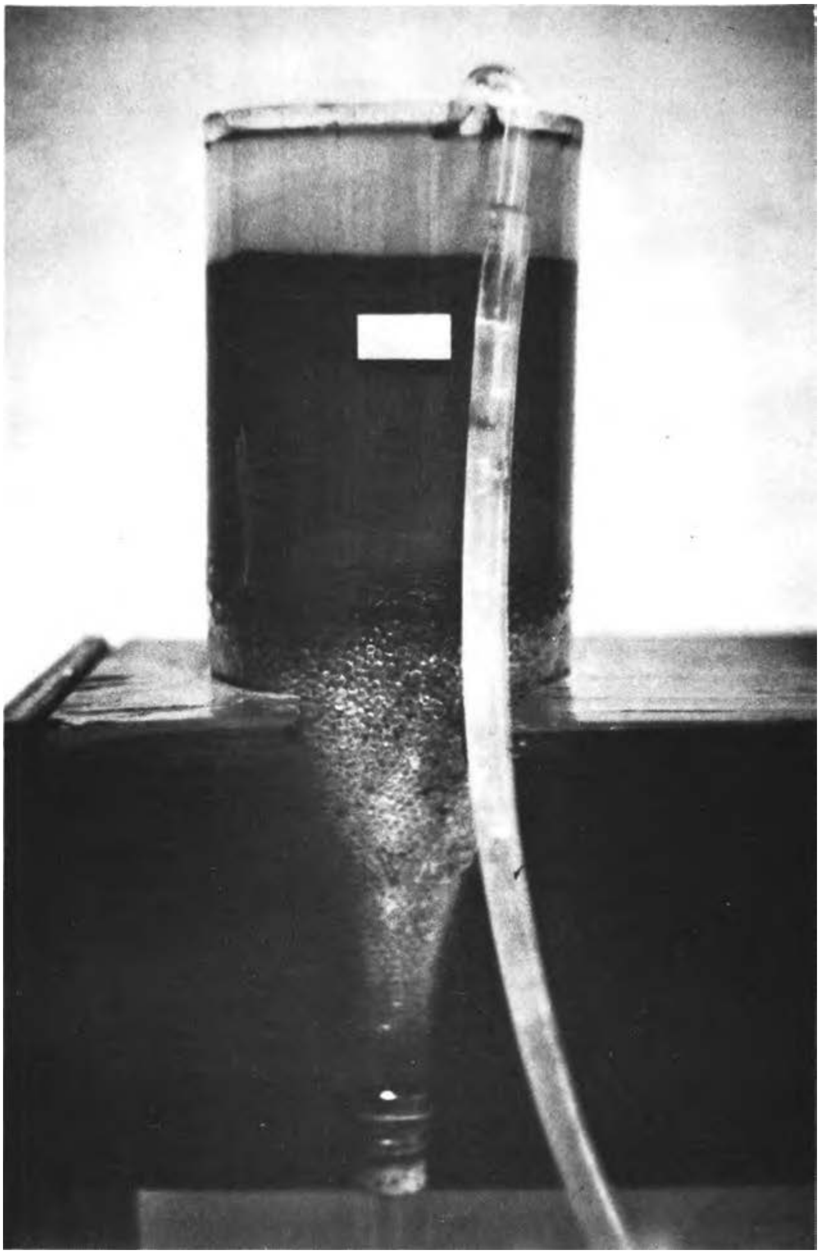

Plate 1. Laboratory seepage flask.

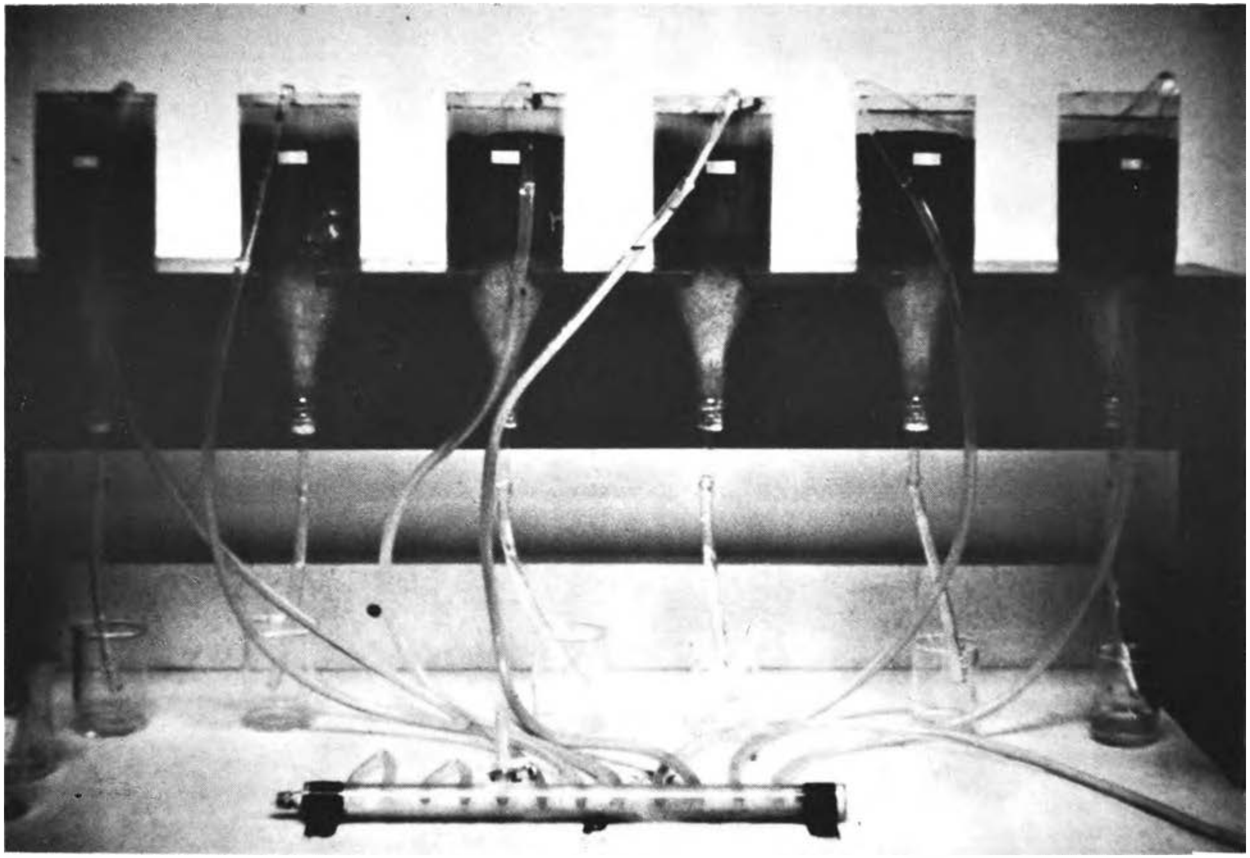

Plate 2. Laboratory installation showing arrangement of seepage flasks.

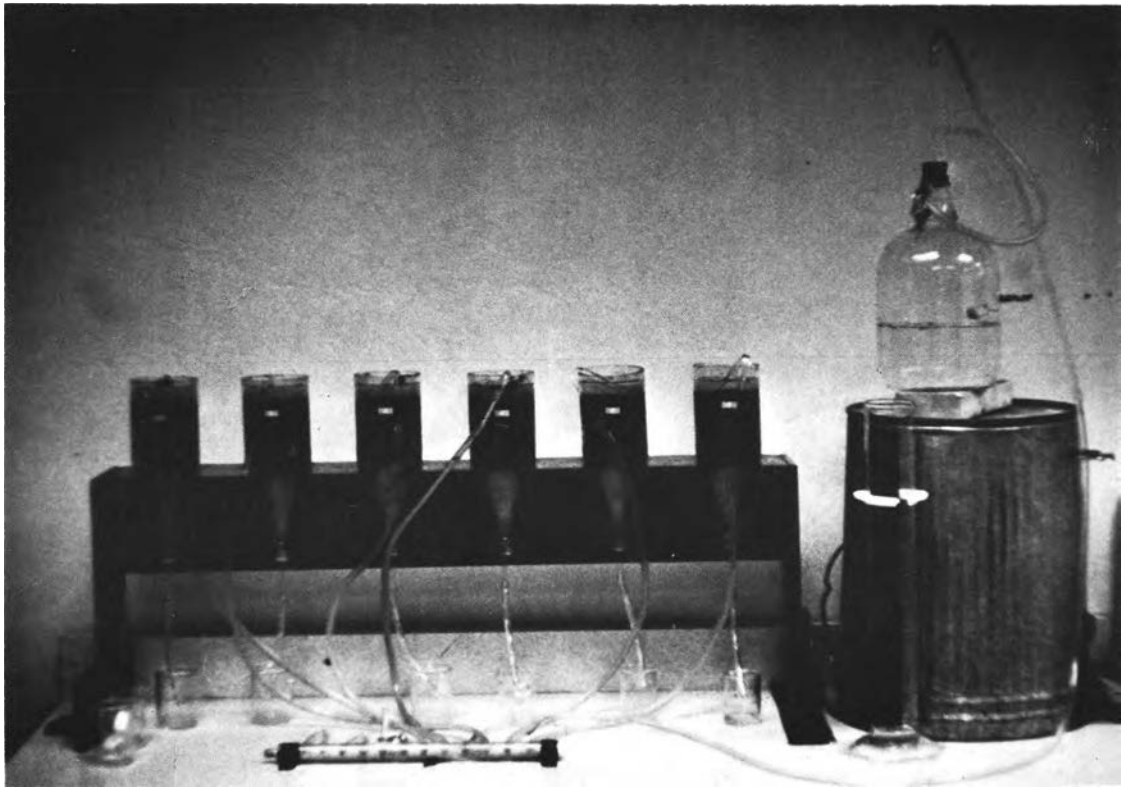

Plate 3. Laboratory installation showing Mariotte syphon system.

Plate 4. Channel basin under construction.

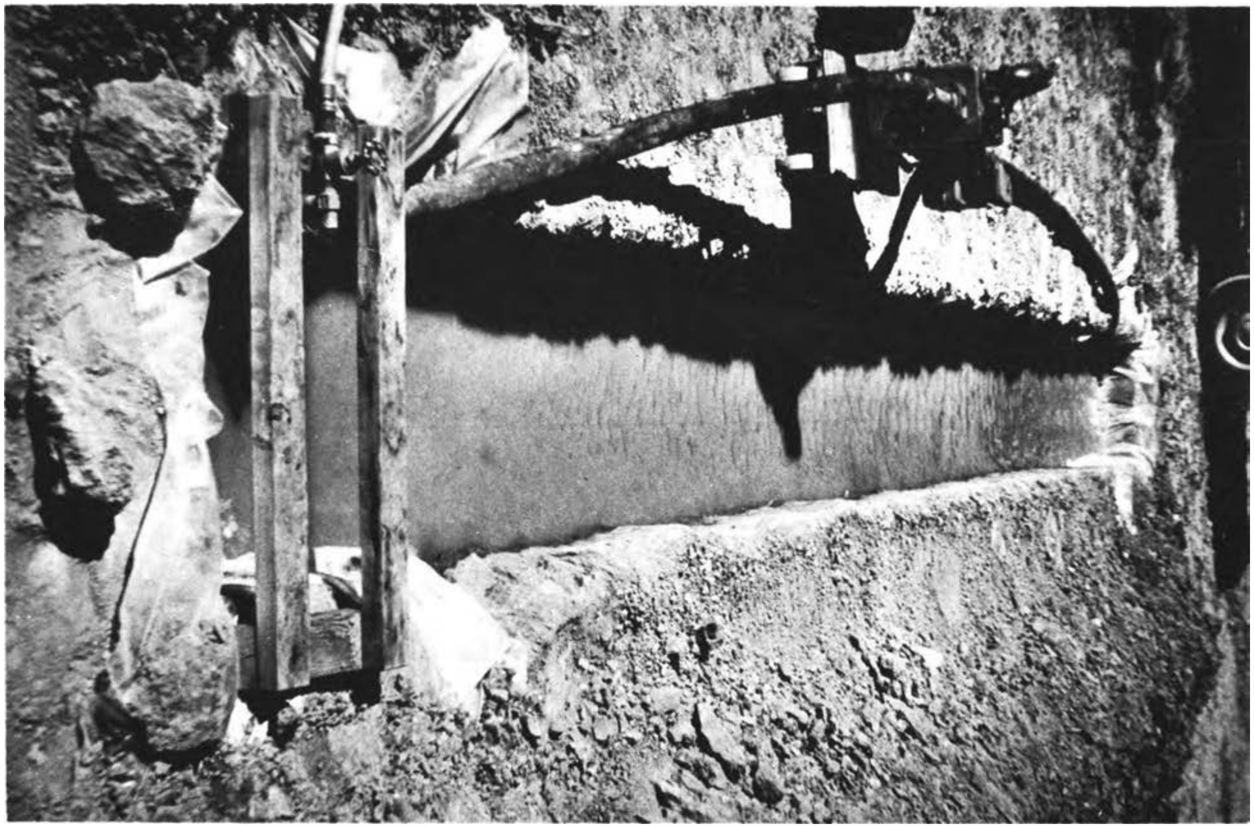

Plate 5. Channel installation during particle orientation period at the Grand Junction field site.

Plate 6. Polyethylene covered channel at the Grand Junction field site.

Plate 7. Hook gauge used in measuring the change in water surface elevation.

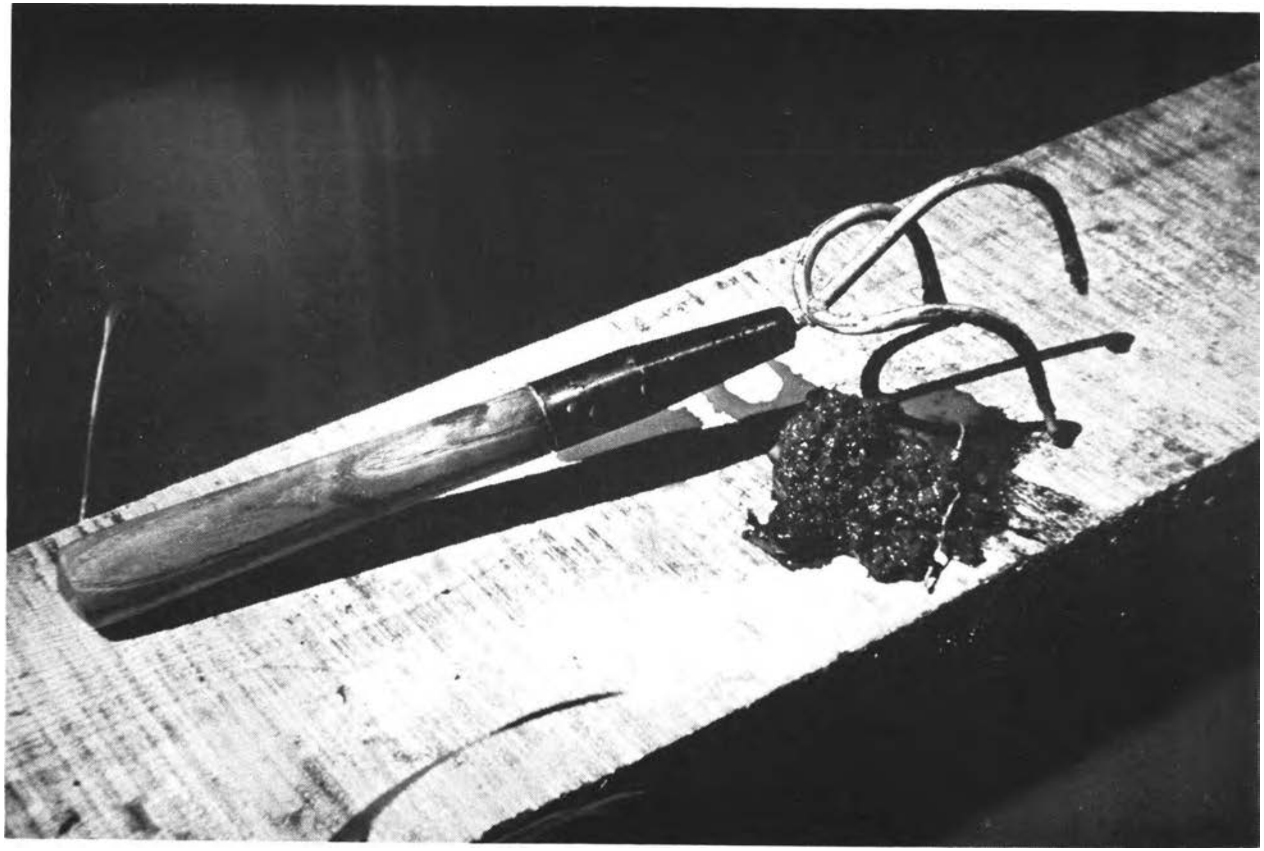

Plate 8. Three-pronged hand tool used in the hand puddling operation.

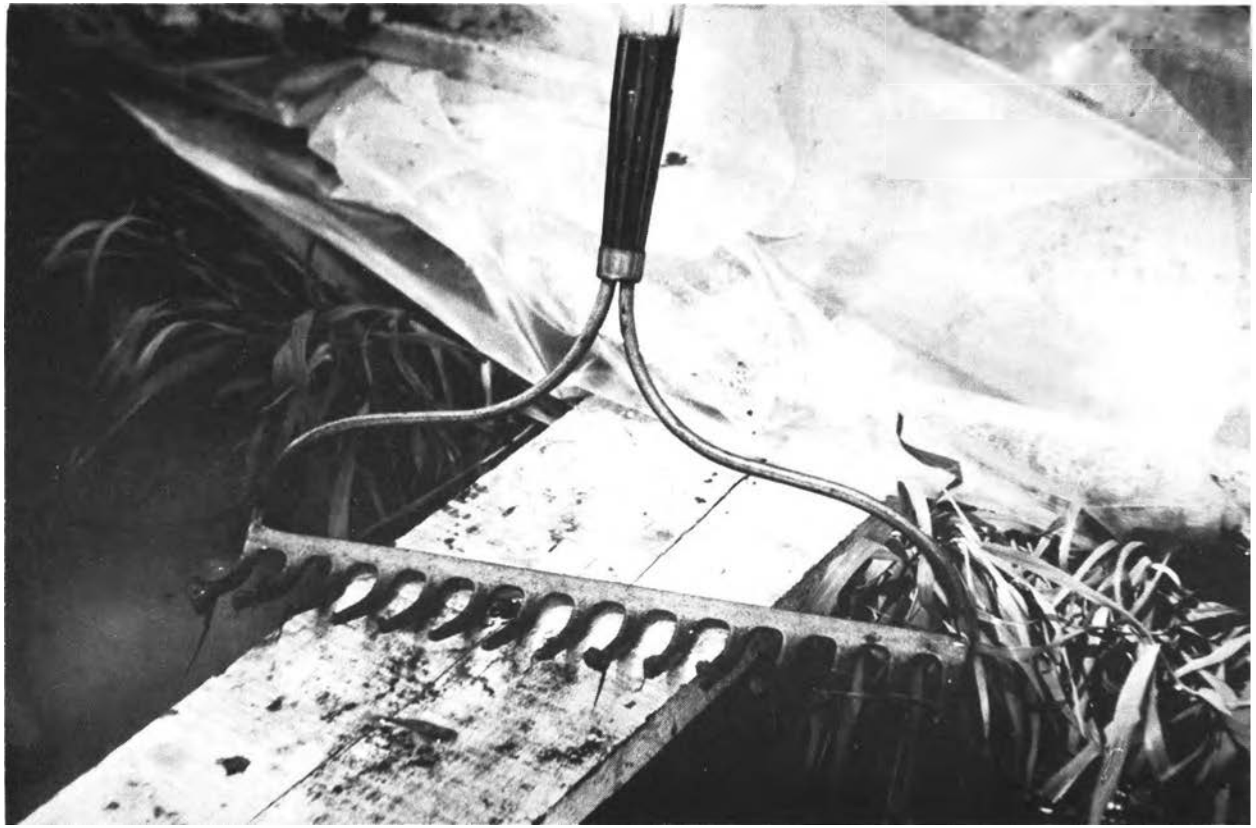

Plate 9. Heavy-tined garden rake used in the hand puddling operation.

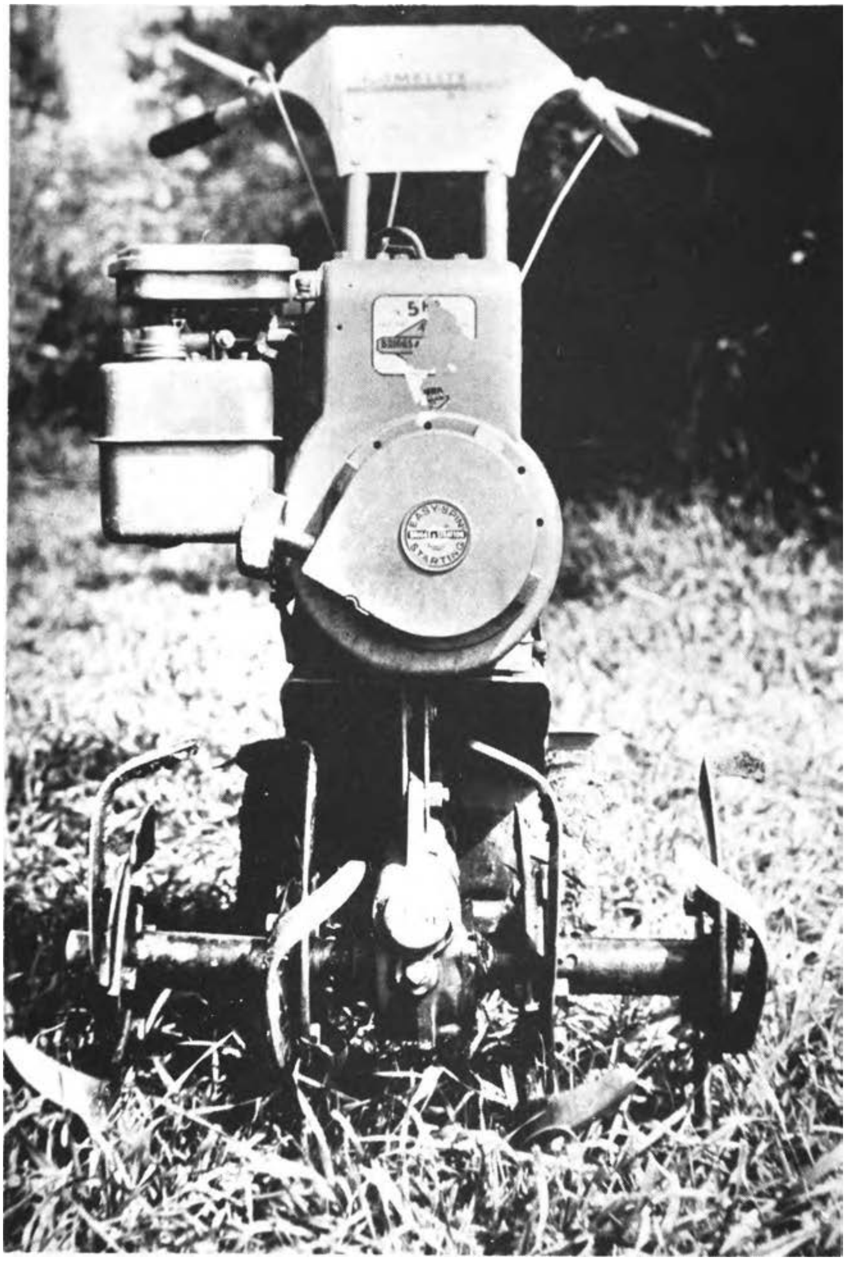

Plate 10. Five-horsepower rototiller used in mechanically puddling the test section soil at the two Fort Collins field sites.

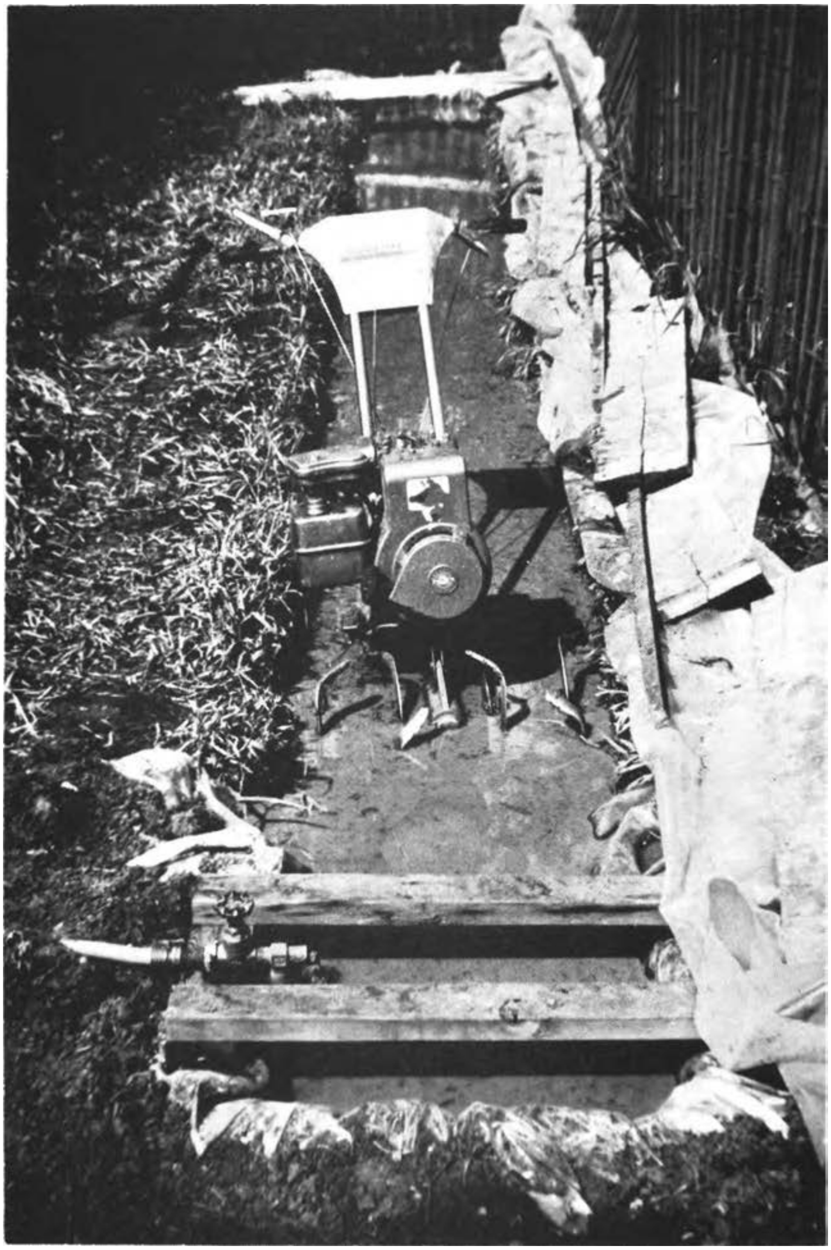

Plate 11. Rototiller puddling at the University Village garden field site.

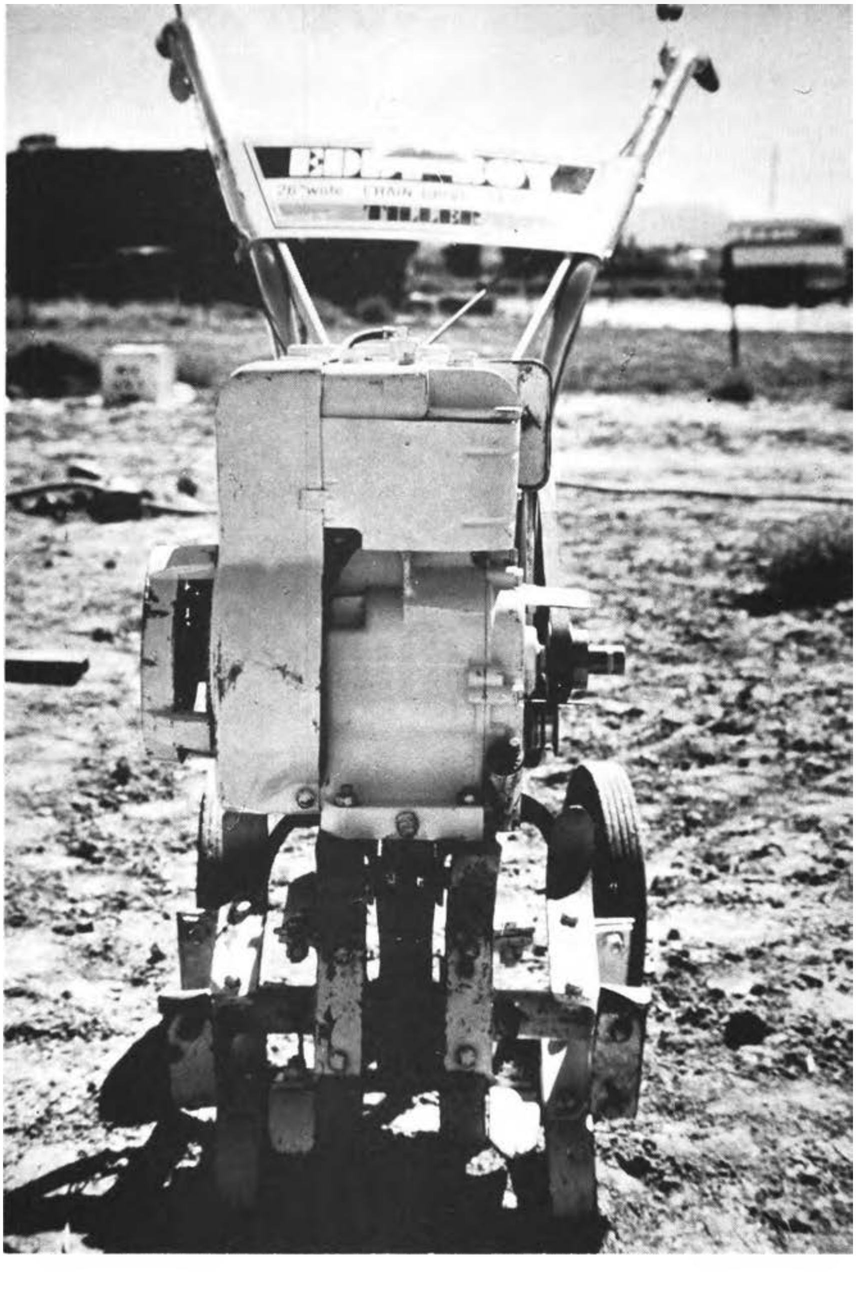

Plate 12. Five-horsepower rototiller used unsuccessfully at the Grand Junction field site.

Plate 13. Cross section through a seven year old, on-farm irrigation channel in New Mexico.

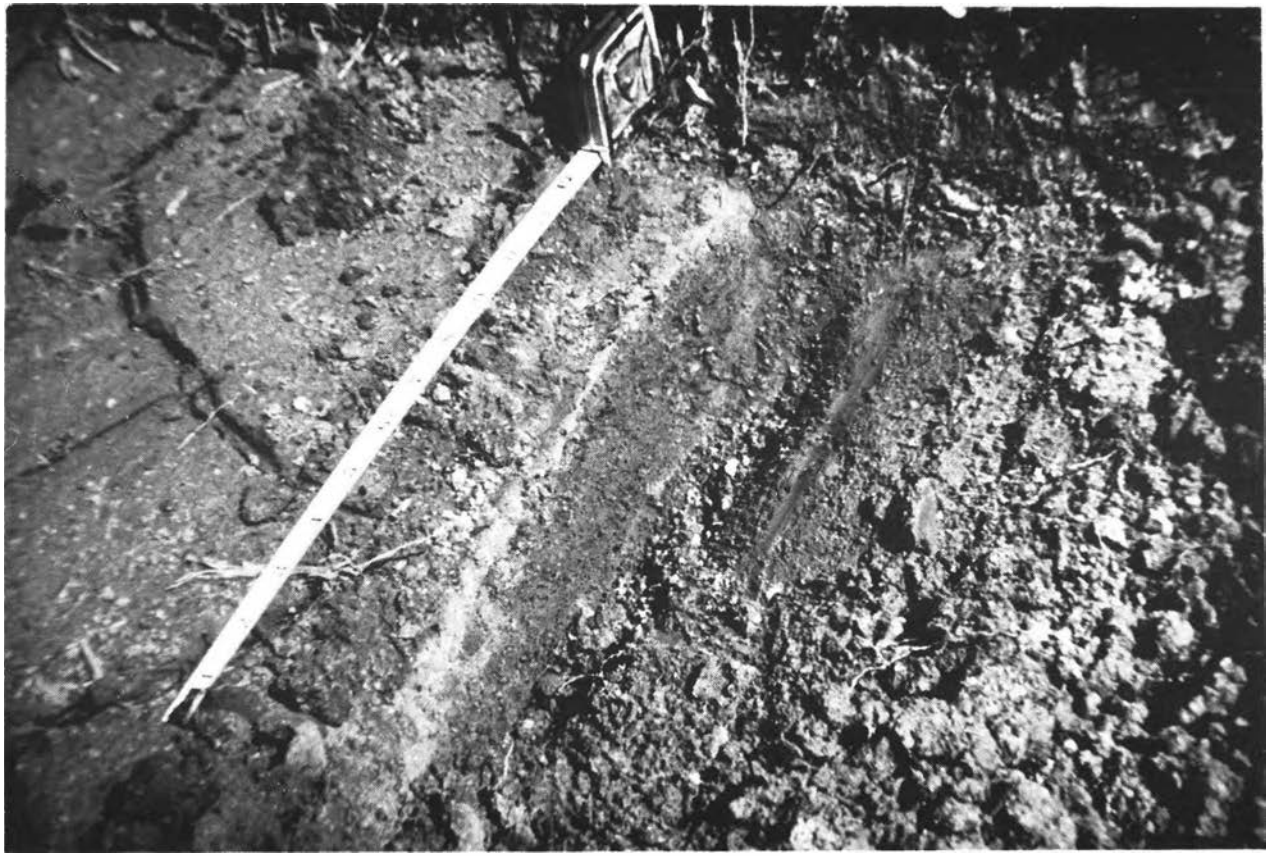

Plate 14. Cross section through the hand puddled layer of the channel test section at the Rigden farm field site.

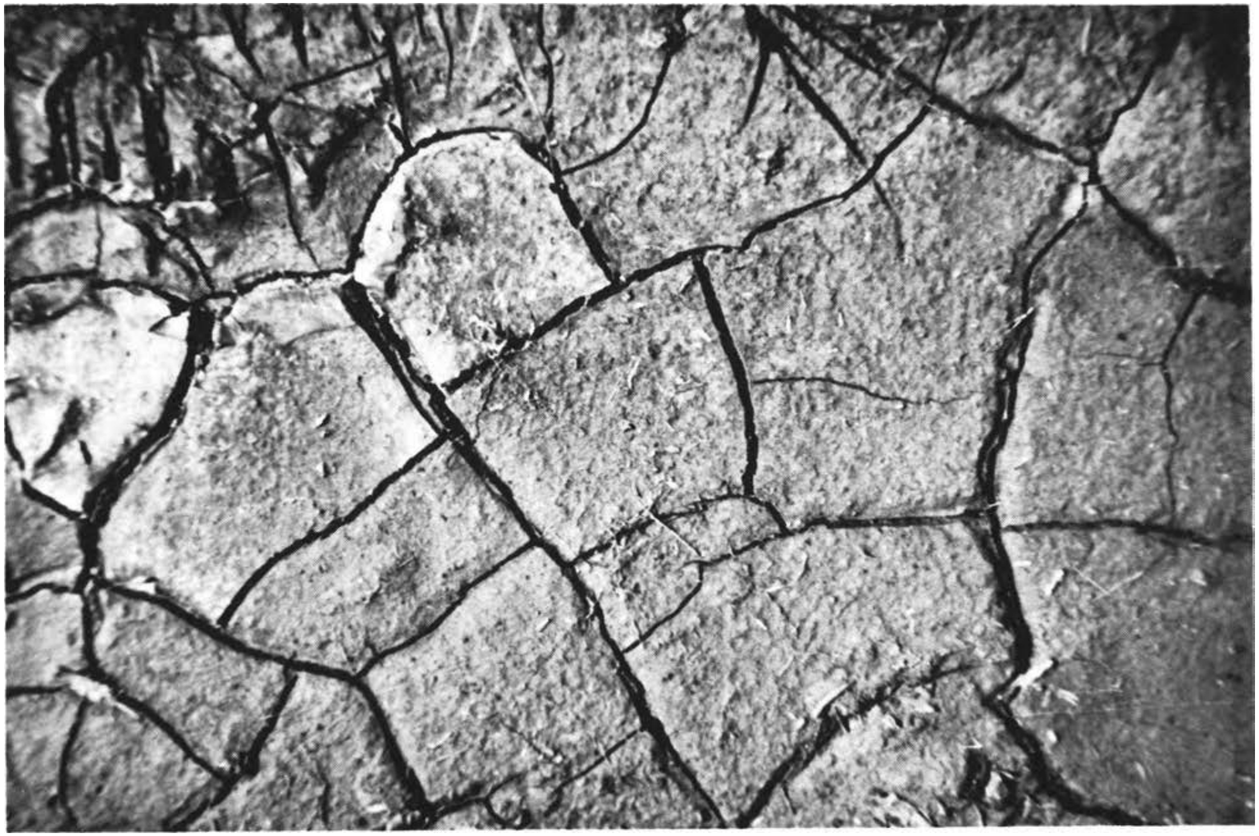

Plate 15. Soil cracks in the hand puddled layer after drying at the Rigden farm field site.

Plate 16. Soil cracks in the hand puddled layer immediately after refilling the channel with water.