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WATER ENTRY INTO A BLACK EARTH UNDER FLOODING

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SUMMARY

A study was made of rates of water entry and various conditions governing them during winter crop and summer fallow on a black earth of the Darling Downs in southern Queensland. The importance of water access *via* the gross cracking system characteristic of the soil over a wide section of the field moisture range was established. Where the void system was not open at the surface, water entering dry fallow soil was shown to be controlled by the increasing depth of wet front in conjunction with flood duration. During the drying cycle under cropping, water entry was controlled by soil percolation rate when wet and by the macro void system when dry. Curves showing changes in infiltration rate into soil below a depth of 4 in. were established for the Waco soil type.

Figures to enable determination of the flood durations necessary to bring the soil moisture in the profile to peak water-holding capacity were established on a Waco soil for a range of antecedent conditions.

I. INTRODUCTION

The practice of water-spreading is being investigated on the black soil Darling Downs in southern Queensland for use in flood mitigation and erosion control. As moisture is a limiting factor in crop growth in the area, the beneficial effect of added water and water storage is also under investigation. Information is necessary on degrees of inundation necessary to benefit crops as well as levels of detention necessary to produce the desired changes in run-off pattern. Basic to this knowledge is information on factors controlling water intake over the full range of antecedent soil conditions.

The predominant soil in areas suitable for spreading run-off is the Waco clay gilgai complex described by Beckman and Thompson (1959). This is a heavy self-mulching clay of high water-holding capacity. Profile differentiation within the root zone (approximately 5 ft) is small. Available water storage capacity is high—up to 2 in. per ft depth of profile. There is evidence that this soil storage capacity is rarely fully utilized under dryland cropping (Waring, Fox, and Teakle 1958).

Water intake recordings on this soil have been extremely variable and range from a rapid addition of 8 in. of water when dry (I. W. D. Barlow, unpublished data) to base infiltration rates of 0·02 in./hr and less when wet (W. J. Roche, unpublished data). This variation appears to be chiefly a result of the phenomenon of gross soil cracking described by Fox (1963). Water entering through cracks penetrates by gravity to the base of the macro void system, allowing multi-directional water entry into dry soil. Stirk (1954) demonstrated that water entry is affected by this soil property on a number of soil types. Lauritzen and Stoltenberg (1940) concluded that stable and inter-connected voids in the soil played a major part in determining water entry.

Gross cracking is the result of a three-dimensional contraction on drying and exists in field soil below a specific moisture percentage. This void space is, however, ineffective in water penetration unless it is open at the surface (Bodman and Colman 1944).

Under surface sealed conditions, water entry occurs only through the soil mass in a wetting front. Many factors affect penetration of water in a wetting front. It is generally conceded that on high clay soils antecedent moisture plays an important role in the early stages of water application (Tisdall 1951). Reinhart and Taylor (1954) considered that infiltration rate of fine-textured soils in the initial period is governed primarily by moisture deficit, and as infiltration proceeds, by low permeability. Bodman and Coleman (1944) established a diminishing infiltration rate:time relation which they attributed to a decrease in moisture potential gradient resulting from a vertical elongation of the water transmitting zone. Guidici (1954) established that on a clay soil, depth of penetration increased with the square root of time. He considered penetration to be independent of gravity. Major controlling factors were surface tension, viscosity and air pressure in the soil matrix.

Advance of a wet front is affected by the antecedent moisture level of soil layers through which it passes. Philip (1957) stated that increased initial moisture reduces infiltration rate but increases velocity of advance of the wet front. As water entry proceeds, the influence on infiltration rate becomes less and ultimately negligible, while the influence on advancing wet front becomes more marked. Hansen (1955) explained the more rapid advance of a wetting front in a moist soil by the fact that less energy is required at the wetting front to expand the meniscus and allow water to enter the soil. Initial flow is in larger channels with less energy expenditure. Green (1962) based his investigations on suction differential at the wetting front and considered that the higher measured equilibrium infiltration rates on a dry soil than on wet soil are due to higher potential gradient in the former case.

Philip (1957) suggested that an increase in depth of water on the soil surface increases infiltration rate and cumulative infiltration. As time increases, the effect on infiltration rate decreases and is ultimately negligible. In dry soil the hydrostatic pressure involved becomes less significant. The effect of depth diminishes in heavier soils where forces involved in water retention become very high (Guidici 1954).

Under most field conditions, there is a high water intake potential in the dry surface layers. This corresponds with the major evaporation zone and for storage purposes can be ignored. Investigations described here were therefore confined to water entering soil below the major evaporation zone, which on this soil is approximately 4 in.

II. METHODS

(a) General

Experimental work was conducted at a number of sites, all on the Waco soil type. Slight variations in soil characteristics occur between sites but where necessary these are specified.

Soil determinations in all trials were made to a depth of 5 ft at intervals of 0-4 in., 4 in.-1 ft, 1 ft-2 ft, 2 ft-3 ft, 3 ft-4 ft, and 4 ft-5 ft.

In assessing levels of soil moisture storage, the 0-4 in. surface soil has been omitted; maximum water-holding capacity 4 in.-5 ft was used as the basis of comparisons between sites.

Moisture determinations were conducted gravimetrically, with drying at 105°C. Standard bulk density moisture percentage relationships for the experimental sites were established, using the method described by Fox (1963). Equivalent moisture depth results were calculated using this data.

(b) Flooding During Crop Growth—Moisture Distribution Uniform

(i) *Profile wet above the level of three-dimensional contraction.*—Field plots under wheat at the late vegetative growth stage were artificially brought to three soil moisture levels within the specified range. At each level moisture was evenly distributed in the profile and all moisture percentages were within the uni-dimensional contraction range. This was achieved by rapid flooding of the plots and maintenance of the water head for varying short durations. Plots at the three antecedent moisture levels were produced in three flood bays. These bays were subjected to flooding treatments of 2, 5 and 9 days' duration. Soil moisture determinations were conducted on all plots immediately before water application and approximately 2 weeks after flooding was completed.

(ii) *Profile dry, with extensive void space.*—Two investigations were carried out on soil within this range. An extensive trial was conducted using flood durations exceeding 2 days. A supplementary study of water entry with flood durations up to 20 min was also made.

A series of plots at three different moisture levels within the specified range, and carrying a stand of wheat, were flooded artificially with 4 depths x 3 durations of flooding. In all cases interconnected void space was open at the surface. Treatments were as follows:—

Average total antecedent moisture levels: 26·1 in., 24·7 in., 23·8 in.

Flood depth treatments: 2 in., 5 in., 8 in., 11 in.

Flood duration treatments: 2 days, 5 days, 9 days.

Sub-blocks of 4 depth x 3 duration treatments were located within blocks of three antecedent moisture levels. Blocks were located at random and replicated three times.

Soil sampling was conducted in each treatment immediately prior to flooding and approximately 2 weeks after water removal.

Short-term flooding was investigated on land in a similar moisture condition to that with the highest antecedent moisture in the above investigation. Water was applied as a head to the soil surface for the following durations: 20 min, 10 min and instantaneous. The last treatment involved a rapid filling of the void system to the soil surface only. There were three replications and soil was sampled on all plots and a series of control plots 3 weeks after flooding.

(c) Fallow Flooding

(i) *Profile with penetrating wetting front.*—Work was commenced on plots with a range of depths of wetting flooded for a fixed duration. This was followed by work on a site of uniform moisture content with plots flooded for varying durations.

A standard flood duration treatment of 3 days was applied to plots with differing antecedent moisture levels resulting from two different lengths of fallowing. These plots were replicated in three flood bays. A third, unreplicated treatment, previously flooded, added a treatment at a higher moisture content. The antecedent moisture range is shown in Figure 3. Each flooded plot was paired with an unflooded control plot with a similar antecedent moisture treatment. Soil sampling was carried out following flooding in all treated and control plots.

Flood duration treatments were varied in plots on a fallowed soil with an average initial wet depth of 2 ft 10 in. Durations of 2·5, 5, 7·5 and 9 days were used on two series of plots. Soil sampling was conducted after flooding at three sites in each plot and similarly in a corresponding unflooded control block.

(ii) *Profile dry with a surface seal.*—Soil on the site used in this work was in an open and grossly cracked condition following harvest of a winter crop. At the time of the study there was a surface seal caused partly by post-harvest low-intensity rainfall and partly by cultivation. Surface moisture levels were characteristically variable, giving a range in total moisture content between 24·5 and 26·5 in.

A treatment was included which had received run-off and was wet to between 28·0 and 28·5 in. total moisture. A small head of water was added to individual plots for durations of 5, 8, 11 and 15 hr. Soil moisture determinations were made immediately prior to water application and 1 month after flooding.

III. RESULTS

(a) Flooding During Crop Growth

(i) *Profile wet above the level of three-dimensional contraction*.—The average antecedent moisture levels on the three treatments used in this work are shown in Table 1.

TABLE 1

CHANGES IN MOISTURE PERCENTAGE IN PROFILE ZONES FROM FLOODING DURING CROP GROWTH: PROFILE WET INITIALLY ABOVE LEVEL OF THREE-DIMENSIONAL CONTRACTION

Total Antecedent Moisture (in.)	Average Moisture Percentage Change Over All Flood Duration Treatments			
	1–2 ft	2–3 ft	3–4 ft	4–5 ft
27·43	·1	1·5	·6	4·0
26·73	·2	·5	3·4	1·6
25·77	2·7	1·1	4·0	−1·8

Antecedent moisture levels for individual treatments were plotted against water increment. No relationship between the two factors could be detected at any flood depth.

Table 1 shows the average moisture percentage change over all flood duration treatments for each antecedent moisture level. Moisture penetration is deeper on initially wetter plots but overall moisture change is of the same order.

Figure 1 shows the relationship between average moisture increment and flood duration. Moisture increment appears to be highly dependent on time. The drop shown in control moisture level in the inter-sampling period is due to crop use. On the assumption that flooded crops use a similar amount of water in that period, a further line was added to Figure 1 showing estimated total water intake due to flooding. This line was terminated at peak water-holding capacity, giving a regression line between percentage peak water in 5 ft of soil and time necessary to fill the soil to 5 ft.

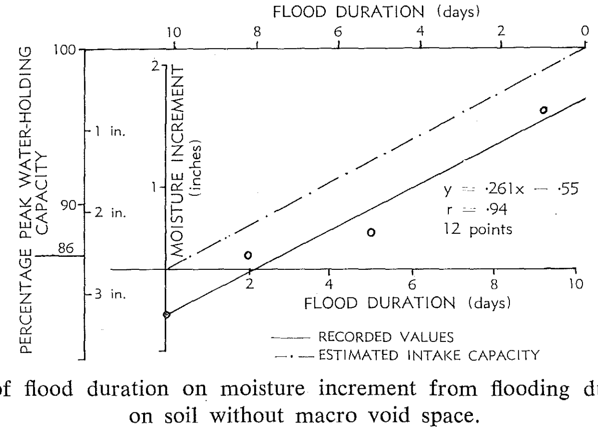

Fig. 1.—Effect of flood duration on moisture increment from flooding during crop growth on soil without macro void space.

(ii) *Profile dry with extensive void space*.—With flood durations exceeding 2 days, rapid water entry took place *via* the cracking systems in all treatments. Table 2 shows the average moisture increments for each treatment. No significant differences between final moisture levels were detected. Depth and duration of flooding did not significantly affect moisture increment over the recorded depth.

TABLE 2

EFFECT OF DEPTH AND DURATION OF FLOODING ON MOISTURE INCREMENT DURING CROP GROWTH: PROFILE DRY WITH EXTENSIVE VOID SPACE

Average Antecedent Moisture Level (in.)	Flood Duration (days)	Flood Depth				Average
		2 in.	5 in.	8 in.	11 in.	
26·1*	2	1·90	2·31	2·28	3·17	2·41
	5	2·70	2·10	3·03	2·49	2·58
	9	2·01	2·39	3·58	2·59	2·64
	Average	2·20	2·27	2·96	2·75	2·54
24·7†	2	2·86	3·16	2·56	1·89	2·62
	5	2·66	2·93	3·44	2·25	2·82
	9	2·86	·70	4·26	1·43	2·31
	Average	2·79	2·26	3·42	1·86	2·58
23·8‡	2	3·74	4·33	3·59	3·57	3·81
	5	3·72	4·72	3·21	3·45	3·77
	9	2·73	3·14	4·07	5·12	3·76
	Average	3·40	4·06	3·62	4·05	3·78

* Necessary difference ($P < 0{\cdot}05$) 1·84
† Necessary difference ($P < 0{\cdot}05$) 3·26
‡ Necessary difference ($P < 0{\cdot}05$) 3·62

In Figure 2, moisture increment on individual treatments is plotted against antecedent moisture. Although variability is high, it is apparent that a relationship existed between these two variables.

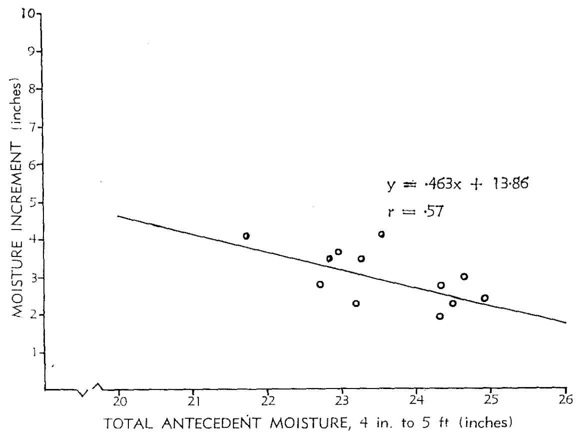

Fig. 2.—Effect of antecedent moisture on water intake from flooding during crop growth on soil with extensive void space.

Table 3 shows the results of the trial with flood durations up to 20 min. Average soil moisture levels after flooding, in relation to untreated control plots, are presented. An increasing level of water intake is noted over the duration range to 20 min. Water intake at 20 minutes' flooding approximates that recorded for long-term flooding on plots at similar antecedent moisture levels.

Average moisture percentage levels at final sampling are also shown in Table 3. It is noted that the moisture increment is located evenly throughout the profile for each increase in duration of flooding.

TABLE 3

EFFECT OF VERY SHORT DURATION FLOODING ON WATER ENTRY DURING CROP GROWTH: PROFILE DRY WITH EXTENSIVE VOID SPACE

Approximate Flood Duration		Total Moisture, 4 in.–5 ft After Flooding (in.)	Moisture Percentages in Profile Zones after Flooding					
			0–4 in.	4–12 in.	1–2 ft	2–3 ft	3–4 ft	4–5 ft
A 20 min . .	. . . . . .	27·43	44·3	46·6	45·3	41·2	40·1	37·6
B 10 min . .	. . . . . .	26·73	37·3	42·8	42·6	41·5	39·4	41·1
C Instantaneous . .	. . . .	25·77	34·1	39·3	39·4	39·6	36·5	40·2
Control . .	. . . . . .	23·13	30·5	32·1	32·4	34·3	34·3	36·8
Necessary differences for significance ($P < 0{\cdot}05$)	Within treatments	2·23	5·7	3·8	5·3	5·2	4·9	7·9
	Treatment *v* control	1·94	4·9	3·8	4·6	4·5	4·3	6·8

(b) Fallow Flooding

(i) *Profile with penetrating wetting front.*—Figure 3 demonstrates the relationship between antecedent moisture and moisture increment, following a standard 3-day flooding treatment.

A high negative correlation exists between the two factors, indicating a reducing rate of water intake with time and increasing depth of wet front. Derived equation from the regression is—

$$y = -{\cdot}515x + 14{\cdot}9 \quad . \quad . \quad . \quad . \quad . \quad (1)$$

On the assumption that the above relationship is linear, it is possible to derive the relationship between moisture increment and time for the specified moisture interval in Figure 3.

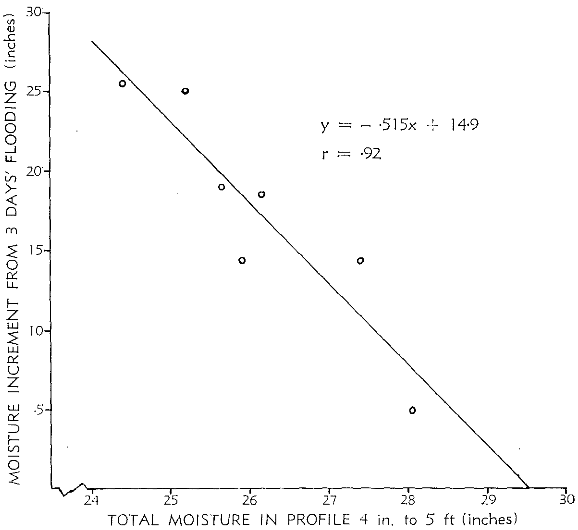

Fig. 3.—Effect of antecedent moisture on moisture increment from 3 days' fallow flooding.

M = total water in profile between 4 in. and 5 ft.

M_{100} = maximum total water in profile between 4 in. and 5 ft.

$$\frac{dM}{dt} = b\,(M_{100} - M)$$

$$\frac{1}{M_{100} - M}\;\frac{dM}{dt} = b$$

$$-\log\,(M_{100} - M) = bt + A$$

$$M_{100} - M = Ae^{-bt}$$

$$M = M_{100} - Ae^{-bt}$$

when $t = 0,\ M_0 = M_{100} - A$

$$A = M_{100} - M_0$$

$$M = M_{100} - (M_{100} - M_0)\,e^{-bt} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (2)$$

Relationship between moisture increment and time is therefore of the form of equation 2.

By substitution of values of M and t derived from equation 1, constant b = ·241.

Equation is therefore

$$M = M_{100} - (M_{100} - M_0)\ e^{-\cdot 241t}$$

Moisture increment results from application of water for four durations to soil wet uniformly to an average depth of 2 ft 10 in. are presented in Table 4. Rate of water entry diminishes with duration of flooding but at a greater rate. An estimated regression curve is presented in Figure 4.

TABLE 4

EFFECT OF FOUR DURATIONS OF LONG-TERM FALLOW FLOODING ON MOISTURE INCREMENT WITH STANDARD ANTECEDENT MOISTURE: PROFILE WITH PENETRATING WET FRONT

—	Duration (days)	Moisture Percentages 0–4 in.	4–12 in.	1–2 ft	2–3 ft	3–4 ft	4–5 ft	Total Moisture 4 in.–5 ft (in.)	Observed Depth of Wetting Front
									ft in.
Final moistures	9	47·9	50·7	48·8	45·3	41·3	38·8	28·76	5 0
	7½	48·4	49·0	47·3	44·2	40·2	37·5	28·00	4 10
	5	47·4	47·7	47·8	44·1	39·3	36·0	27·58	4 6
	2½	46·7	47·2	46·0	41·5	36·5	35·1	26·71	3 10
—	Control	46·7	47·0	45·3	38·2	33·3	33·6	25·94	2 10
Moisture increments	9	1·2	3·7	3·5	7·1	8·0	5·2	2·66	2 2
	7½	1·7	2·0	2·0	6·0	6·9	3·9	2·06	2 0
	5	·7	·7	2·5	5·9	6·0	2·4	1·64	1 8
	2½	0	·2	·7	3·3	3·2	1·5	·97	1 0

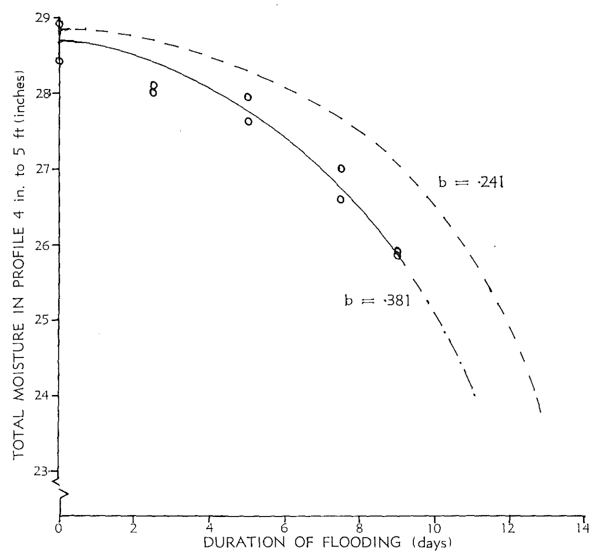

Fig. 4.—Effect of flood duration on total profile moisture from fallow flooding. ($M = M_{100} - Ae^{-bt}$)

As the parameters peak water-holding capacity and field capacity are essentially similar on the sites of this and the previous study, it is reasonable to compare them directly. The dotted line in Figure 4 is a reproduction of the derived line from equation 2.

The results suggest that the relationship over the measured range probably closely follows the derived relationship from the first experiment. This was fitted closely to the directly recorded data from the second trial and an average relationship for the soil postulated:

$$M = M_{100} - (M_{100} - M_0)\, e^{-\cdot 296t} \quad \ldots\ldots\ldots\ldots (3)$$

This is presented in Figure 5. Axes have been added to determine flood duration necessary to fill the soil to 5 ft from within the specified antecedent moisture range.

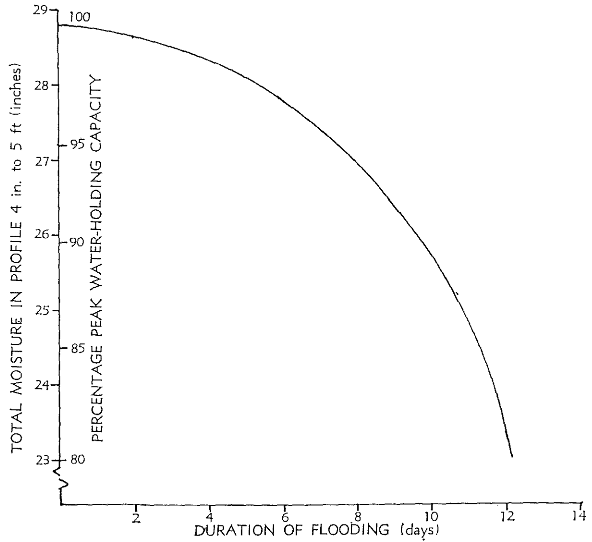

Fig. 5.—Effect of duration of fallow flooding on moisture storage between 4 in. and 5 ft on Waco soil. ($M = M_{100} - Ae^{-296t}$)

(ii) *Profile dry with a surface seal.*—An overall relationship between antecedent moisture level and moisture increment, covering all duration treatments, is presented in Figure 6.

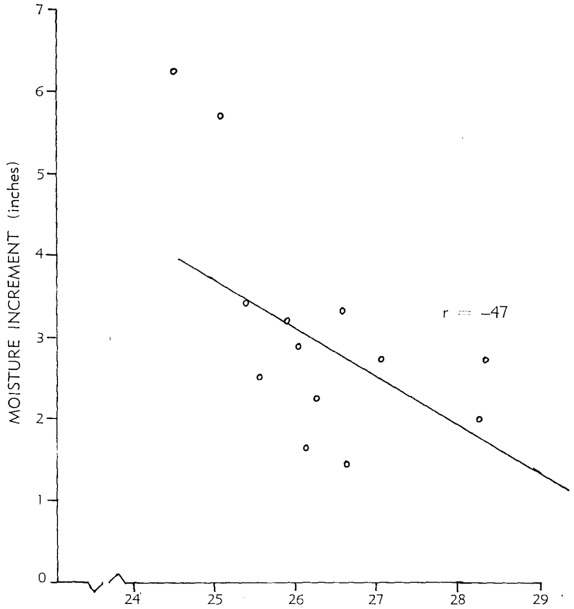

Fig. 6.—Effect of antecedent moisture on moisture increment from flooding on a dry fallow with a surface seal.

Two sites with below 25 in. of water in the profile at flooding averaged a 6 in. water intake and filled to approaching peak water-holding capacity. No treatment with above-25 in. antecedent moisture accepted more than 3·5 in. It is obvious that the mechanism of water entry differed on the initially drier plots. On these, moisture levels were such that cracking occurred at or very close to the soil surface, and as final moisture levels approached maximum water content, it was assumed that the void system was active in water entry at these sites.

A regression analysis of the remaining sites in Figure 6 suggests that there is some degree of moisture increment dependence on antecedent moisture.

The relationship between average moisture increment and flood duration is presented in Figure 7.

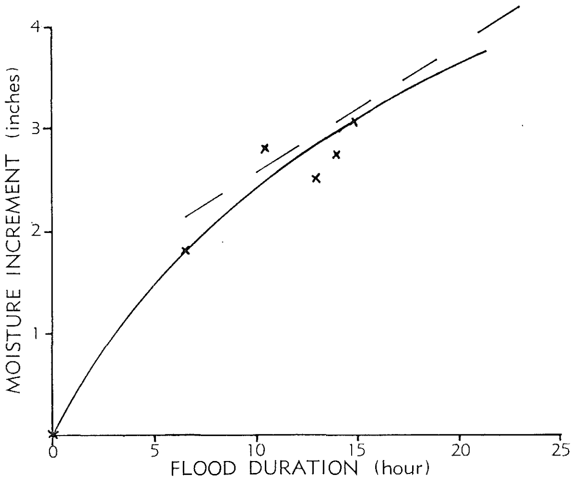

Fig. 7.—Effect of short-term flood duration on moisture increment from flooding on a dry fallow with a surface seal.

IV. DISCUSSION

(a) Flooding During Crop Growth

Water entry into soil with uniform moisture distribution above the level of three-dimensional contraction appeared to vary directly with flood duration. This, and the lack of dependence on antecedent moisture, suggests that the water intake rate remained constant throughout the recorded range. It is therefore likely that infiltration through the surface soil layers controlled water intake in this case. The recorded infiltration rate was approximately 0·01 in./hr.

When the profile was dry and extensively cracked, water intake from flood durations of 2 days and over was related only to total antecedent moisture. As no significant differences in final moisture levels were detected, it is evident that the major factor governing water intake was moisture deficit below peak water-holding capacity. Flooding for the shortest duration (2 days) was able to satisfy this deficit. Subsequent penetration to below 5 ft may have occurred with longer flood durations but this did not have a detectable effect on moisture level in the top 5 ft.

The high antecedent moisture treatment approached the range of unidimensional expansion at all depths and cracks were in the early stage of development. Water access was sufficiently rapid to satisfy the moisture deficit before the cracks closed. The results presented in Table 3 show that a deficit of this order was satisfied within 20 minutes' flooding.

Water penetration of the type recorded in this work resulted in a wet and dry core effect. This was evident as a high level of variability in results at sampling. The variability increased as antecedent moisture level decreased and was of a very high order in the lowest moisture treatment, which approached wilting point below 1 ft.

In the instantaneous flooding treatment in Table 3, just sufficient water to fill the cracking system was added. Subsequent water movement into the soil adjacent to the cracks was observed to be sufficient to close the void system. No further water was added and it is expected that soil moisture equilibrium would result at a level approximating that at the completion of three-dimensional expansion. This was confirmed by average equilibrium moisture determinations between 4 in. and 3 ft in Table 3. These were 39·3, 39·4 and 39·6%, compared with the calculated point on the bulk density-moisture regression of 39%.

(b) Fallow Flooding

In the soil profile with a penetrating wet front, decreasing infiltration rate with time and increasing wet depth was consistent with a control on water intake at the advancing wet front, as suggested by Bodman and Colman (1944).

In comparing the moisture increment/time relationship in the range between 80 and 100% peak water-holding capacity it is noted that while infiltration rate remained constant with an initially even moisture distribution (Figure 1) the infiltration rate decreased with time over the same moisture deficit when wetting a dry soil with an advancing wet front (Figure 5). This suggests a possible differential energy requirement between wetting soil in the three-dimensional and unidimensional contraction ranges.

With a dry profile with a surface seal, the results in Figure 7 and the established dependence on antecedent moisture suggest that the relationship between moisture increment and duration was curvilinear, as it was with soil wet to a greater depth. However, the rate of change of infiltration rate was higher than on wetter soils. The discontinuous line in Figure 7 is the extrapolation of the slope of the derived line in Figure 5 at approximately 80% peak water content. This relates well with the upper limits of the proposed line of best fit for the drier soil. It is therefore likely that the relationship postulated in Figure 3 does not hold below 80% peak water content. The relationship probably grades into one of increasing change of infiltration rate, possibly under the additional effect of gravity in wetting the surface soil.

(c) Infiltration

It is apparent from the results of the work described that addition of water up to the saturation deficit may be, for design purposes, instantaneous. This will be true at any time that there is a void system open at the surface. With soil wet above the level of cracking, the saturation deficit will be satisfied at an infiltration rate of 0·01 in./hr.

Water intake in a wetting front is probably the most usual form of fallow accumulation. A knowledge of variation in infiltration rate with time and increasing wet depth is desirable to enable assessment of the value of fallow rainfall and flooding.

Infiltration in relation to antecedent moisture will be considered first.

From equation (3) $M = M_{100} - M_{100}\, e^{-\cdot 296t}$

$$M = 28{\cdot}8 - 28{\cdot}8\, e^{-\cdot 296t}$$

$$\frac{dM}{dt} = 8{\cdot}5_e{}^{-\cdot 296t}$$

$$\frac{28{\cdot}8 - M}{28{\cdot}8} = e^{-\cdot 296t}$$

$$\frac{dM}{dt} = 8{\cdot}5\ \frac{(28{\cdot}8 - M)}{28{\cdot}8}$$

$$\frac{dM}{dt} = 8{\cdot}5 - {\cdot}296\, M$$

This straight-line relationship is the postulated variation above 80% peak water content. Below this a curvilinear relationship is probable and this has been derived from Figure 7. The suggested line is presented in Figure 8.

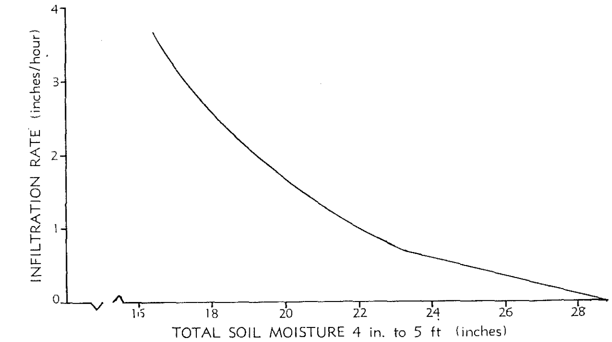

Fig. 8.—Effect of increasing soil moisture storage on infiltration rate into initially dry soil.

With regard to infiltration in relation to infiltration duration, an arbitrary commencing point was established at the estimated wilting conditions for the Waco soil between 4 in. and 5 ft, namely 16·8 in.

$$M = 2{\cdot}8 - 2{\cdot}8_e{}^{-\cdot 296t}$$

$$\frac{dM}{dt} = 8{\cdot}5_e{}^{-\cdot 296t}$$

Infiltration up to 2 days' duration was estimated from Figure 7. The suggested overall relationship is presented in Figure 9.

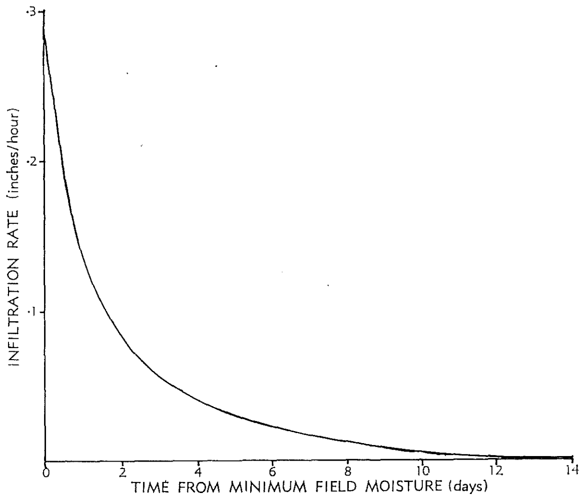

Fig. 9.—Variation in infiltration rate with increasing infiltration time from minimum field soil moisture conditions.

(d) Water-holding Capacity

On the heavy clay black earth soils, the energy relationships involved in water movement and extremely low rates of water movement through the soil matrix render the term "field capacity" meaningless unless related to the time which has elapsed since a major change in overall moisture status. Significant continuing changes in water distribution continue to occur 1 month after flooding. Major changes, however, appear to cease within 3 weeks. At this time interval

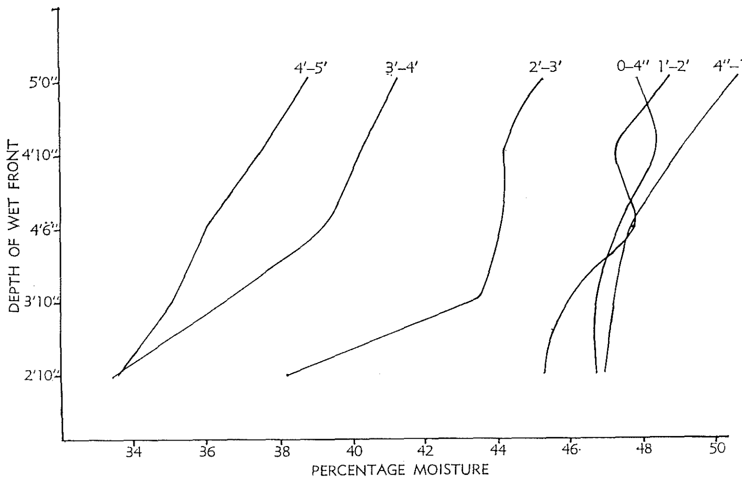

Fig. 10.—Percentage moisture in profile zones for different depths of wetting.

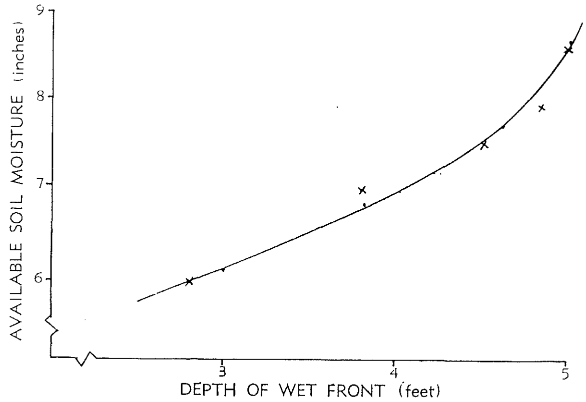

Fig. 11.—Relation between wet soil depth and available moisture on a Waco soil.

the moisture distribution is assumed to have reached an equilibrium. At this assumed equilibrium point, significant differences in recorded moisture levels of profile zones are apparent with increasing depth of wet front. Variation for a site wet between 2 ft 10 in. and 5 ft is shown in Figure 10. The resulting available moisture levels for this site are presented in Figure 11.

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