HYDRAULIC OPERATING CHARACTERISTICS OF LOW GRADIENT BORDER IRRIGATION SYSTEMS

by

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SUMMARY

Intensive study was made of 41 border irrigation plots to determine combinations of gradient, length, intake rate characteristics, surface hydrulic resistance and stream size that result in high irrigation distribution efficiency. Gradients ranged up to 0.005 foot per foot.

Water distribution efficiency is independent of stream size within the range of 0.03 to 0.12 cfs. per foot border width. Border gradient was not a significant variable within the range studied. The critical variable is cutoff time which determines whether or not there will be surface runoff and to some extent parallel advance and recession rate curves. The latter is necessary if equal intake opportunity time is to occur everywhere along the border.

The operating criteria for cutoff time is distance of advancing front at cutoff, X, compared to length of border, L. For heavy textured soils, the ratio should be: $0.33 \leq X / L \leq 0.75$, while for light textured soils it should be: $0.9 \leq X / L \leq 1.1$. Water distribution efficiencies of 80 to 95 percent can be consistently obtained.

In typical operation, the water is applied <u>for efficiency</u>, rather than for a given depth of irrigation. Frequent applications will be necessary to supply crop needs during periods of peak consumption use. Automation in irrigation will remove the labor constraints to frequent irrigation and thereby make feasible high efficiency irrigation on low gradient borders.

Introduction

Surface irrigation methods are used to apply water on more than 60% of all lands irrigated, yet efficiency of water utilization under current practices is seriously low. Great savings in water can be realized if design and operating criteria are developed. This study is part of an extensive project being conducted cooperatively by Colorado State University and the USDA Agricultural Research Service covering many aspects of the problem--including the hydraulic characteristics of different surface irrigation systems.

The objective of this study is to find out how to apply water with high distribution efficiency on low gradient border systems. Low-gradient borders offer an approximation to the ideal level basin without the prohibitively short runs.

Efficiency of surface irrigation methods has been given limited attention. Willardson and Bishop (6) have presented a method of estimating border irrigation efficiencies as influenced by the soil intake rate, time for water to reach the end of the border and time for a desired depth of water to infiltrate into the soil. Shockley, Woodward and Phelan (5) presented a quasi-rational method of border irrigation design based on the requirement of a given irrigation depth. They emphasized that the most uniform irrigation could be contained if the intake opportunity time were the same for the entire length of the border.

One of the earliest references to the concept of uniform intake opportunity time was that of Lewis and Milne (4). They pointed out that parallel advance and recession provides uniform intake opportunity time and may be obtained by stopping inflow before the advancing front reaches the end of the border.

Irrigation Concept

Even though the concept of optimum efficiency resulting from uniform intake opportunity times has been recognized, this idea has received little attention by other researchers. Systems have been designed to allow the fewest possible number of irrigations per season. For this to be accomplished the maximum allowable soil water deficit must be reached in the root zone prior to each irrigation and then the total profile refilled. Advantages of this design are that fewer irrigations result in less water loss by evaporation during and immediately following irrigation and labor requirements are minimal. However, designing for the fewest possible irrigations is inadequate because available root zone storage is not constant for various crops in a rotation, and will change during the season for many crops. A border designed for a high application often cannot be given a low application when such is desired, thus deep percolation loss results. The irrigation efficiencies obtained when irrigating for different applications can vary considerably.

The objective of this study was to determine design and operation criteria for maximum water distribution efficiency. The concept of having uniform intake opportunity time throughout the length of the border was the controlling factor in determining stream sizes and application times. It was assumed that irrigation scheduling could be altered to correspond with the most efficient application and that the most efficient application becomes feasible with mechanization and automation.

Procedure

Three border irrigation systems on different soil types were studied. Trial and error techniques were used to obtain parallel advance and recession curves (uniform intake opportunity time) and to minimize runoff. Adjustments in stream size and cutoff time (time at which input stream is discontinued) were made by reference to previous irrigations on a border and concurrent irrigations of adjacent borders. Data were taken to completely account for the irrigation water both during and after an irrigation.

During each irrigation the inflow to the borders was measured with Parshall flumes and any runoff was measured with broad crested rectangular weirs set at the average elevation of the downstream end of the border. Measurements were taken of the advance, recession, and depth of flow at known times to provide a continuous accurate record. Depth data were taken with staff gauges on steel bench marks set at the average cross-sectional elevation at selected stations along the border. Cylinder infiltrometers were used to determine the intake rate functions. Soil water measurements were taken using either gravometric sampling or neutron moisture probes to determine the water in the soil profile both before and after an irrigation. Detailed topographic data were taken to allow calculation of surface storage volumes.

Experimental Sites

Studies at Scottsbluff, Nebraska, were on a soil of medium intake rate classified as Tripp fine sandy loam. The borders had been constructed four years prior to the beginning of this experiment with maximum cuts and fills of about one foot. At Scottsbluff the borders had slopes ranging from 0 to 0.0017 and were 37 to 44 feet wide and 250 to 850 feet long. Row crops and alfalfa were grown. Additional information on crops and irrigations on the Scottsbluff site was presented by Jensen and Howe (3).

Studies at Grand Junction, Colorado, were on soils of low intake rate classified as Billings silty clay loam and Ravola and Fruita clay loams. At Site S near Grand Junction the borders had slopes of 0.004 to 0.005 and were 30 feet wide and approximately 1100 feet long. On the second site at Grand Junction, Site M, borders were constructed with slopes ranging from 0 to 0.0012, were 25 feet wide, and 650 to 850 feet long. Crops were bromegrass, bromegrass-alfalfa, and milo.

At Site S the field cover changed from a growing barley crop to thick stands of bromegrass and bromegrass-alfalfa during the period June 1 to September 15, 1965. Although the borders had been constructed the preceding summer, soil compaction did not appear to be a problem. Maximum cuts and fills did not exceed 0.5 foot.

Borders at Site M, also were constructed the year before the experiment was started. Cuts and fills up to 3 feet were made. Soil compaction was partly corrected by deep chiseling immediately after construction. Small areas of raw Mancos shale were exposed. These produced very little vegetative cover the first year but a fair crop the second year.

Table 1 summarizes the physical dimensions of the experimental borders for this study. The standard deviation of the average border elevations is shown only for the Grand Junction sites. Insufficient data were available for the Scottsbluff borders to define the variability of the border from the least square line of slope.

TABLE 1

PHYSICAL CHARACTERISTICS OF EXPERIMENTAL BORDERS

Border	Slope	Standard Deviation (feet)	Width (feet)	Length (feet)
Scottsbluff				
1	0.00042		36.6	750
2	0.00086		40.0	840
3	0.00169		37.0	625
3s	0.00024		44	550
3n	0.00016		44	684
4s	0.00024		44	550
4n	0.00025		44	693
5s	0.00011		44	570
5n	0.00013		44	677
6s	0.00030		44	525
6n	-0.00006		44	733
7s	0.00020		44	540
7n	0.00015		44	460
8s	0.00045		44	500
8n	-0.00010		44	506
11(a)s	0.00031		44	450
11(b)s	0.00078		44	415
12(a)s	0.00002		44	400
12(b)s	0.00001		44	380

TABLE 1 (Continued)

PHYSICAL CHARACTERISTICS OF EXPERIMENTAL BORDERS

Border	Slope	Standard Deviation (feet)	Width (feet)	Length (feet)
Site M				
1	0.00017	0.0010	25.9	650
2	0.00038	0.0013	25.6	770
3	0.00064	0.0027	25.3	810
4	0.00077	0.0064	25.2	830
5	0.00033	0.0035	24.1	835
6	0.00075	0.0022	25.1	850
7	0.00096	0.0044	24.3	855
9	0.00051	0.0041	24.8	850
10	0.00081	0.0057	24.4	850
11	0.00069	0.0283	26.1	850
12	0.00017	0.0042	25.2	850
13	0.00001	0.0058	26.9	850
14	0.00056	0.0111	25.8	850
Site S				
1	0.00494	0.0184	30.0	977
2	0.00520	0.0143	30.3	1018
3	0.00511	0.0148	30.4	1055
4	0.00505	0.0131	29.5	1094
5	0.00496	0.0123	30.2	1112
6	0.00479	0.0177	29.9	1112
7	0.00463	0.0126	30.2	1112
8	0.00456	0.0172	30.2	1112

RESULTS

Intake

Stream size required to attain uniform intake opportunity time on Site S decreased from 0.11 to 0.06 cfs per foot of border width as the season progressed, Figure 1. Intake opportunity time increased from about 60 to 120 minutes, infiltrated depth decreased from approximately 4 to 3 inches, and recession rate decreased from 10 to 5 feet per minute.

The fact that infiltrated depth decreased while intake opportunity time doubled evidently is related to the difference in consumptive use of a vigorous growing barley crop as opposed to seedlings of brome and alfalfa. Lower consumptive use would result in higher antecedent soil moisture for the irrigations following barley harvest and reduce infiltrated depth. Irrigation intervals were kept nearly the same to provide more hydraulic data.

A preliminary analysis of the hydraulic resistance did not indicate an increase in crop retardance. Therefore, the reduced recession rate must be primarily influenced by the reduced intake rate.

In 1966, it was necessary to decrease from 0.07 to 0.05 cfs per foot of border width as alfalfa root systems developed. Infiltrated depth was fairly constant for the season at four inches per irrigation.

Stream size required to attain uniform intake opportunity time on Site M remained nearly constant at 0.04 to 0.05 cfs per foot of border width in 1966, Figure 2. Infiltrated depth started at 2 inches and increased gradually to 4 1/4 inches at the end of the season. The low infiltrated depth in the early part of 1966 could be because of combined effects of soil compaction due to border construction the preceding fall

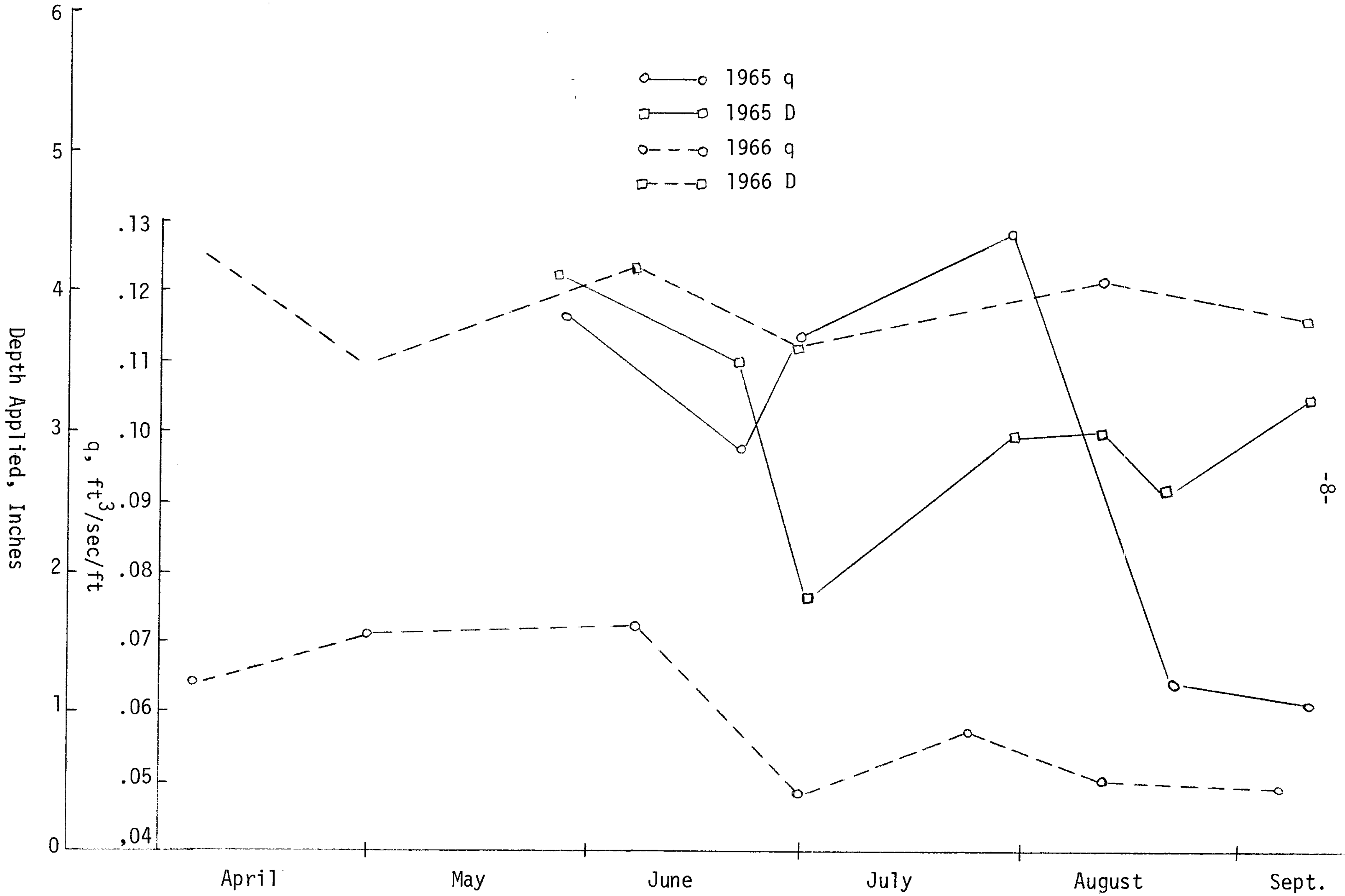

Figure 1. Seasonal trends for input stream and input depth for Site S, Grand Junction, Colorado

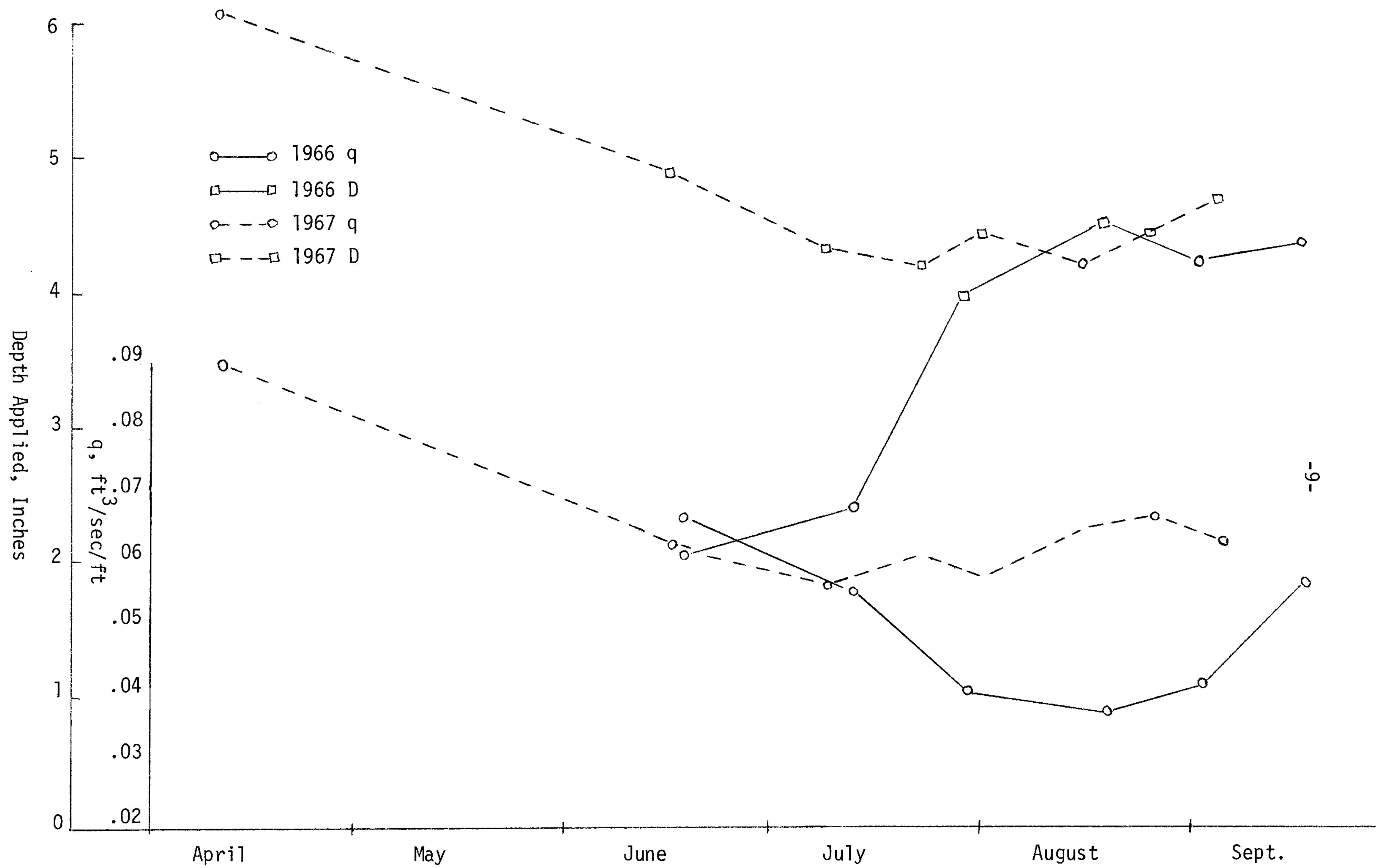

Figure 2. Seasonal trends for input stream and input depth for Site M, Grand Junction, Colorado

and the shallow root zone of the new brome-alfalfa seeding. In 1967 stream size was constant at about 0.06 cfs per foot of border width while intake depth remained fairly constant at 4 1/4 inches after a high early season deficit was met.

An extreme example of the effect of antecedent soil moisture on infiltrated depth is in separate irrigations on two consecutive days on Border 4, Site M. Intake curves in Figure 3 show the second irrigation had an infiltrated depth equal to 15 percent of the first irrigation at 10 minutes and gradually increased to 30 percent of the first irrigation at 500 minutes. The high degree of variability is assumed to be partly caused by varying degrees of cracking exhibited in these soils. Soils that crack have high initial infiltrated depth, 3 to 4 inches during the first two hours for the experimental area.

Optimum irrigation efficiency is highly dependent upon the intake characteristics of the soil. Figure 4 shows the range in intake of the medium and fine textured soils of the experimental areas. Intake measurements at Scottsbluff were made with cylinder infiltrometers and at Grand Junction the entire border was used as an infiltrometer, Gilley (1). The paired curves envelope 75 percent of the intake measurements. The solid lines represent the medium textured Scottsbluff soils. The enveloping curves for the two Grand Junction sites were nearly the same and are represented in Figure 4 by a single pair of broken lines. The higher accumulated depths are greater than the lower accumulated depths by approximately 50 and 100 percent for the medium and fine textured soils, respectively.

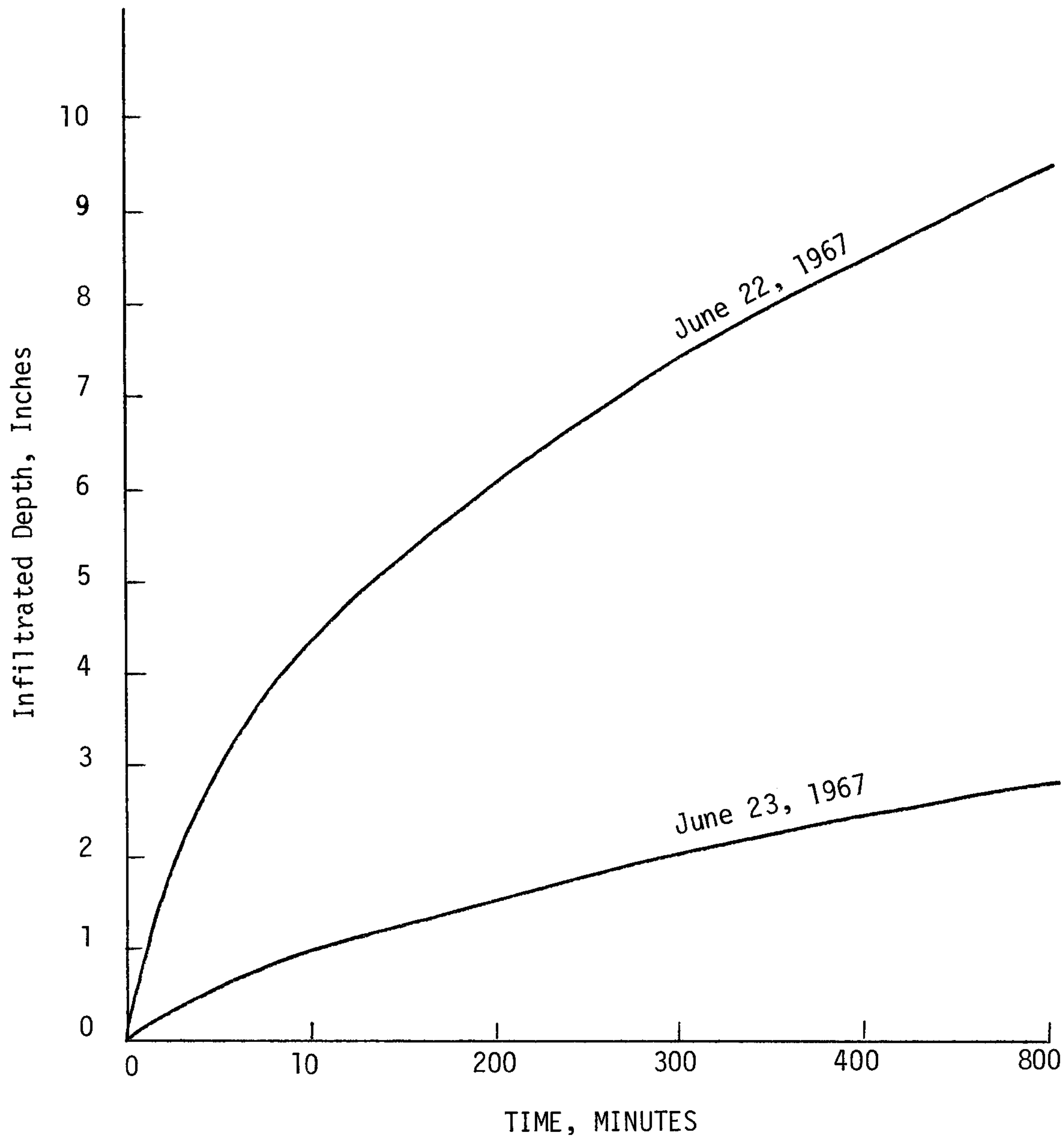

Figure 3. Comparison of infiltration on two consecutive days, Border 4, Site M.

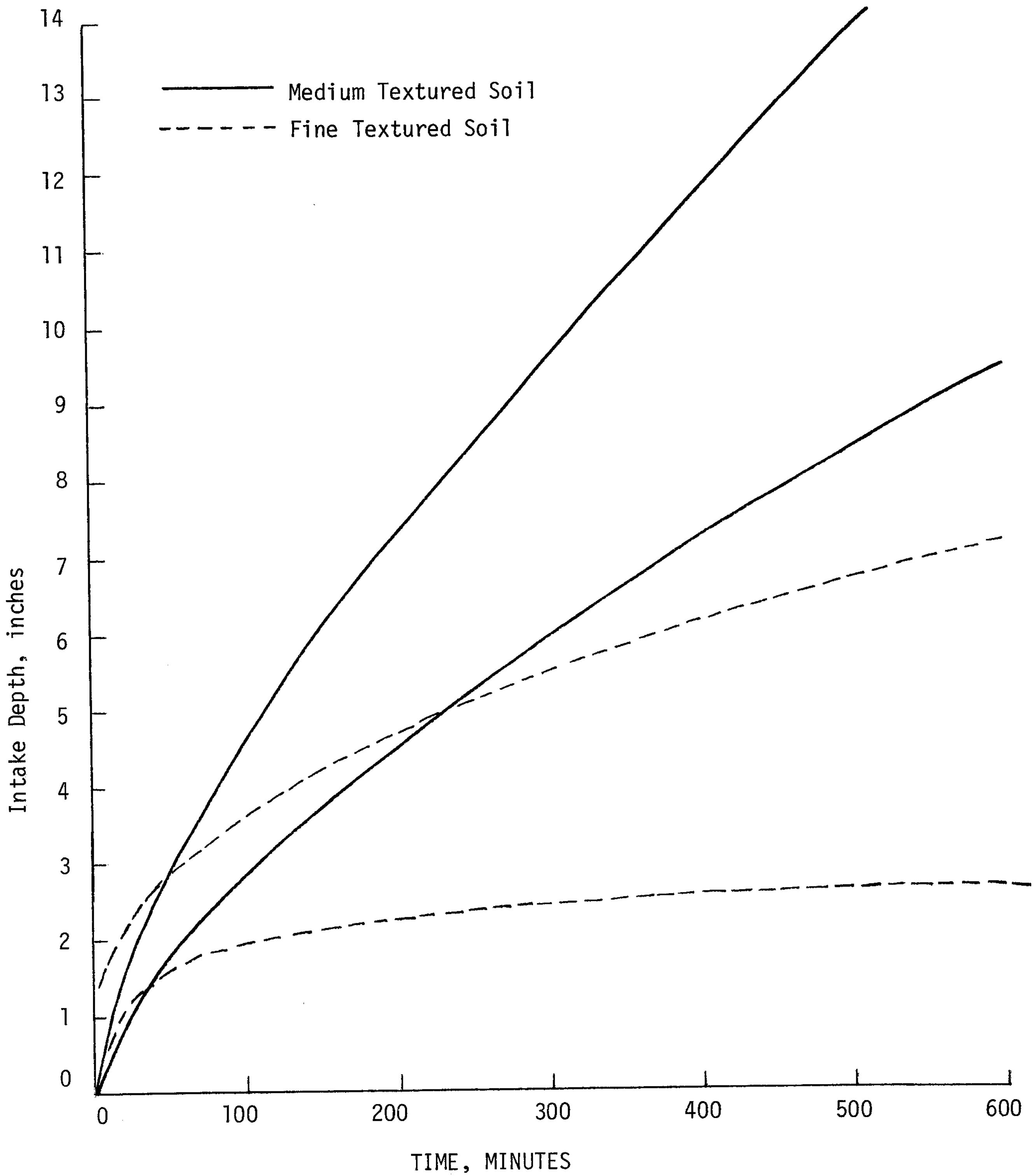

Figure 4. Range in intake depth of the medium and fine textured soils of the experimental areas.

After approximately 5 hours and 12 hours, intake rates for the medium and fine textured soils approached a constant value of approximately 0.75 and 0.05 inches per hour, respectively.

Water Distribution Efficiencies

The evaluation of an irrigation system requires knowledge of various irrigation efficiencies. These experiments were designed primarily to maximize water distribution efficiencies and minimize surface runoff. The distribution efficiency was defined by Hansen (2) as:

$$DE = 100 \left[1 - \frac{y}{d}\right]$$

where y = average of the absolute deviations of the measurements

d = average measurement.

Distribution efficiencies were calculated for measurements of intake opportunity time (DE_t) and soil moisture (DE_w).

Table 2 shows by sites and by years the percent of all irrigations with DE above 80 and 90 percent. The efficiencies based on soil moisture are those which truly represent the final water distribution for use by the crop. Since it was not possible to obtain soil moisture measurements for the 1965 season, the uniformities of intake opportunity times are shown for comparative purposes.

Thirty percent of all irrigations had at least 90 percent DE_w and 85 percent of all irrigations had at least 80 percent DE_w. These DE_w's were summarized from all irrigations in spite of the fact that stream size was by intent not always optimum.

Surface Runoff

The borders at Scottsbluff were diked at the lower end to prevent runoff. These borders, on sandy loam soil, could be irrigated

TABLE 2

SUMMARY OF DISTRIBUTION EFFICIENCIES
BASED ON INTAKE OPPORTUNITY TIME AND SOIL MOISTURE

Location	Year	Percent of Applications with DE_w greater than 80%	Percent of Applications with DE_w greater than 90%	Percent of Applications with DE_t greater than 80%	Percent of Applications with DE_t greater than 90%
Scottsbluff	1960	61	22	86	34
	1961	75	8	92	50
	1962	67	17	50	17
Grand Junction					
Site S	1965			100	50
	1966	87	0	95	36
Site M	1966	97	26		
	1967	92	49		

satisfactorily. However, the borders at Grand Junction (with the lower basic intake rate) had surface runoff when cutoff time was overestimated. Table 3 shows that seasonal percent runoff varied from 0.3 to 5.2 percent for the three years of study at Grand Junction. Even though the percent runoff is small, it would contribute to the increased DE_w's on the Grand Junction site compared to the Scottsbluff site where runoff was not allowed.

Advance and Recession Curves

Figure 5 shows a nearly ideal advance-recession relationship on a 0.005 slope. The DE_t for this irrigation was 91 percent and the corresponding DE_w was 96 percent. Roughness in the recession curve is due to intake variability and irregularities in grade.

The border irrigation stream advanced at a uniform rate and the rapidly increasing volume of water removed the effects of surface irregularities. However, the receding front with decreasing surface storage volume is strongly influenced by soil surface irregularities as evidenced by the way the recession curves vary with these irregularities, Figure 6.

A more typical advance-recession relationship is shown in Figure 7. The sharp increase in intake opportunity time at the lower end of the border is due to the water having been turned off a few minutes too late causing ponding. The slope of this border is 0.00024. DE_t was 88 percent and DE_w was 81 percent. For this irrigation, DE_w was less than DE_t. In the example of Figure 5, DE_w was greater than DE_t. Intake opportunity time for both irrigations falls in a zone of their respective intake range where a percentage change in time produces

TABLE 3

PERCENT RUNOFF FROM BORDERS AT GRAND JUNCTION

Site	Year	Crop	Irrigations	Run Off %
S	1965	Close	46	4.7
S	1966	Close	50	4.8
M	1966	Close	39	5.2
M	1966	Row	13	0.3
M	1967	Close	47	3.3
M	1967	Row	11	3.8

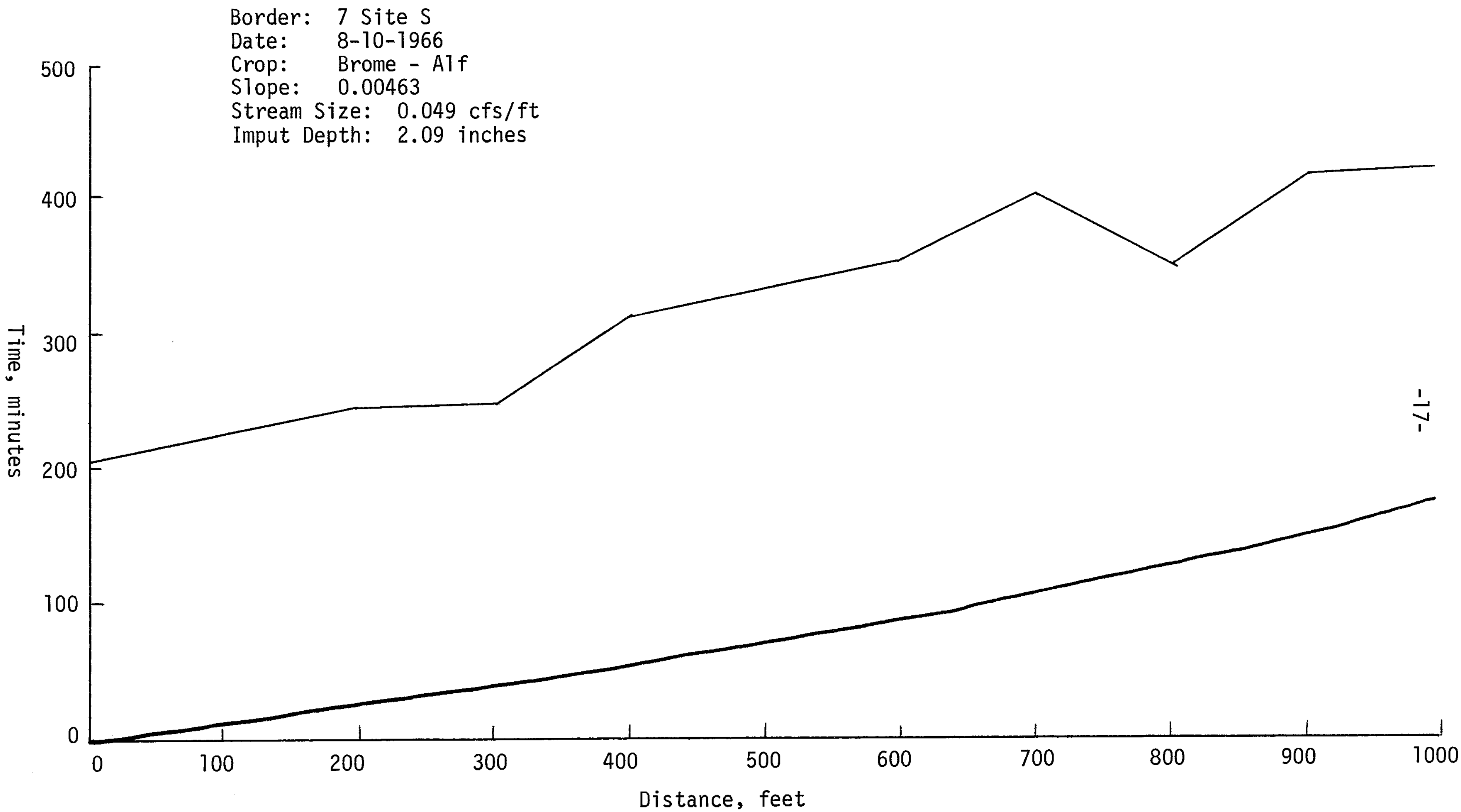

Figure 5. Advance-recession curve for Border 7, Site S

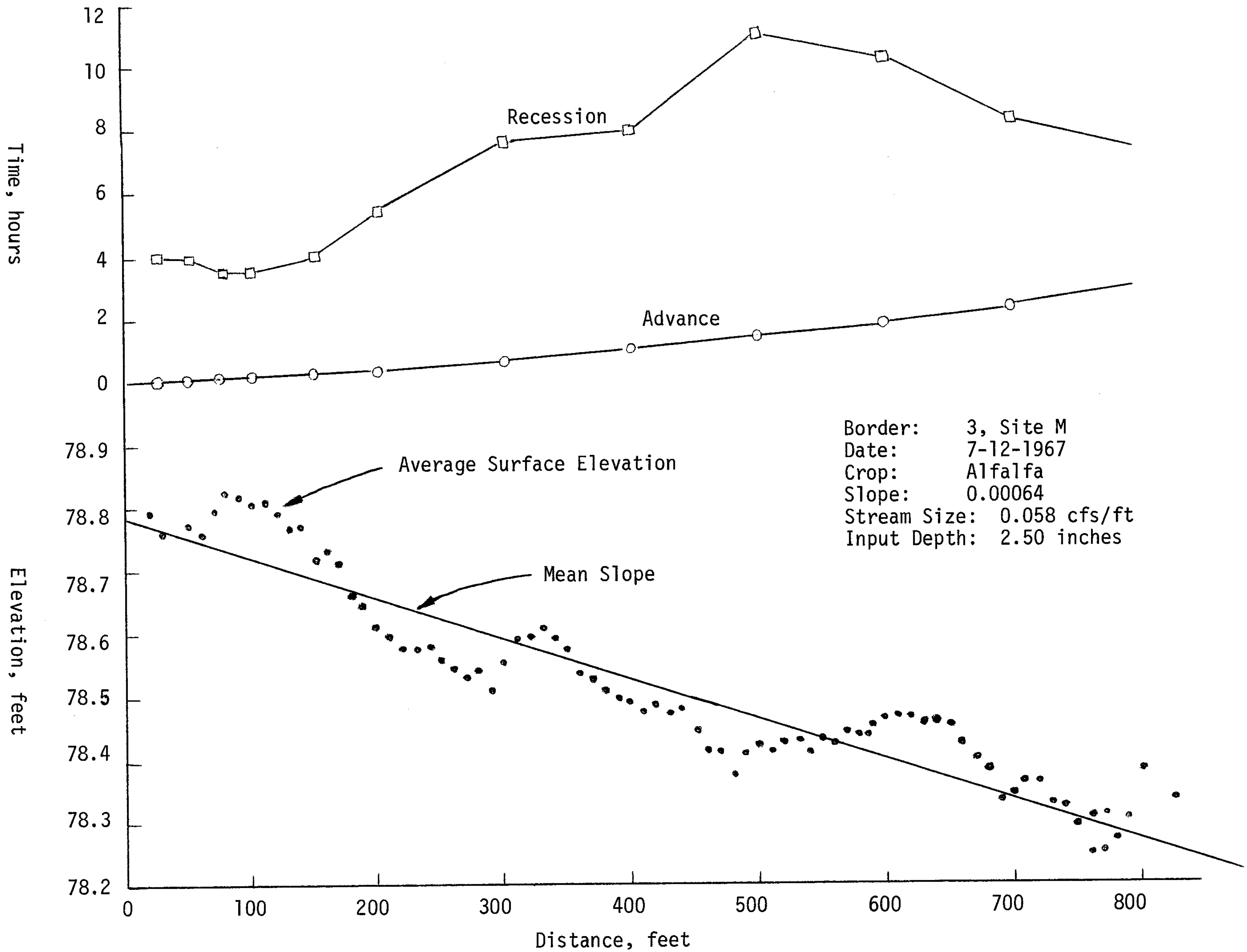

Figure 6. Advance-recession curve for Border 3, Site M

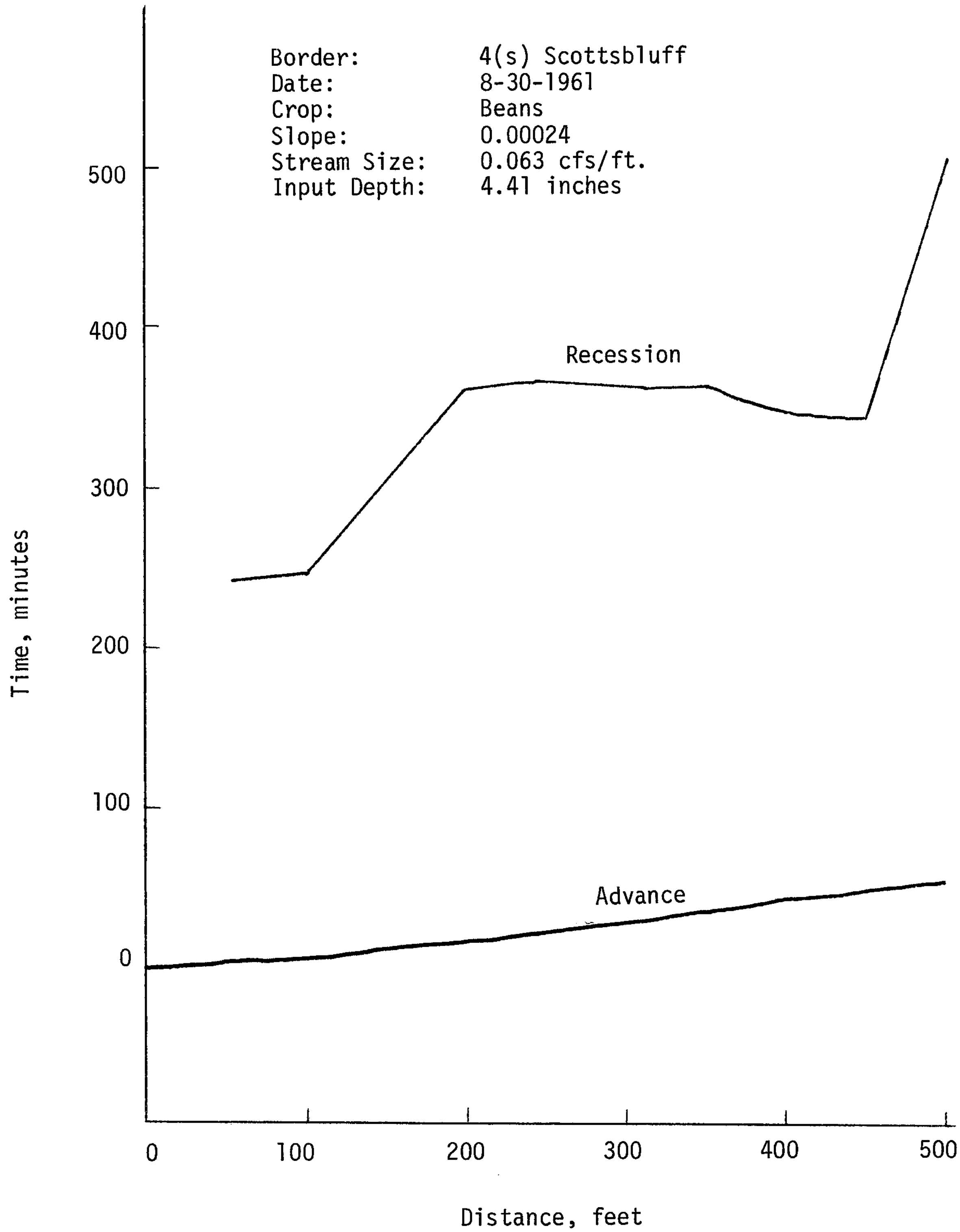

Figure 7. Advance-recession curves for Border 4(s), Scottsbluff

approximately a like percentage change in intake depth. So either water or time uniformity could be higher.

Stream Size and Slope vs. Efficiency

An ideal border with parallel advance and recession lines, homogeneous soil, correct stream size, and perfect grade would be expected to approach 100 percent DE_w. Therefore, a plot of DE_w against stream size should produce a curve showing the stream size for maximum DE_w.

Figure 8 shows DE_w of all irrigations plotted against stream size per foot of border width. Separate symbols are used to differentiate among locations and, at site M, between row and close growing crops. Variability in intake rate and surface irregularities have masked out any trend that theoretically should exist. The scatter of DE_w's for a given stream size at any site shows that DE_w was for practical purposes independent of stream size. The error in selecting the stream size may cause some of the scatter but most is attributable to the variation in intake rate, hydraulic resistance and border irregularities. However, any stream size within the experimental range usually produced a DE_w above 80 percent. The same range of stream size resulted for the three sites.

Figure 9 shows DE_w for all irrigations plotted against slope. There appears to be no trend as to the most desirable slope within the low gradient range (0-0.001). The two sites at Grand Junction with comparable intake characteristics have the greatest range in slope. Water distribution efficiencies are slightly lower on the site with the steeper slope. The increased intake opportunity time on the lower gradient site may cause the slight increase in efficiency. The change in efficiency may also be a function of the degree of slope variability

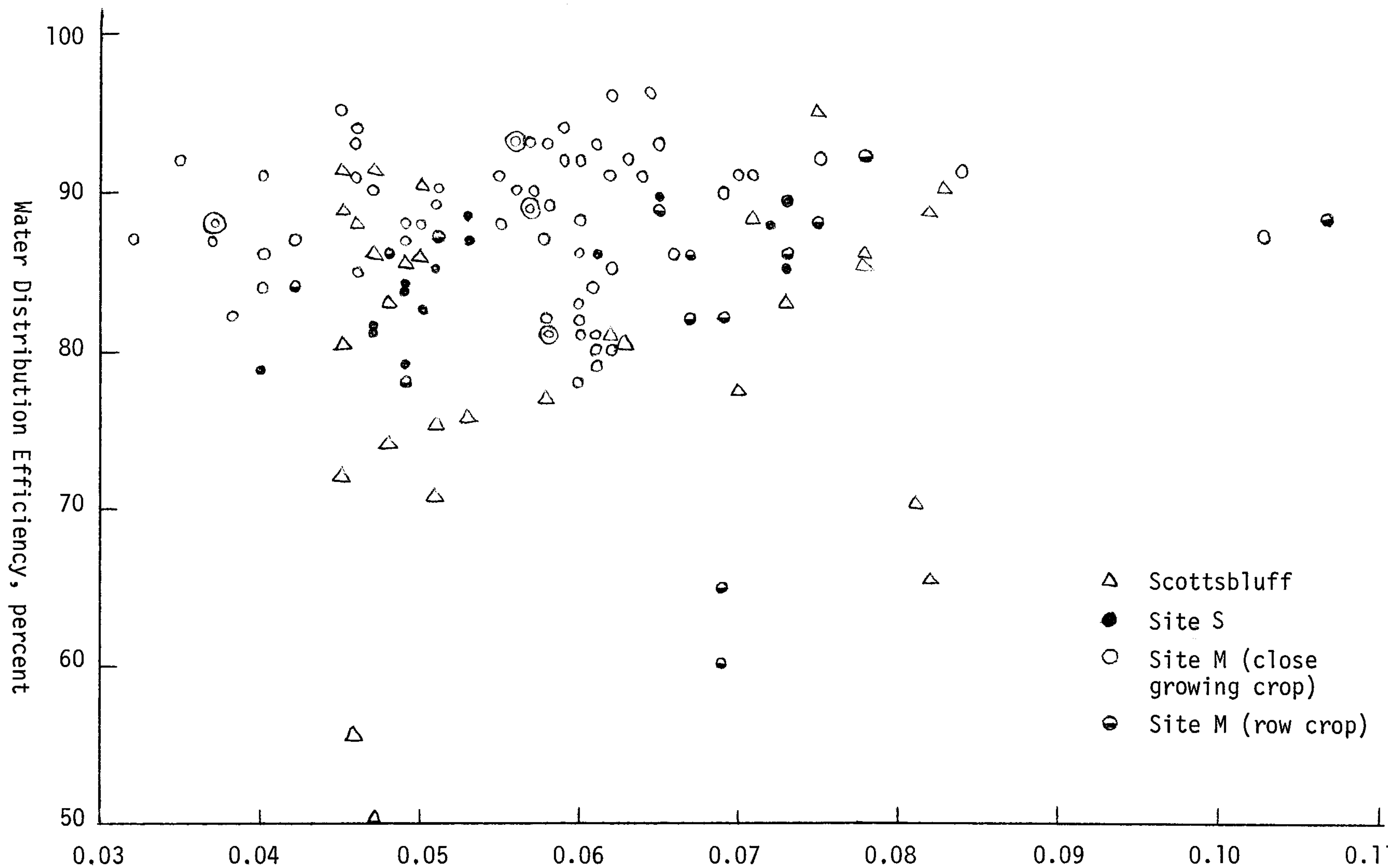

Figure 8. Effect of stream size on water distribution efficiency

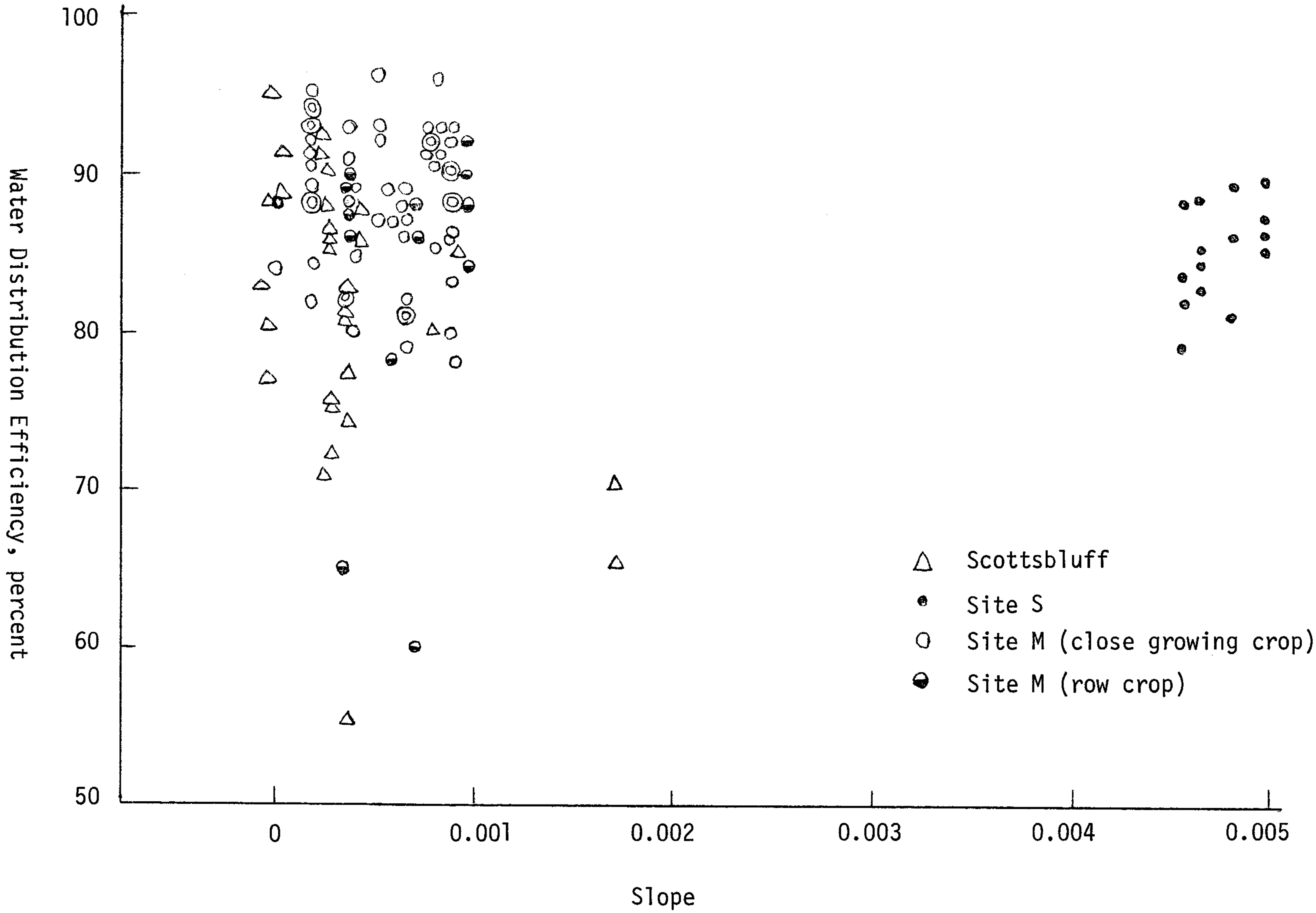

Figure 9. Effect of slope on water distribution efficiency.

in the longitudinal direction. The standard deviation in Table 1 gives some indication of the slope variability. The borders on Site S were constructed with level cross slopes but followed slight natural longitudinal undulations. Efficient irrigations were obtained with these borders and they should be given consideration in the economics of a system design.

All irrigations in the 0.004 to 0.005 range of slopes were on close growing crops. Figure 10 shows DE_W vs. slope for sugar beets on slopes of 0.0004 to 0.0017. The advance-recession curves were nearly parallel for all six irrigations. With slightly increased slope, irregular areas of ridge tops were not covered with water which probably caused the lower DE_W for the irrigations on the 0.0017 slope. Borders with slopes less than 0.001 were entirely covered with water and differences in slope had less effect on DE_W.

The DE_W for one irrigation does not present the entire picture of the seasonal irrigation efficiency. Seasonal DE_W's were determined by accumulating the increases in soil moisture at individual sampling points. Comparison of soil water data for two irrigations, Table 4, shows that intake for the second irrigation is compensatory to the first irrigation. Where intake depth was below average at a station for the first irrigation it was often above average for the second irrigation, and vice versa. Combining the input depths for the two irrigations cancelled out some of the deviations so that the DE_W for the combined irrigations, 78 percent, was higher than for either the first or second irrigation alone, 70 and 66 percent, respectively.

Seasonal DE_W's were higher than the average for the individual irrigations for nearly all borders in the study. This doubtlessly is

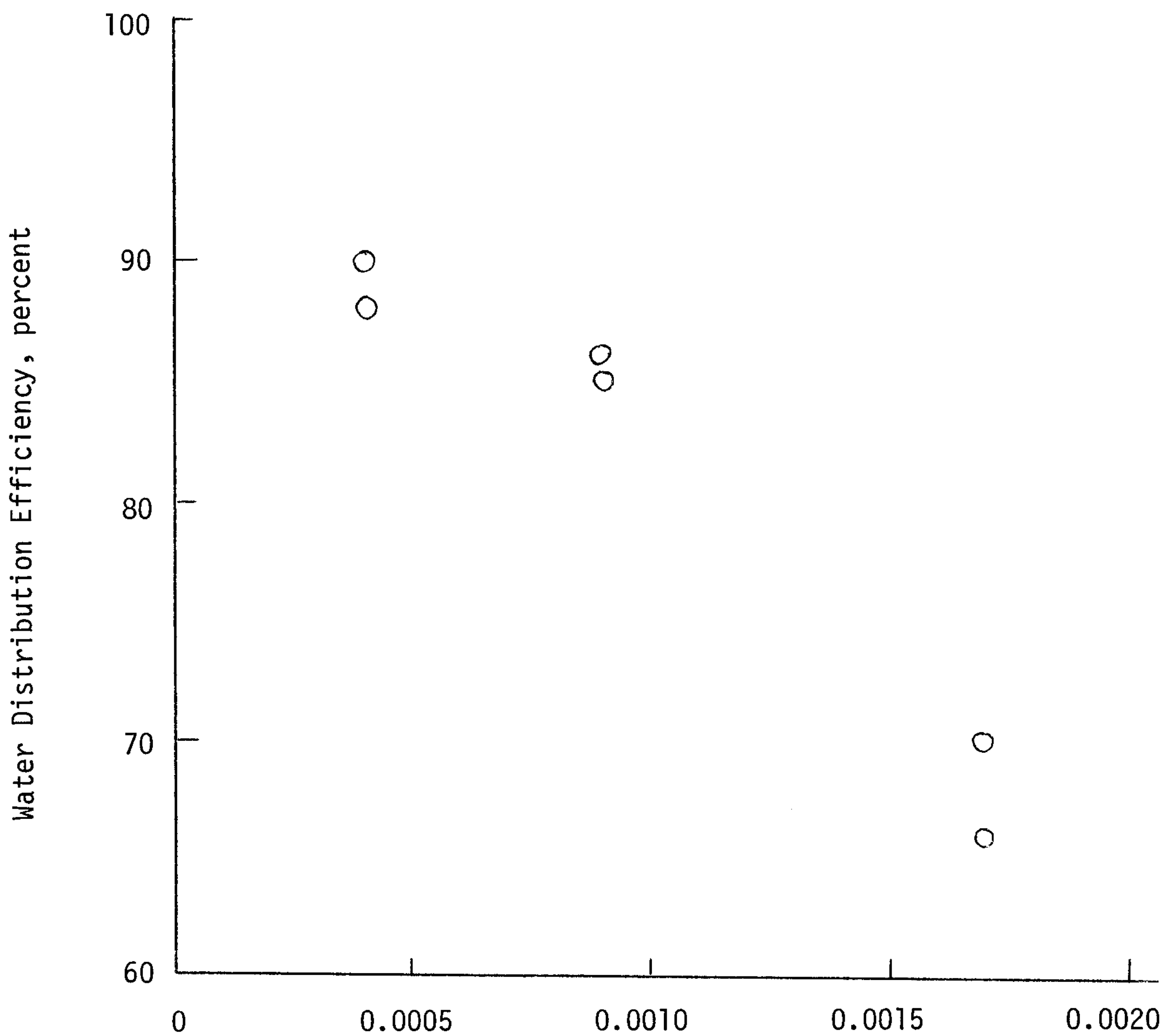

Figure 10. Effect of slope on water distribution efficiency for sugar beets, Scottsbluff, Nebraska, 1962.

TABLE 4

COMPENSATORY INTAKE BY STATIONS

BETWEEN TWO IRRIGATIONS ON SUGAR BEETS

Border 3, 1962, Scottsbluff

Deviations from Mean

Station Ft.	July 27 ins.	August 22 ins.	Combined ins.
50	+1.71	-1.08	+0.63
100	+0.82	-2.04	-1.22
150	-0.19	+0.75	+0.56
200	+0.18	+0.24	+0.42
250	-0.08	-1.47	-1.55
300	-1.57	-1.57	-3.14
350	-0.04	-1.52	-1.56
400	-0.59	-1.82	-2.41
450	-1.02	+4.67	+3.65
500	-1.03	+0.88	-0.15
550	-0.36	+1.37	+1.01
600	+2.15	+1.56	+3.71
Percent DE_w	70	66	78

Seasonal DE_w -78

Mean DE_w -(70 + 66)/2 = 68

due to both compensating intake and compensating experimental error. The compensation increased as DE_w's for the individual irrigations decreased, Table 5. The mean DE_w is the average of the individual DE_w's for the season.

DISCUSSION

Design Implications

Borders designed to apply a relatively large depth of water often require low gradients and long intake opportunity times. By designing for the depth which can be applied during the time of high initial intake rate, steeper slopes can be used and maximum area covered. The increased slope will often be more compatible with existing field shapes and grades, thus decreasing border construction costs.

This initial infiltrated depth may not always completely refill the root zone. There are some advantages to this:

1. Reduced percolation loss
2. Reserve root zone storage capacity would be available for rainfall that may occur immediately after an irrigation.
3. The more frequent irrigations would maintain lower tensions in the top layer of the soil profile where most root activity occurs.

Automation is needed for border irrigation because efficiency of a border system depends primarily on precise cutoff time; 35 minutes on one border, 40 minutes on the next and so on, day and night. An advantage of a minimum number of irrigations per season is that fewer irrigations require less labor on normally irrigated systems. If a border system were automated it would make little difference in labor requirement whether eight irrigations or only five were applied in a season.

TABLE 5

SEASONAL WATER DISTRIBUTION EFFICIENCIES
AND MEAN WATER DISTRIBUTION EFFICIENCIES

	Border	Mean DE_w	Seasonal DE_w
Site S	5	86.0	89.1
	6	85.4	88.6
	7	85.0	90.7
	8	82.2	88.8
Site M	1	93.0	94.8
	2	88.8	93.7
	3	83.2	88.9
	4	92.0	92.5
	5	87.3	91.9
	6	82.3	90.6
	9	92.0	94.6
	10	91.2	95.2
	11	78.0	86.1
	12	88.7	93.3
Scottsbluff	1	88.9	92.9
	2	85.5	83.6
	3	68.0	77.6
	3s	87.3	91.0
	4s (1960)	82.3	90.7
	4N (1960)	79.4	79.3
	4s (1961)	80.9	85.0
	4n (1961)	80.2	82.9
	5s	78.8	87.3
	6s (1960)	64.9	75.9
	6n (1960)	70.8	81.6
	6s (1961)	80.1	90.3
	6n (1961)	91.4	95.6

Cutoff Time

Table 6 is a listing by crops, by years, and where trends exist, by months, of the ration X/L

where X = distance from upstream end of border to the advancing front at cutoff time, and

L = the length of the border.

The water was cut off when the advancing front reached a predetermined distance estimated by trial and error. Unfortunately, proper timing varied with a number of factors.

The Scottsbluff experiments did not allow surface runoff, and any excess applied water over-irrigated the lower end. With moderate intake-rate, ponding did not last for a great length of time. All X/L ratios were close to unity at Scottsbluff and appear to present a simpler solution to control than at Grand Junction where the lower intake soils introduced considerable variability in X/L. Values for Grand Junction ranged from 0.33 to 0.75, as compared to 0.9 to 1.1 for Scottsbluff. Neither stream size nor crop retardance were appreciably different between the two locations.

Variation for Site S was considerably less for 1966 than for 1965. This might be attributed to more uniformity in intake rates and crop retardance in 1966. The stream size required for parallel advance and recession greatly influenced X/L.

The X/L ratio for Site M also was much more uniform in the second season of operation, again probably due to less variability in intake rate and crop retardance. There was no appreciable difference in X/L for Sites S and M, although slopes were 0.005 and less than 0.0001,

TABLE 6

SUMMARY OF RATIO OF DISTANCE ADVANCE AT TIME OF STREAM CUTOFF TO TOTAL BORDER LENGTH FOR THE BEST IRRIGATIONS

Year	Crop	X/L	Date	q ft^3/sec/ft
Scottsbluff				
1960	Sugar Beets	.95 - 1.0	Season	0.045
	Corn	.95 - 1.0	Season	0.045
	Alfalfa	1	Season	0.045
1961	Sugar Beets	0.88	July	0.045 - 0.057
	Sugar Beets	0.93 - 1	August	0.045 - 0.075
	Beans	0.91 - 1	Season	0.045 - 0.075
1962	Sugar Beets	0.83 - 1	Season	0.081
Site S				
1965	Alfalfa-Brome	0.48 - 0.72	June	0.042 - 0.116
1965	Alfalfa-Brome	0.36 - 0.48	July	0.107 - 0.128
1965	Alfalfa-Brome	0.34 - 0.68	August	0.060 - 0.142
1965	Alfalfa-Brome	0.49 - 0.66	September	0.051 - 0.083
1966	Alfalfa-Brome	0.53 - 0.72	Season	0.053 - 0.072
Site M				
1966	Alfalfa & Milo	0.55 - 0.88	July	0.039 - 0.058
1966	Alfalfa & Milo	0.71 - 0.75	August	0.032 - 0.060
1966	Alfalfa & Milo	0.71 - 0.80	September	0.040 - 0.059
1967	Alfalfa	0.71 - 0.73	April, June	0.059 - 0.077
1967	Alfalfa	0.50 - 0.64	July, August, September	0.046 - 0.075
1967	Milo	0.73 - 0.84	Season	0.051 - 0.073

respectively. Crops did not significantly affect X/L for the maximum irrigation efficiency.

In general, stream size ranged from 0.05 to 0.1 cfs per foot of border width. This range was limited on the low end by the stream size needed to cover the border and on the high end by the ability of the dikes to contain the water. Maximum flow depths were about six inches. Dikes could be constructed higher but become more difficult to manage and occupy a disproportionate percent of the land area. As shown in Figure 8 variations in stream size within the practical range had no measurable effect on DE_W.

The flow data of the more efficient irrigations will be analyzed for a method of predicting cutoff time for use with automatic turnouts. The automation of borders similar to those at Scottsbluff could utilize a sensing device at the lower end of the border to control cutoff. On soils of lower intake rate it may be necessary to establish a different reference system for signaling proper cutoff time. If predictions for these soils are too inaccurate, it may be desirable to incorporate a pump back system and allow runoff.

CONCLUSIONS

For border irrigation on the soils and with the ranges of both stream size and slope included in these experiments, conclusions are as follows:

1. Water distribution efficiency is for practical purposes independent of input stream size within the range of 0.03 to 0.12 cfs per foot of border width.

2. Water distribution efficiency is for practical purposes independent of slope in the low gradient range (0 to 0.001) and for the steeper slopes with close growing crops.

3. All three soils studied had a high initial intake, three to four inches during the first two hours. This application appears to be the minimum depth that can be applied by border irrigation with high efficiency.

4. The critical variable for an efficient irrigation was cutoff time. Operation, not design, was the key to efficient irrigation. Water distribution efficiencies between 80 and 95 percent resulted for nearly all irrigations, if advance and recession curves were approximately parallel, if the water was turned off from the border at such time that there was no runoff and the end of the border was neither under-irrigated nor over-irrigated. Automatic turnout controls are needed for satisfactory irrigation of borders.

5. Even though good efficiencies were obtained on the higher gradients, it was easier to obtain them on the low gradients. The peak efficiencies were never obtained on the higher slopes; however, this may be attributed to less precision grading.

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