Cablegation: III. Field Assessment of Performance

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ABSTRACT

FLOW rates into and out of furrows were monitored as a cablegation system irrigated a field. The resulting data were used to calculate furrow intake rates as a function of time. The initial supply rates to the furrows were within ± 13 percent of the designed flow rates. Seventy-eight percent of the variation was associated with deviations of the pipe elevation from the design grade. The computer model of this system predicts that deviations in flow rates resulting from elevation deviations will decrease as grade becomes steeper than the 0.28 percent used in this study.

Seventy-three percent of the water applied to the field infiltrated. Intake opportunity times averaged 11.0 h at the top end and 8.3 h at the bottom. The furrow intake rate, I_r, was related to the average intake opportunity time, T, by the equation $I_r = 48.6 + 214/T$. From these data it can be calculated that water applications at the bottom of the field averaged 84 percent of the application at the top end.

Runoff rate was relatively constant and total runoff was only about half of that which would have occurred under fixed set surface irrigation. Variability of furrow infiltration rates was high and 10 percent reduction in furrow supply rates would have resulted in water not reaching the ends of some furrows.

In general, the cablegation system provides more uniform water application than is normally achieved with other surface irrigation systems. The automatic cutback in supply reduces runoff and the runoff is more easily reused because of its steady flow.

INTRODUCTION

"Cablegation", as described by Kemper et al. (1981), is an automated surface irrigation system in which a single pipeline at the head of the field serves to both transport the water and distribute the water to furrows. Pipe size is chosen so that when the full supply of water is flowing, the pipe will be slightly less than full where the pipe is at minimum grade. Orifices, provided at intervals corresponding to the furrows to be irrigated, are drilled 30 deg from vertical on the upper side of the pipe. A plug blocks the flow of the water, causing the water to "back up" in the pipe and to be emitted from a number of the holes upstream from the plug. This number is determined by the slope and size of the pipe, the spacing and size of the orifices and the rate of supply. The orifice nearest the plug delivers the maximum discharge. Going upstream from the plug, the head is less and the flow from successive orifices is reduced until an orifice is reached at which there is no flow. When the pipe is at the design grade, all orifices further upstream are above the water level and do not discharge. The plug is pushed downstream by the water pressure and its speed (2 to 14 m/h) has been governed by a battery operated, variable-speed, DC electric motor to which the plug is connected via a cable and reel.

This paper presents an evaluation of performance of a cablegation system in terms of orifice discharges, advance of water with time in the furrows and flow into and out of the furrows. Furrow infiltration rates are also deduced as a function of time, and their interaction with the distribution system is discussed.

DETAILS OF THE SYSTEM

A pipeline 229 m long was laid across the head end of a rectangular alfalfa field. The field (and the furrows) were 108 m long. The average slope of the pipeline was 0.28 percent. The polyvinyl chloride (PVC) pipe had an inside diameter of 197 mm. The orifices were spaced 76 cm apart, and most of them had a diameter of 19 mm. Since the furrows served by orifices near the top and bottom ends of the pipe will not go through the complete cycle, application times and orifice sizes were adjusted as discussed by Kemper et al. (1981). Total water applied to those end furrows was approximately the same as that supplied to furrows served by orifices going through the full cycle.

Since substantial deviations from predicted flow rates due to lodging of grass blades in the orifices was observed in previous trials of the system, a screen (2.4 wires/cm) was installed in the supply line. This screen removed most trash from the supply water. When a blade of grass did come through the screen and lodged in the edge of an orifice, flow readings before and after removal indicated a change in flow rate of 10 to 15 percent.

EXPERIMENTAL SET UP AND OBSERVATIONS

At 9:30 p.m. on August 12, irrigation was started with the plug positioned just below orifice number 50 so as to irrigate the first 50 furrows. The reel and plug remained stationary until 4:07 a.m. the next morning. Then the motor was turned on and the rheostat was adjusted so the plug moved down through the pipe at a speed of 6.7 m/h (22 ft/h). The following observations were taken:

1 Furrow supply rates were determined at the even numbered orifices by measuring the time required for the water jetting from the orifices to fill a 5 liter container. Flow was also measured near the supply pipe in every

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tenth furrow using small trapezoidal flumes.

2 Runoff rates were determined on every tenth furrow by using manometers to measure the head drops across orifice plates which had previously been calibrated in the hydraulics laboratory.

3 Each hour, temperatures were determined of the air, supply water, water leaving the furrow and of the water leaving the field.

4 Elevation along the pipe was measured and deviations from designed elevations were determined.

5 Furrow advance rates were determined on even numbered furrows. To facilitate these determinations, stakes were set at 16 m intervals along every tenth furrow.

6 Total runoff from the field was determined continuously using a Parshall flume in free flow condition and a stage recorder.

7 Total inflow to the pipe was measured using the head loss across an orifice immediately upstream from the stand pipe. However, this calibration was accurate only when the plug was sufficiently far down the pipe that backwater did not extend up to the standpipe.

The gasketed PVC pipe was in sections 10 m long and the grade was staked at 10 m intervals corresponding to the joints of the pipe. During installation, the installers sighted along the top of the pipe and filled or excavated until the center sections were on essentially the same grade as the joints. However, this sighting was not possible in a curved section (i.e., orifices 190 through 200). In other sections some settling occurred when the pipe filled with water and the supporting soil became wet during previous irrigations.

Elevations of the orifices along the pipe are compared to the designed elevations in Fig. 1. The maximum discharge observed through each orifice is also shown in this figure. The pipe was at higher than design elevation at orifices number 190 to 198 and was at lower than design elevation at the location of orifices such as number 80 and 120.

The inflow and outflow rates for every tenth furrow from #60 to 130 are plotted in Fig. 2. Water was generally supplied to the furrows for about 10 or 11 h and runoff occurred for 7 to 9 h, which indicates the intake opportunity times at the top and bottom ends of the furrows.

The plots of air temperature and of water temperatures in the supply line, at the bottom end of furrows and at the flume as well as at where it leaves the field are shown in Fig. 3. The distribution of times taken by the water to advance down the furrows is plotted in Fig. 4. Orifice flow rates measured at 4:20, 6:00 and 7:00 p.m.

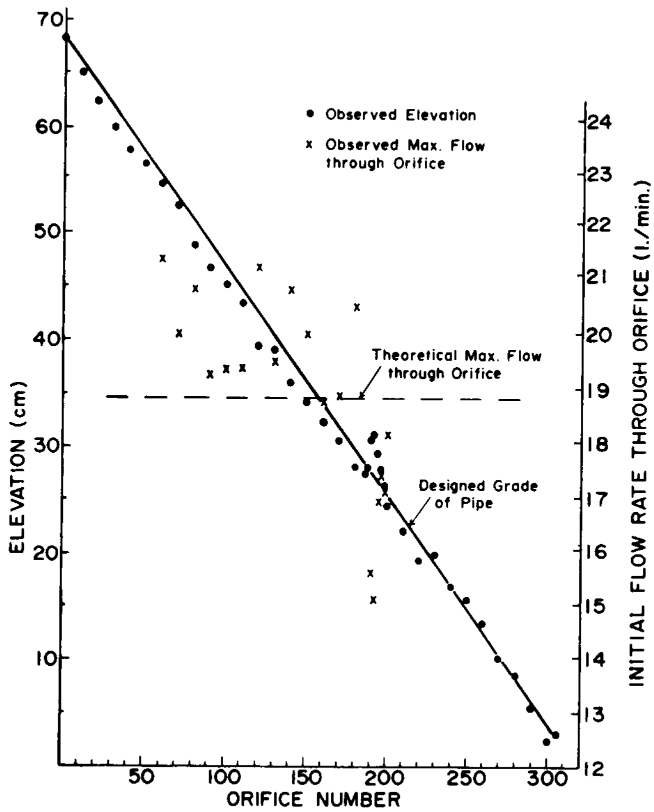

FIG. 1 Deviations of pipe elevations from designed elevations and their effects on maximum flows through orifices.

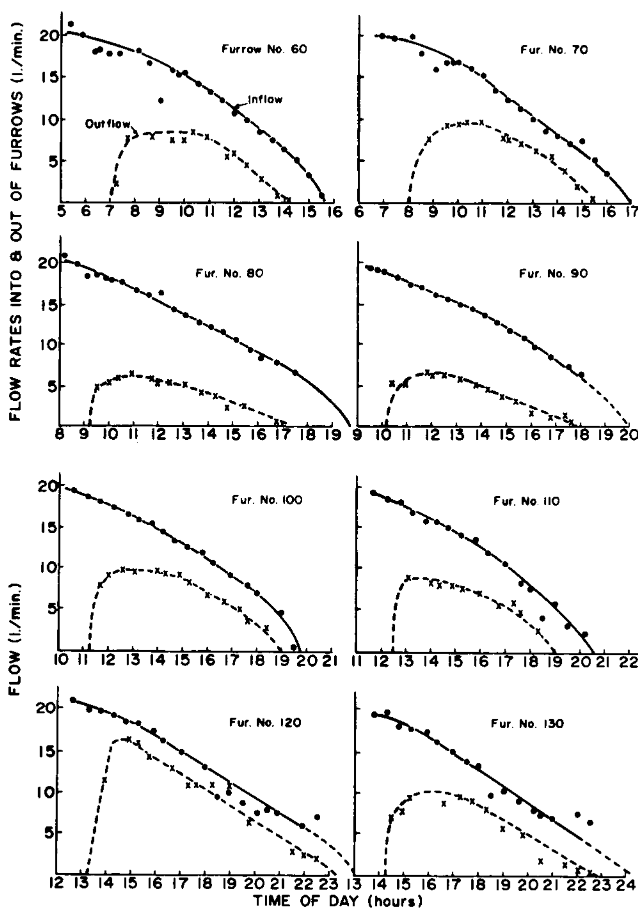

FIG. 2 Inflow and outflow rates for the indicated furrows.

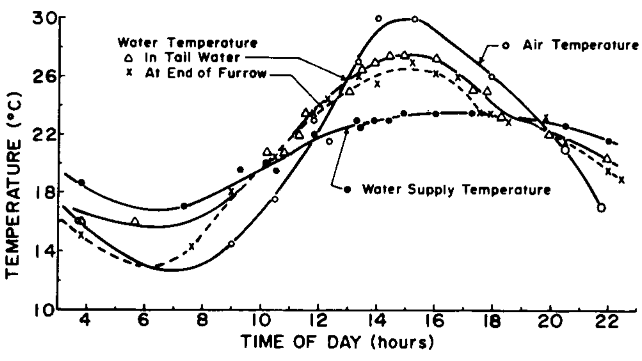

FIG. 3 Temperature of the air and of water in the supply line, near the lower ends of the furrow and at the flume where tailwater ran off the field.

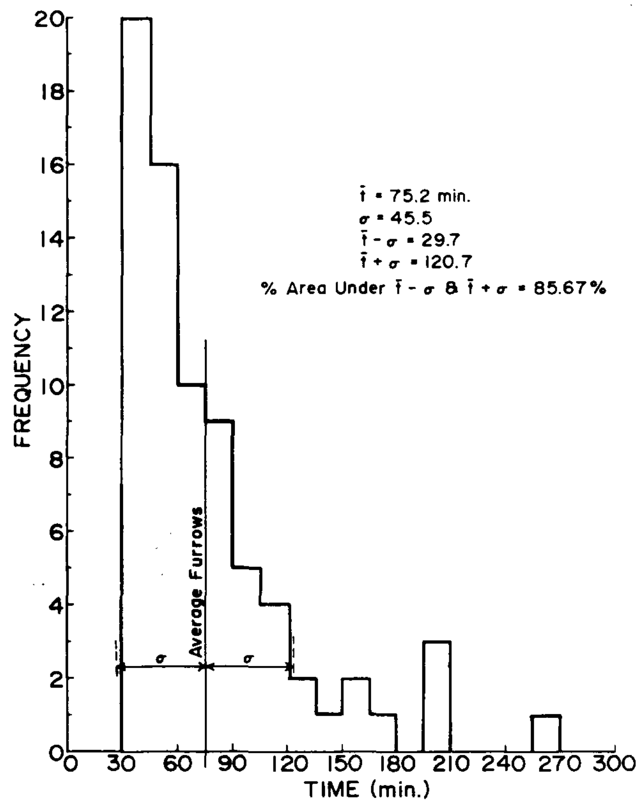

FIG. 4 Distribution of times required for the water to reach the bottom ends of the furrows.

are plotted and the pipe supply rates, Q, at those times are given in Fig. 5.

DISCUSSION AND ANALYSIS

Factors Affecting Furrow Supply Rate

Initial furrow supply rates, q_i, occurring just after the plug had passed the orifices, tended to be higher than average when the orifices were below the designed grade and vice versa (Fig. 1). To evaluate the effect of deviation from design elevation on initial or maximum furrow supply rate, q_i, a plot of q_i vs. the ratio

$$R_h = \left(\frac{17.1 + \hat{y} - y}{17.1}\right)^{1/2} \qquad [1]$$

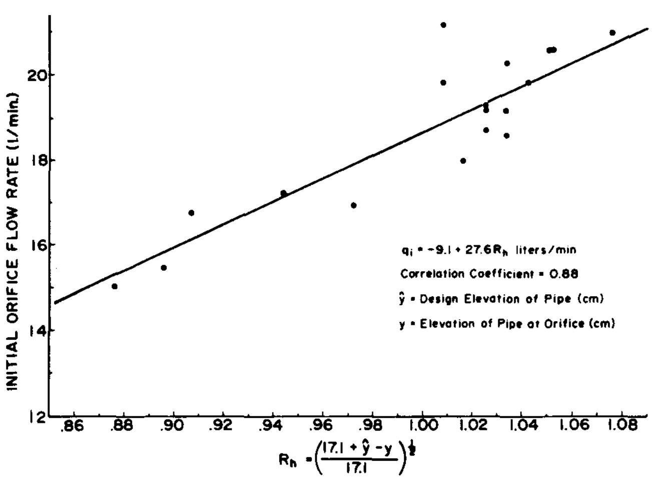

FIG. 6 Estimating the portion of the variation of orifice flow rates that was due to deviation of pipe elevations from designed elevations.

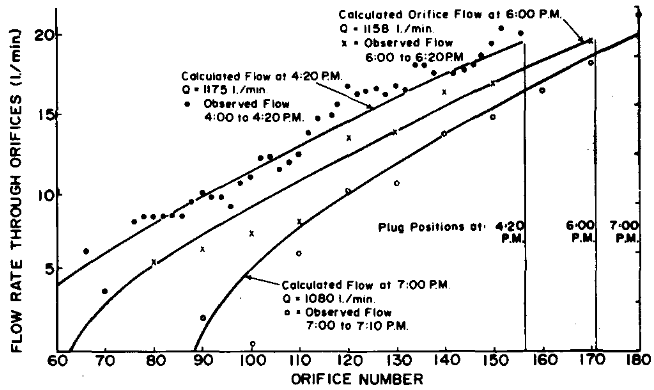

FIG. 5 Flow rates predicted and observed from orifices at 4, 6 and 7 p.m.

for the points indicated in Fig. 1 is given in Fig. 6 where 17.1 cm is the initial head predicted by the model at the orifice, $\hat{y}$, is the design elevation of the orifice and y is actual elevation of the orifice. Since q_i is proportional to the square root of the head of water in the pipe at the orofice, the function R_h sould be linearly related to q_i. Linear regression analysis of Q_i (liter/min) and R_h indicated that

$$q_i = 27.6 R_h - 9.1 \qquad [2]$$

with a correlation coefficient of 0.88. The best estimate of the portion of the variation in furrow supply rate which is related to deviations of orifice elevation from the design grade is the square of the correlation coefficient, which is 0.78. A major part of the remaining 22 percent of variation in flow rates was probably due to variations in orifice sizes or variation in the rate of total supply at the head of the pipe at the times when q_i was measured.

The pipeline was curved in an S shape in the range of orifice numbers 190 to 230. The radius of curvature reached a minimum of 70 m in the reach where orifices were numbered 190 to 200. The question arose as to whether the centrifugal force at these curves was a significant factor causing observed decreases in flow from these orifices on the inside of these curves. Since the orifices are drilled 30 deg from vertical toward the furrow side, they are about half way (5 cm) from the middle toward the side as indicated by the distance L in Fig. 7. The equation (i.e., Rouse, 1946, p 260)

$$\frac{dh}{dr} = \frac{V^2}{Rg}, \qquad [3]$$

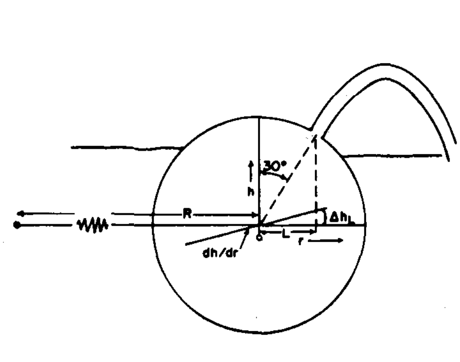

FIG. 7 Pipe cross section and associated factors and equations considered in calculating effect of pipe curvature or deviation of pressure head at the hole from the pressure head in straight sections of pipe.

describes the gradient in head across a curved pipe, where h is the increase in pressure head (cm), V is the mean velocity of water in the pipe (cm/s), R is the radius of curvature of the curved pipe (cm), r is the distance (cm) from the central vertical plane of the pipe in the direction of R (and $r \ll R$) and g is the gravitational acceleration. These factors and their relationships are diagrammed in Fig. 7. The difference in pressure head at an offcentered outlet from the pipe due to the curvature of the pipeline and centrifugal force can be calculated, since $r \ll R$, as

$$\Delta h_L = L\, dh/dr = LV^2/Rg. \quad [4]$$

This difference is positive on the outside of the curves ($L > 0$) and negative on the inside of the curves ($L < 0$). In the most curved section of the cablegation pipeline where R = 7000 cm and at the highest velocities encountered (80 cm/s), since L was 5 cm and g = 980 cm²/s Δh_L was only 0.0047 cm. This shows that the curvature of the pipeline used in this study was a negligible factor in pressure head and rates of flow from the orifices.

Flow rates from the orifices measured from 4:00 to 4:40, 6:00 to 6:10, and 7:00 to 7:10 p.m. are plotted along with the rates predicted by the computer model at 4:20, 6:00 and 7:00 p.m. (respective solid lines) in Fig. 5. Inputs required by the computer model are given in detail by Kincaid and Kemper (1982). In general they include total inflow rate, Q, to the pipe at that time; pipe diameter, D; slope of the pipe, S; orifice diameter, d; distance between orifices, and the Hazen-Williams roughness coefficient, C. Comparison of measured with calculated orifice flow rates indicates good agreement at 4:20 p.m. Flows appreciably below those predicted at 6:00 and 7:00 p.m. were generally associated with bits of trash (mostly blades of grass) which occasionally lodged on the downstream side of the orifices with one end inside and the other outside the pipe. These blades of grass which lodged more frequently at the low flow rate orifices caused surprisingly large reductions in flow rates, which illustrates the need for trash screens to maintain designed orifice flow rates.

Factors Affecting the Rate at Which Water Advances in the Furrows

Substantial variations in rates of water advance in the furrows are indicated in Fig. 4. The following factors probably contributed to these variations:

1 Differences in supply rates for different furrows,

2 Change in fluidity of water due to change in temperature,

3 Difference in nature of furrow, soil compaction vegetation, slope, cracks, residue, previous irrigation, etc.

To evaluate the degree to which time, t_a, required for water to reach the end of the furrow is dependent on initial furrow supply rate, q_i, regression analyses were run on these two variables assuming several functional relationships between them. The relationship indicated in equation [5] had a correlation coefficient of 0.65, which was the highest of those tested. Assuming this relationship, 42 percent of the variability in time to wet the furrows can be attributed to variation in furrow supply rate.

Linear $t_a = 332 - 0.78\, Q_i$,

Logarithmic $t_a = 1618 - 613 \log_{10} Q_i$,

Inverse (1) $t_a = -196 + \dfrac{89205}{Q_i}$,

(2) $t_a = 9000/(Q_i - 210)$ . . . . [5]

In equation [5], t_a is in minutes and q_i is in liters/minute (L/min). Using equation [5] we estimated that when $q_i < 210$ cc/s, the water would not reach the end of the furrows in this study.

In the range of temperatures encountered in irrigation, increasing the temperature by 1 °C increases the fluidity of water by about 2.7 percent. Fig. 3 shows that temperatures of water in the tail end of the furrows varied by about 13 deg during the observation period. Supply water temperature was about 7 deg higher at 3:00 p.m. than at 6:00 a.m. This average increase in the furrow water temperature of about 10 percent should increase the fluidity and rate of infiltration of the water by more than 25 percent. The expected increase in time for water to reach the ends of the furrows in midafternoon when temperatures of water in the furrows reach a maximum is not apparent in the data obtained in this study. Other uncontrolled factors, such as previous irrigation history, may be obscuring effects of this temperature factor on infiltration and furrow advance rates which have been observed in previous studies (Kemper et al., 1982). The increase in temperature and fluidity of furrow water from 7:00 to 9:00 a.m. may have been a factor in causing more infiltration at 9:00 a.m., so that the combined outflow from the furrows (Fig. 8) did not increase as much as would have been predicted from the increase of the inflow.

There were no obvious major sinks such as gopher holes causing the marked reductions observed in advance rates in the "slow" furrows. Supply rate to these furrows was normal and consequently intake rates of soils in these furrows must have been higher than in nearby furrows. detailed inspection showed more plant residue from the alfalfa in these furrows than in nearby furrows. Aarstad and Miller (1981) found that applying straw in the furrows at rates of 360 kgm/ha (320 lb/acre) increased infiltration rates by 50 percent. The amount of residue in the "slow" furrows of our alfalfa was greater than 360 kgm/ha. Consequently, this residue was probably a major factor holding back the flow of water, increasing the wetted perimeters and increasing infiltration rates. Some farmers in the area remake furrows after each alfalfa cut-

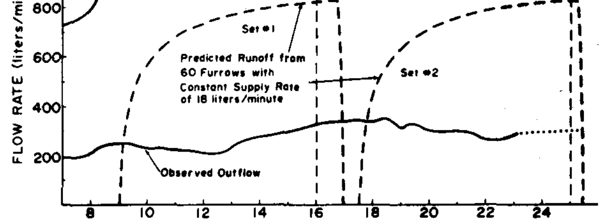

FIG. 8 Supply and runoff from the field.

ting. This practice also fills some gopher holes in the furrows and pushes tailings out of furrows which were blocked.

Another factor which may have caused some of the variability in furrow advance rates is previous irrigation history. For instance, it is possible that water did not get to the ends of some of these slow advance rate furrows during the previous irrigation the net effect of these and other factors affecting furrow advance in similar fields is a high coefficient of variation of the time required for water to reach the ends of the furrows, even when supply rate of water to successive furrows is essentially the same. In this study, the average time was 75 min and the standard deviation, assuming normal distribution of these times, was 45 min yielding a coefficient of variation of 60 percent.

However, frequency analysis (Fig. 4) indicates that the furrow advance time is not normally distributed, and consequently there are probably other types of statistics better suited to this phenomena than the statistics of normal distributions. The limit of our statistical capabilities were reached before we found a better one. The fact that the water in about 2 percent of the furrows took over 3 h to reach the end of this field where application rates were reasonably uniform, leaves the "farmer" with the following alternatives:

1 Apply sufficient water to all furrows to assure that water reaches the ends of the furrows with highest infiltration rates and accept runoff rates of the order of 25 percent.

2 Reduce the variability of water advance rate by frequent removal of plant and soil materials from the furrows.

3 Reduce the water supply rate to the furrows so there is less runoff from the normal furrow, saving water and accepting the yield reductions which would occur if about 2 percent of the rows are not wetted to the ends.

4 Intensively monitor the progress of the water down the furrows and runoff rates, and adjust supply rates to the furrows to get the water through all furrows with a minimum of runoff.

The alternative(s) implemented by the farmers will be strongly affected by the costs of: water, cleaning the furrows, and labor; the effect of underirrigation on yield of missed rows; and the value of the crop and on the opportunities for reuse of the runoff water. Opportunities for reuse of the runoff water can often be engineered into the system at a lower cost than the labor required to intensively monitor each furrow.

Infiltration Rates

Inflow and outflow rates from every tenth furrow from number 60 to 130 are plotted in Fig. 9 as a function of the average intake opportunity time for the furrow. Since these furrows did not include any of the extremely slow advance rate furrows, the "rate of infiltration for the furrow" can be approximated for a time after the first hour by subtracting the outflow rate from the inflow rate. Such subtractions provided the data points shown in Fig. 10.

Fig. 9 shows a rate of runoff curve that was constructed assuming the inflow rate is constant and that the infiltration rate is the same as was observed for the cablegation irrigation run. Comparison of the average observed runoff rate in Fig. 9 with the runoff rate predicted assuming a constant rate of supply, gives a reasonable, albeit slightly high, estimate of the reduction in runoff resulting from cutback of the supply rate.

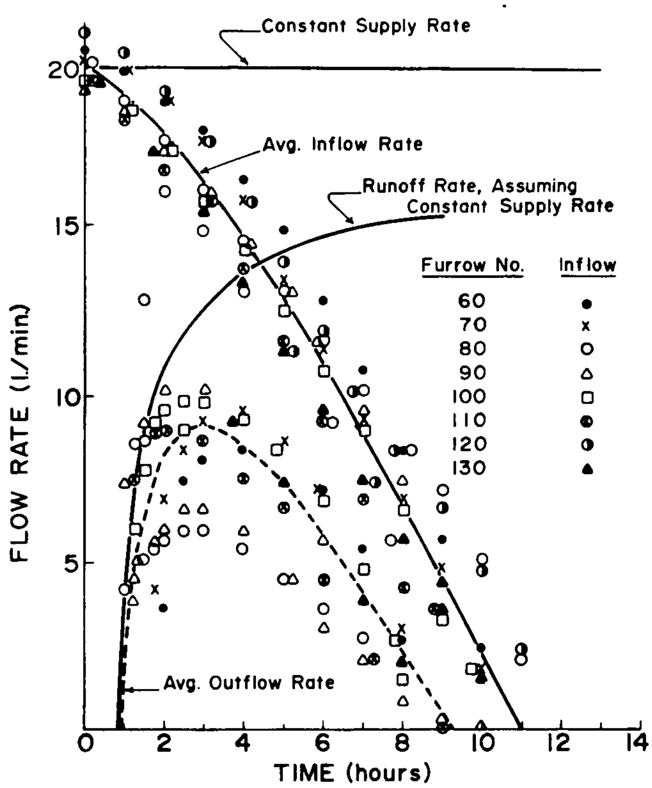

FIG. 9 Average inflow and runoff rates for the indicated furrows and estimated average runoff if supply rate had been constant.

In Fig. 10, the intake rates for all observed furrows were averaged at hourly intervals along the "average intake opportunity time" coordinate and used to draw the "average" curve shown in this figure. Since water was generally not present in the whole furrow when the average furrow intake opportunity times T < 1 hour and

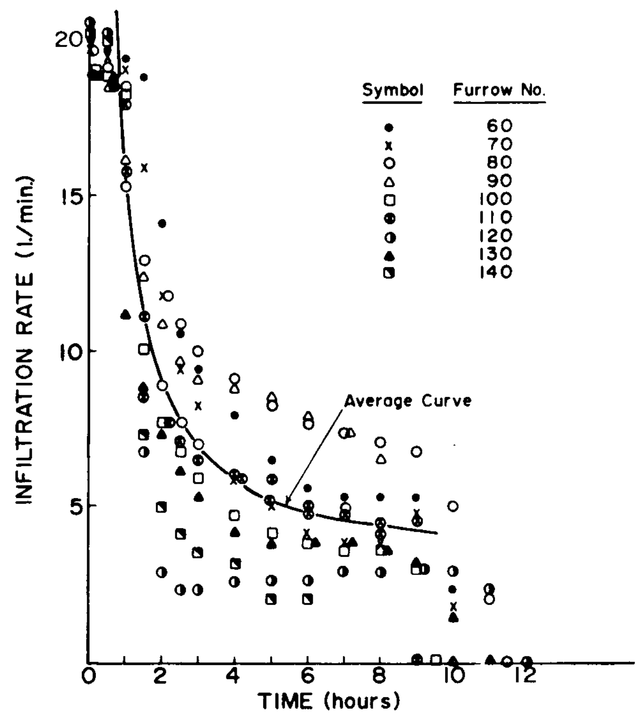

FIG. 10 Furrow infiltration rates as a function of time for which water has been supplied to the furrow.

when T > 9 hours, these portions of the average curve have not been drawn. Throughout the period 1 < T < 9 hours, the average infiltration rate, I_r, can be fit by the function,

$$I_r = 2.9 + 12.8/T \qquad [6]$$

where T is the average furrow intake opportunity time (hours), so that the correlation coefficient of the actual averages to the respective points on the calculated curve is 0.998. This Portneuf soil is known (e.g., Kemper et al., 1981) for relatively constant sustained furrow infiltration rates as indicated by the constant in equation [6].

Runoff

Observed total inflow and total runoff were plotted in Fig. 8. For the 9:00 a.m. to 10:00 p.m. period, the runoff was 27 percent of the water applied. Making the same assumptions as in Fig. 9, the runoff predicted for constant supplies are indicated as the dashed lines in Fig. 8. Assumming two successive 8.7-h sets of 60 rows, each row was supplied with 18 L/min and the set was changed at 16:00. The sets were "changed" after 8.7 h because that was the time(Fig. 9) after which the cablegation system did not keep water in the lower ends of all furrows. These calculations indicate that more than 50 percent of the applied water would have run off in such sets. This constant supply rate of 18 L/min is the average of what was applied during the first 3 hours by the cablegation system.

RESULTS AND CONCLUSIONS

When deviations of orifice elevations from design elevations were less than 3 cm and no debris was lodged in the orifices, initial flow rates from the orifices were within ± 13 percent of those predicted. About 80 percent of the observed variations in initial flow rate between orifices was associated with deviations of orifice elevations from design elevations. The model predicts that sensitivity of flow rates from orifices to the deviations in orifice levels from designed levels will decrease as the head increases.

Obtaining flow rates within 10 percent of those designed requires removal of trash from the water. The screen should be sufficiently fine to remove even small blades of grass. This requires that the screen have at least 8 meshes per centimeter.

Seventy-three percent of the water applied to the field was retained in the field and 27 percent ran off. Intake opportunity time averaged 11 h at the top end of the fields and 8.3 h at the bottom end. Assuming that the curve relating intake rate to average intake opportunity time is the same on soil at the top end of the field as at the bottom, the average amount of water applied to soil at the bottom end would be 84 percent of that applied at the top end.

The fraction of the total water infiltrated by the field was about 25 percent higher as a result of the reduction in furrow supply rate with time by the cablegation system as compared to the portion of the water that would have been retained if the rate of supply had remained constant.

Runoff from this field irrigated by a cablegation system was relatively constant compared to the intermittent runoff expected from normal fixed irrigation sets. Consequently this runoff water causes less erosion, requires a smaller drainage-way and is easier to use on lower fields for irrigation.

While the average furrow supply rates could have been decreased to reduce the amount of runoff, a decrease in supply by more than 10 percent would have resulted in water in at least one and possibly in four of the 308 furrows not reaching the end.

Where the runoff water can be reused on other fields or pumped back to the supply ditch at reasonable cost, it is generally less expensive to oversupply the average infiltration rate by 20 to 30 percent than to do the detailed monitoring and adjusting to compensate for heterogeneity of furrow infiltration rates.

In general, the cablegation system provides more uniform water application than is normally achieved with surface irrigation systems. The runoff is reasonably low and more readily useable because of its continuous nature.

When cablegation is being considered as an improved irrigation system for a field furrow supply and outflow, data collected during irrigation could be used to determine furrow infiltration rates and optimize cablegation system design for these specific rates. However, differences that will occur in infiltration, caused by cultivation, species, previous irrigation history, etc., rates require that the system have a substantial range of rates at which it can deliver water to furrows.

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