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CABLEGATION: AUTOMATED SUPPLY FOR SURFACE IRRIGATION

W. D. Kemper,* T. J. Trout, and D. C. Kincaid

U.S. Department of Agriculture
Agricultural Research Service
Snake River Conservation Research Center
Kimberly, Idaho 83341

I. Background for Development

As competition intensified and water sources became limited, successful irrigation farmers reduced labor input and increased application efficiency of their irrigation. Sprinkler systems, such as the center pivot, enabled them to do both. While energy costs were low, the economic feasibility of sprinkler irrigation was sound. But energy costs have risen without comparable increases in prices of farm products. Rising energy prices drastically reduce the net returns of farmers whose systems consume large amounts of expensive energy. The limited supply of fossil fuels and their rate of depletion signify eventual shortages and continuing increases in energy prices. Consequently, assessments were made of where energy was being used in irrigated farming systems. Between 30 and 45% of the nonsolar energy involved in raising a crop of sprinkler-irrigated corn or wheat in the western United States is consumed in irrigation (Pimmental, 1980) when pumping from surface water. For crops such as beans or alfalfa, which require little or no nitrogen fertilizer, the energy used to pressurize water for sprinkling can be as high as 60 to 80% of the total. The energy required for sprinkler irrigation is commonly three to five times that required for operation of trucks and tractors on the farms.

It became apparent that irrigation methods requiring less energy input must be developed if irrigated farms are to remain economically viable. Substantial headway has been made toward decreasing the energy input

* Present address: National Program Staff, U.S. Department of Agriculture–Agricultural Research Service, Building 005, Beltsville Agricultural Research Center, Beltsville, Maryland 20705.

to sprinkler irrigation. However, practical considerations indicate that a lower limit of energy consumption of about 40% of the original levels will still be necessary for sprinkler irrigation. Farmers who can achieve desired application efficiencies with improved surface irrigation systems will avoid one of the major energy costs involved in their farming operations.

In 1979 funds were appropriated to the Agricultural Research Service of the United States Department of Agriculture to develop systems and management practices which would reduce the vulnerability of irrigation farmers to increasing energy costs. Cablegation is a product of that research. It is currently in use on over 70 fields in eight of the western United States.

II. Description of the System

Cablegation is an automated method of supplying water for surface irrigation. The system can save labor and water compared to other surface application methods.

A. For Supplying Water to Furrows

1. *The Physical System*

Cablegation (as described for furrow irrigation by Kemper *et al.*, 1981) is a form of gated-pipe system. The gates or outlets are positioned near the top side of the pipe and are always open. The pipe is laid on a precise grade, and a plug moves slowly through the pipe, causing water to flow through the outlets, in sequence, to furrows in the field.

A pipeline is used both to convey the water along the top edge of the field and to distribute equal amounts to each furrow. The pipe is sized large enough to carry the water flow on the available slope without completely filling its cross section (Fig. 1). Outlets are placed near the top of the pipe's circumference (offset 20 to 30° toward the field from the pipe's vertical centerline) and spaced to correspond to the spacing that will be used for the furrows or corrugates during the crop rotation cycle. Water flows in the pipe below the level of the outlets until it approaches the plug. This obstruction causes the water to fill the pipe and flow from outlets near the plug. Hydraulic head in the pipe increases until the sum of flow rates from the outlets is equal to the supply rate. The outlets near the plug are under the highest head and deliver water at a maximum rate, whereas those farther upstream from the plug flow at lower rates, as indicated in Fig. 1.

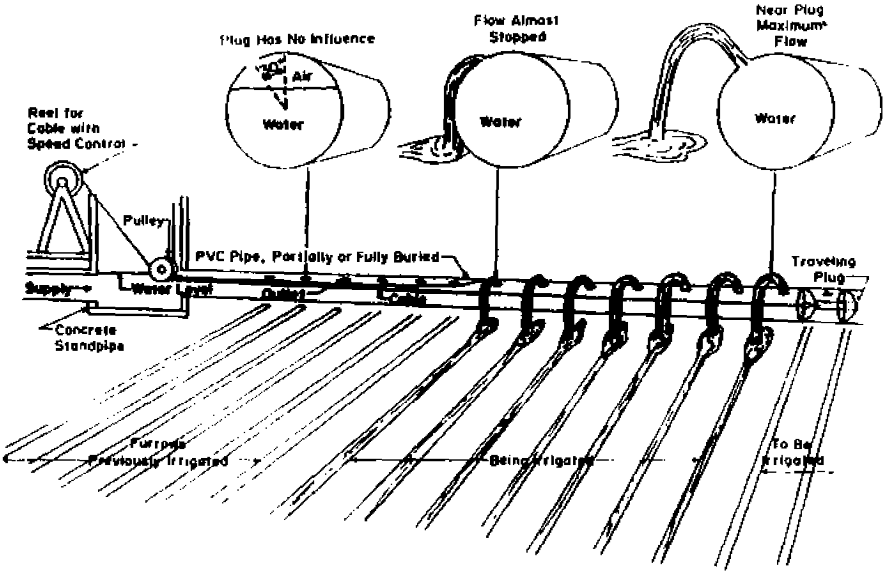


FIG. 1. General arrangement of the controls, pipes, and outlets in a cablegation system serving furrows. Pipe cross sections show water levels upstream from the plug.

To automate the system, the plug is allowed to move downslope through the pipe at a controlled rate. A cable on a reel at the inlet structure is attached to the upstream end of the plug. The rate at which the cable is reeled out determines the rate at which the plug moves and at which irrigation progresses across the field. The water pressure provides the force to move the plug.

As the plug moves past a specific outlet, water flows out of that outlet at a relatively high rate. As the plug moves further down the pipe, the flow rate from the specific outlet decreases and eventually drops to zero. Thus, a cutback flow is provided.

2. *Furrow Supply Rate Changes*

a. As Affected by Time and Plug Speed. Figure 2 shows the effect of time and plug travel speed on the supply rate of water to a furrow when the pipe slope, outlet diameter, and the system supply rate are constant. Initial furrow supply rate is high, which helps advance water down the whole furrow quickly. Then the furrow supply rate diminishes, resulting in less runoff than when supply rate is constant. The total irrigation time and gross application for a given system supply rate are determined by the plug travel speed.

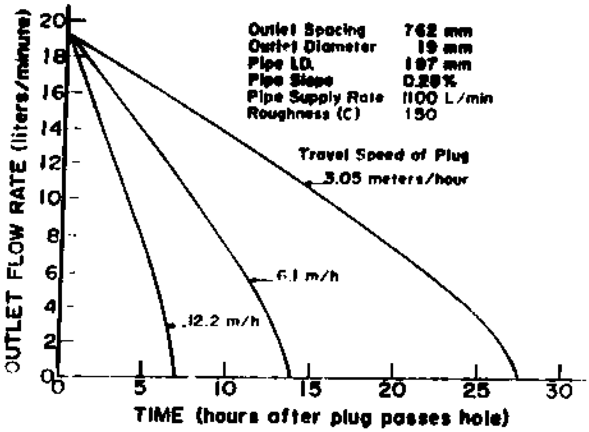


FIG. 2. Effect of time and plug speed on furrow supply rate after plug has passed the hole serving that furrow.

b. As Affected by Differences in Total Supply. Note that as pipe supply rates Q approach maximum pipe-capacity flow rates (that is, $Q/Q_c \rightarrow 1$), the supply to a furrow is prolonged at low rates. This "outlet dribble" generally waters only the upper end of the field and increases the nonuniformity of irrigation. Consequently, pipe supply rates Q should be less than $0.85Q_c$.

One way to decrease the furrow supply rate is to decrease the system supply rate. However, as indicated in Fig. 3, reducing the system supply rate Q from 0.8 to 0.4 of its maximum capacity Q_c decreases the initial furrow supply rate by only about 20%. Time of furrow supply is decreased more than flow rate by such reductions in system supply rates.

One farmer with two cablegation systems with fixed-size outlets uses this limited flexibility by splitting his water between the two systems on most irrigations, but applying his total supply rate to one field at a time during the first irrigation following plowing.

The limited increase in furrow supply rate that can be achieved by increasing pipe supply rate is often not sufficient to match high infiltration rates that occur throughout a season or from season to season. One means of achieving this match is to decrease the furrow intake rates. In some cases, this can be achieved by compacting the furrow (e.g., Kemper *et al.*, 1982) or by practicing surge irrigation (e.g., Bishop *et al.*, 1981). However, most farmers to date have chosen to install adjustable outlets which allow them to match a broad range of furrow intake rates.

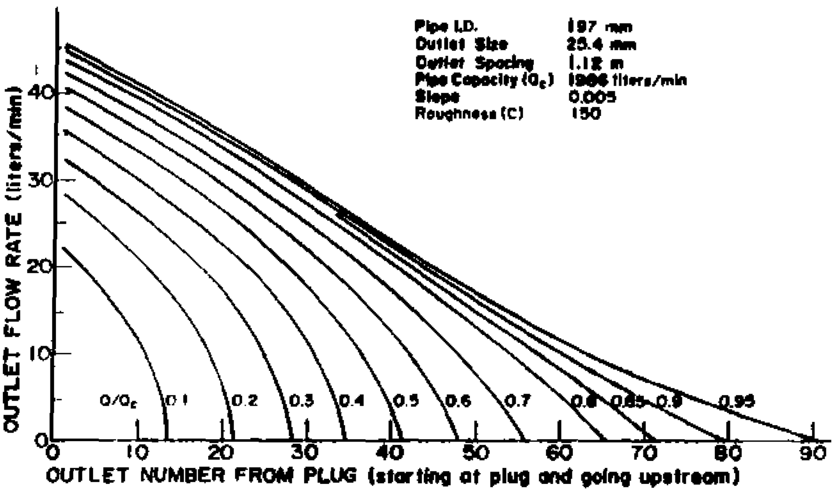


FIG. 3. Distribution of outlet flow with supply at various fractions of pipe flow capacity.

c. As Affected by Outlet Size. The magnitude of change in furrow supply rate that can be achieved with change in outlet size is indicated in Fig. 4. If the pressure at the outlet remained constant, flow would be proportional to the area of the outlet, or the diameter squared for round holes. However, as outlet size increases all along the pipe, the pressure of water in the pipe decreases and the initial flow rate is approximately proportional to the three-halves power rather than the squared power of the round outlet diameters.

B. For Supplying Bordered Strips

Bordered strip irrigation is often the most efficient method for surface irrigating close-growing crops such as alfalfa, pasture, and small grain (Booher, 1974). It is often an effective method of achieving reasonably uniform irrigation on high-intake-rate soils. Relatively narrow strips, bordered by dikes 10 to 15 cm high, are leveled or graded so there is no side slope. Water is introduced at the top end of such strips at high rates to push it over the strip quickly. Use of laser technology has allowed precise grading of such strips and allowed farmers to surface irrigate high-intake soils with satisfactory uniformity.

An unavoidable consequence of concentrating the water on such a relatively small area is that it must be changed to a new area frequently.

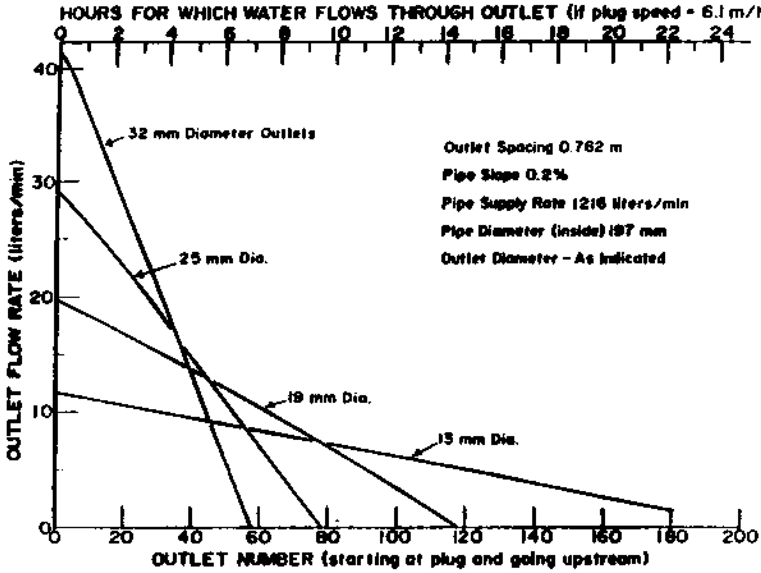


FIG. 4. Effect of outlet diameter (in millimeters, as indicated on each curve) on number of outlets flowing and the rate and time for which they flow.

Farmers have observed that bordered strip irrigation almost forces them to "live on the supply ditch." Figure 5 shows a form of cablegation adapted to bordered strip irrigation. In this form, the pipe is buried to get it out of the way of grazing animals and farm equipment. Risers from the pipe provide a supply of water to each bordered strip in sequence, beginning as the plug passes that riser and stopping when the plug passes the

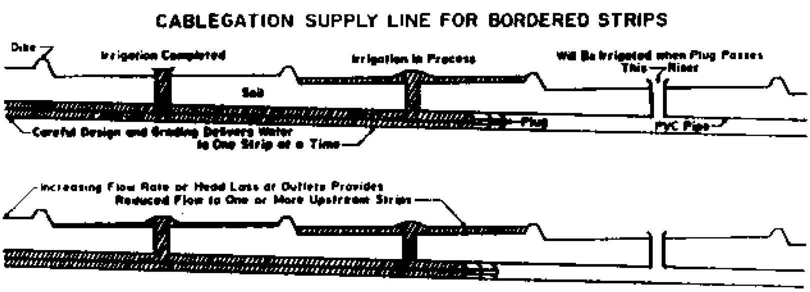


FIG. 5. Cablegation system adapted to bordered strip irrigation.

next riser if the difference in elevation between the risers provides sufficient head to push the total supply rate out of the lower riser (i.e., top sequence in Fig. 5). If total supply rate is increased, as indicated in the second sequence of Fig. 5, a reduced flow may continue from the second riser upstream from the plug. Further increases in total supply rate can maintain flow from the third riser upstream from the plug. This provides a reducing supply rate, somewhat similar to that provided for furrow irrigation. Partial blocks on the outlets, increasing their resistance to flow, can also spread the water out over more risers when system supply rate is constant. The type of system shown in Fig. 5 can also be used on level basins.

A common constraint to applying cablegation to borders and basins is inadequate field cross slope to provide the elevation drop between risers required to discharge the desired flow from economically sized outlets. Extra grade required to operate the system can be generated by elevating the initial outlets and installing the outlets on a steeper grade than the field, as shown in Fig. 6. This solution does require sufficient water supply head at the inlet to operate the first outlet.

C. Benefits Derived

Due to the automatic nature of cablegation, labor is saved. The need to adjust individual outlets is reduced. Since duration of irrigation can be adjusted without imposing restrictions on the farmers' schedules, application amounts can be closely matched to crop needs and soil characteristics. The decreasing application rates more closely match most soil infiltration rates and can thus advance water quickly across the field without causing high runoff. Cablegation runoff is fairly constant over time and can be efficiently reused.

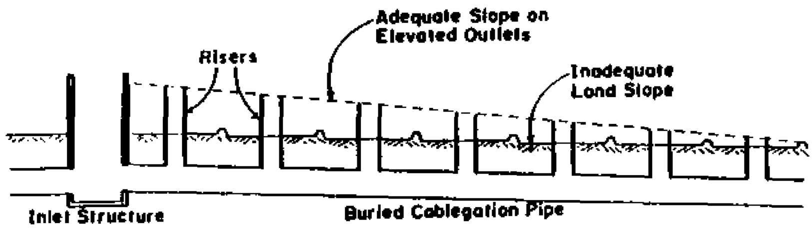


Fig. 6. Supply rate sequences to bordered strips as total supply rate increases.

D. Applicability

Cablegation can be used on most fields where other forms of surface irrigation have been, or could be used. Outlets along the pipe must be on grades of at least 0.002 m/m. Methods for achieving these grades when cross slope is less than 0.002 m/m will be outlined in a following section.

III. Basic System Components

A. Pipe Size and Grade

Pipe size needed is determined by water-supply rate, slope on which the pipe will lie, roughness of the pipe walls, and temperature (viscosity) of the water. For practical purposes, irrigation water is assumed to have a temperature of about 20°C. At this viscosity, the Hazen–Williams formula relating the remaining factors is

$$S_f = 6.17 \times 10^6 (Q_c/C)^{1.85} D^{-4.87} \tag{1}$$

or

$$Q_c = 2.15 \times 10^{-4} C S_f^{0.54} D^{2.63} \tag{1a}$$

The term S_f is the head gradient along the pipe in meters per meter due to friction, Q_c is the flow rate in liters/minute, D is the inside diameter of the pipe in millimeters, and C is the roughness coefficient of the pipe. This "roughness" coefficient is actually larger when pipes are smoother. For instance, the value of C is about 150 for polyvinyl chloride (PVC) pipe, and for rougher aluminum pipe a value for C of 130 is commonly assumed. Depending on the conditions of use, nutrients in the water, etc., the pipe may need to be cleaned occasionally to maintain these coefficients.

To avoid prolonged dribbling as flow from outlets in the cablegation pipe decreases (see Fig. 3 and the related discussion for the reasons for this recommendation), it is recommended that pipe size be large enough so the head loss calculated from Eq. (1) will be less than 75% of the grade on which the pipe will be laid or, equivalently, that Q be no more than 85% of Q_c calculated from Eq. (1a).

The pipe must be placed and maintained on a precise grade to achieve desired uniformity of water delivery. When the grade is low (<0.4%), pipe (or outlet) elevation must be maintained within 1 cm of the designed grade. Pipelines placed on steep slopes can generally tolerate more variation from the designed grade than those on flat slopes and still maintain reasonably uniform delivery. If the pipe diameter is somewhat larger than that needed to carry the flow, outlets in sections of pipe which have settled slightly below designed grade levels are less likely to continue to dribble as the plug passes farther downstream. Changes in grade between sections along a cablegation pipe require changes in outlet size to achieve the same furrow supplies in both sections. The minimum slope at which carefully laid cablegation pipes have worked properly with practically feasible maintenance is 0.002 m/m.

Because of current price considerations and the resistance to degradation when the pipes are in contact with soil, PVC pipe has been used extensively to date. Any schedule or type of pipe can be used in cablegation systems as long as there are no internal constrictions which will stop the plug and the pipe is sufficiently rigid to maintain a reasonably round shape. Polyvinyl chloride pipe (IPS, gated, and PIP schedules) and aluminum gated pipe have commonly been used. Plastic pipe exposed to sunlight should have ultraviolet inhibitors to prevent rapid deterioration.

B. Traveling Plugs and Pipe Fittings

The plug must fit snugly inside the pipe to minimize leakage past the plug, but it must also slide down the pipeline as tension on the cable is released. Many of the original plugs were constructed using commonly available plastic bowls or buckets, as indicated in Fig. 7. Each bowl was clamped between metal plates spaced about one pipe diameter from each other as shown in Fig. 7. Two bowls were used to maintain alignment of the plug in the pipe and to improve sealing. The circumferences of the bowls were trimmed so they would just slip inside the pipe. Most PVC pipe has uniform inside circumference. When pipe sections are deformed to oval shapes, the bowls deform also and maintain reasonably good seals.

Reductions in pipe circumferences are formed on the male ends by some manufacturers to strengthen the ends and facilitate easy coupling of

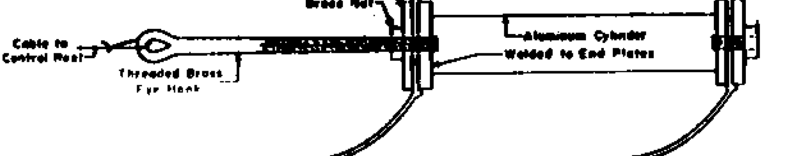


Fig. 7. Plug constructed using high-density polyethylene salad bowls as gaskets.

the pipe. These reductions should be avoided if possible because they tend to catch and hold plugs and reduce the carrying capacity of pipe. However, many farmers who already have aluminum gated pipe with such reductions have converted to cablegation. If the pipeline is to remain in place, the best solution is to cut off the constricted ends. However, if the farmers move the pipe annually they are reluctant to remove the strengthened and constricted ends. Plugs required to go through such constrictions must have ability to compress. The polyethylene bowls illustrated in Fig. 7 do not have this ability. However if the polyethylene bowls are slotted as indicated in Fig. 8, they can generally pass through such constrictions.

Commercially manufactured plugs are now available where the noncompressible plastic bowls have been replaced by compressible flexible PVC gaskets (Fig. 9). These gaskets flex sufficiently to pass the constrictions common in T-fittings, the rolled male ends of aluminum gated pipe, the insides of gates, etc. However, in constructing the pipeline it is best to keep the inside of the line as smooth and uniform as possible. For instance, when large risers are needed, saddles cemented around holes cut in the pipe do not form constrictions in the pipe of the type formed by most cast T-fittings.

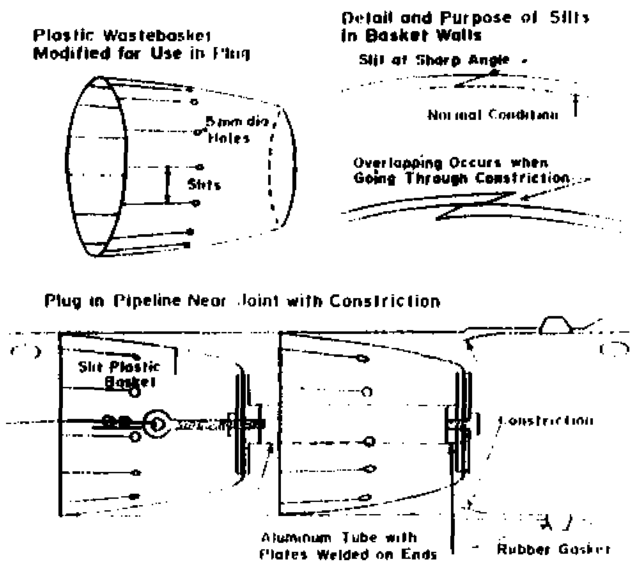


FIG. 8. Plugs using gaskets made of polyethylene waste baskets slotted so they can squeeze through pipe with constrictions.

Leakage past the plugs range from nearly 0 up to 20 liters/min and is generally negligible in systems carrying 1,800 to 6,000 liters/min.

C. Cables and Reels

The cable must hold the force of the pressure head against the plug, the drag of the water on the cable, and any surge forces resulting from sudden changes in rate of plug travel or water supply rate. This has required cables to control loads from 10 to 300 kg, depending primarily on the slope, diameter, and depth of the pipeline. Cables used have ranged from 40-kg test braided Dacron fishing line to steel and polypropylene cables with over 300 kg test strength. As larger diameter cables are used, the dimensions of the reels must be increased to store a greater volume of cable.

The reel is designed to store the cable between irrigations and to allow the cable to the paid out at the desired rates during irrigating. When a reasonably constant speed is desired, the effective diameter of the reel

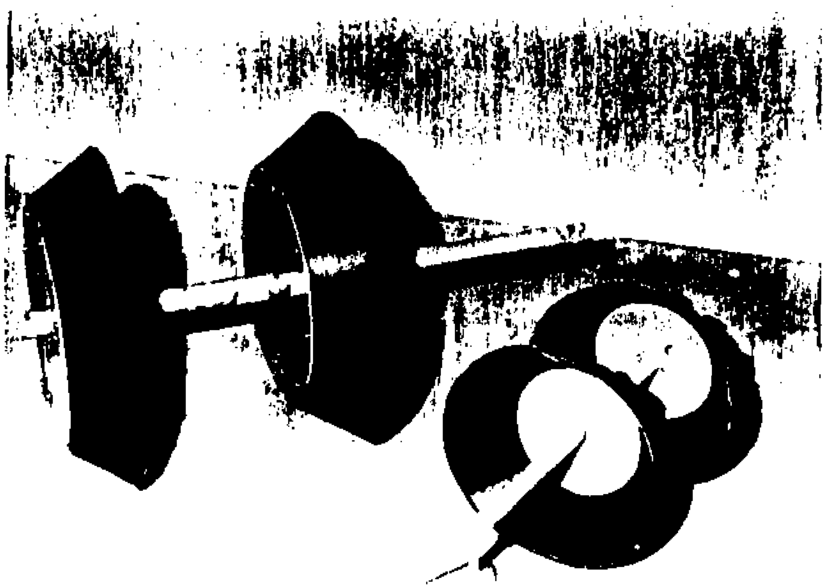


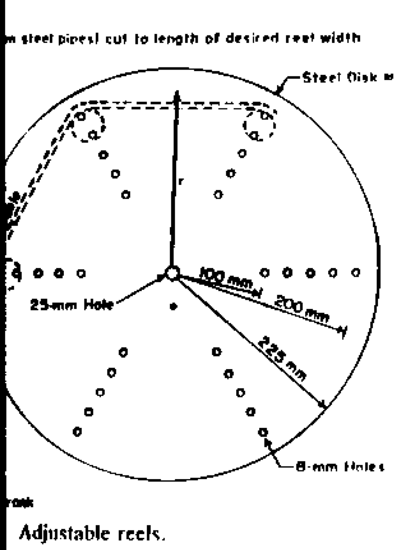
FIG. 9. Plugs with compressible, flexible PVC gaskets designed and manufactured for cablegation. (Courtesy of Cablegation Controls, Inc., Route 1, 1718 East, 3000 South, Wendell, Idaho 83355.)

the drum width must be sufficient to store
out too much buildup of cable on the reel.
of being released from the speed control
manually rewound onto the reel at the end
as been removed from the end of the cable.
various cable sizes and field layouts are
Cablegation Manual (Kemper *et al.*, 1985).
own in Fig. 10 have been used for many
the bolt and spacer positions reel diam-
chieved. Width of the reel is determined by

SMS

lug down the pipe. The rate of the plug's
everal types of mechanisms depending on
The power required for speed control can
water on the plug which is exerted on the
he water on a paddle wheel, dc batteries,

nonly used type of controller is the "wa-
d (1985). The basic components of wa-
ed in Fig. 11. Torque exerted by the cable



Adjustable reels.

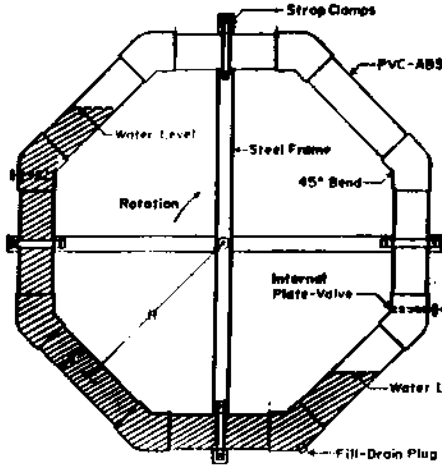


FIG. 11. Waterbrake type of

on the reel tends to turn the attached wa
of the water race, valved baffle plates (c
Box 242, Hansen, Idaho 83334, and illus
water in the race and push it higher on
torque it exerts on the connecting sha
supports, balances the torque exerted b

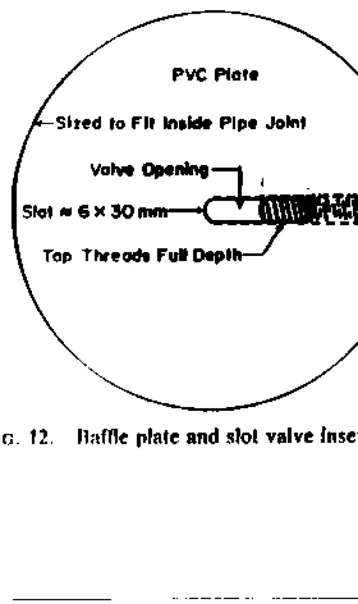


FIG. 12. Baffle plate and slot valve inse

rotation of the race and reel is increased by increasing the size of the opening in the baffle plates by backing the threaded rod out of the slot.

The most technologically advanced type of controller developed to date uses a microprocessor-controlled timer to activate a solenoid which releases a latch on the reel and allows the reel to make one turn before it latches again (i.e., Fig. 13, courtesy of Cablegation Controls, Inc., 1718 East, 3000 South, Wendell, Idaho 83355). To keep the reel rotation speed down and avoid sudden stops and associated stress on the latch and cable, the reel is coupled to a hydraulic pump. A valve in a line directly connecting the pump inlet and outlet restricts the hydraulic fluid flow and slows the rate at which the pump and reel can turn.

Other controllers utilizing ac electric power, wet cell batteries, or paddle wheels imposed in the flowing water (e.g., Kemper *et al.*, 1985, pp. 6, 180, 181) are also being used to control the rate of cable and plug movement in the pipe.

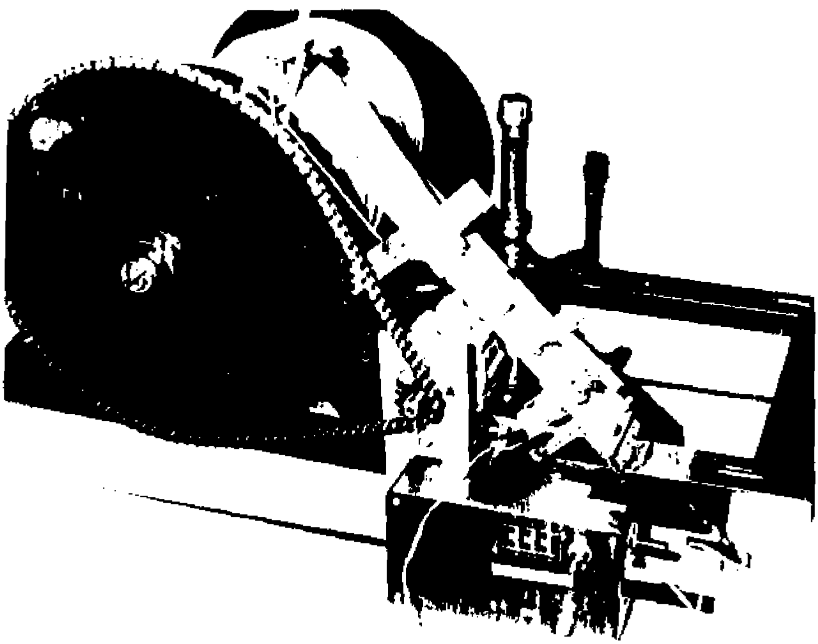


FIG. 13. Electronic timed-release controller. (Courtesy of Cablegation Controls, Inc.)

E. Outlets for Supplying Furrows

a. Purpose of Outlets. An outlet is normally required to supply water for each irrigation furrow. Outlets can be installed directly on surface pipe or can be attached to risers from buried pipe.

Outlets often fulfill purposes in addition to water distribution. Adjustable outlets allow flow rates to be varied with soil intake rate changes. They also give a system flexibility and simplify design. A disadvantage of adjustable outlets is that they allow the unconscientious irrigator to set water nonuniformly. Energy-dissipating outlets reduce the outflow jet velocity and redirect the flow toward the soil surface. This reduces erosion at the head of the furrow and prevents the jet from being blown away from the furrow by wind. Energy dissipation and redirection of the jet are commonly needed when pressures at the plug are greater than 400 mm. Cutoff outlets abruptly stop flowing when the flow rate decreases below a critical value. This improves intake uniformity by reducing or eliminating tail-end recession.

b. Predicting Discharge from Outlets. The flow through an outlet is proportional to the flow cross-sectional area and to the square root of the head or pressure and can be calculated by the outlet-discharge equation

$$q = C_d A(2gH)^{0.5} \qquad (2)$$

where q is the flow rate, C_d is the discharge coefficient which will vary with the shape and configuration of the outlet, A is the area of the outlet constriction (narrowest point), g is the gravitational acceleration and H is the head (pressure) on the outlet.

When q is in liters/minute, A is in square millimeters, and H is in millimeters

$$q = 0.0084 C_d A H^{0.5} \qquad (3)$$

c. Slide Gates Made for Standard Gated Pipe. Flexible plugs (e.g., Figs. 8 and 9) will migrate past regular gated-pipe slide gates. These slide gates, manufactured in large quantities, are the least expensive adjustable type of outlet. Use of gated pipe with precut rectangular holes eliminates the need to drill holes to attach outlets. The flow area of standard wide-open slide gates is about 1450 mm², or equivalent to a 43-mm-diameter round hole. Discharge coefficients decrease from about 0.8 when the gate is nearly closed to 0.65 when it is open. Some irrigators depend on their visual perception to adjust gates to uniform flow. Coefficients of variation of the resulting flows depend somewhat on the farmer, but commonly range around 25%. Coefficients of variation can be reduced to around 7%

if a wooden or metal gauge of the desired width is inserted into each slot and the gate closed against this gauge to achieve more uniform openings.

Slide gates do not provide significant energy dissipation and thus they are not normally recommended in systems which develop heads greater than 400 mm. Slide gate gaskets and spring clips deteriorate over time and may allow the gates to move easily. Cablegation plugs can move such loose gates, changing the openings. Loose gates should be replaced or tightened by placing a rubber strip between the gate and the pipe wall.

If water supply to a cablegation line stops, pressure against the plug diminishes and the somewhat elastic cable will often pull the plug upstream past a few outlets. The upstream angle of the gaskets on the plug will hook sufficiently on some types of gates to slide them. Triad Corporation (P.O. Box 130, Alda, Nebraska 68810) now manufactures gates which can be locked in place.

d. Outlet Design. Outlets have been designed to dissipate energy, redirect and adjust the flow, and cut off the dribble. Figure 14 shows a type of outlet which provides adjustability, energy dissipation, and cutoff. It can be attached directly to the pipe with the rubber bushing, or to a riser with a slip coupler. Removable orifice disks, available in several sizes from 12- to 22-mm diameter, are inserted into the coupler or bushing. Adjustment requires slipping out the gooseneck and replacing the disk. The gooseneck directs the flow to and parallel with the soil surface. Since

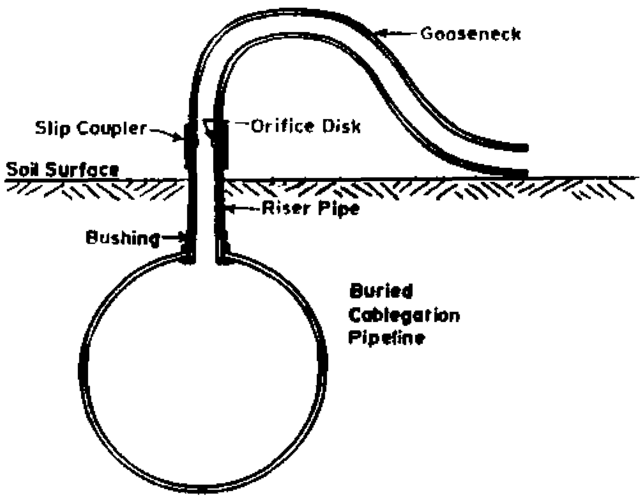


FIG. 14. Gooseneck outlet on a riser. (Courtesy Cablegation Controls, Inc.)

the outflow end is larger than the constricting orifice disk at all but the maximum flow rate, the outlet generally provides energy dissipation.

The gooseneck outlet operates as a siphon, and the outflow end determines the reference elevation. When the flow rate decreases below a critical value, air moves up the tube and breaks the siphon. The cutoff flow for the 25 mm-diameter gooseneck is about 15 liters/min. As long as the head required to provide this critical cutoff flow is less than the height of the top of the gooseneck above the outflow end, the cutoff will be complete.

Because the outflow end of the gooseneck establishes the reference outlet elevation, it is important that the end be on grade. Goosenecks which tip upward or sag will discharge relatively less or more water. This can result in significant nonuniformity in systems with little slope along the pipe.

An adaptation of the gooseneck outlet made from PVC pipe and ABS plumbing fittings is shown in Fig. 15. When drop tubes are vented just below the orifice disks, the orifice disks, rather than the outflow ends, become the effective outlets and conformance of their elevations to the desired grade is the primary prerequisite for uniform furrow supply. This type of outlet with risers has been used to create the desired grade on outlets from a cablegation line on a field with no cross slope. They can also be used to continue a cablegation line across a low area without constructing an elevated pad.

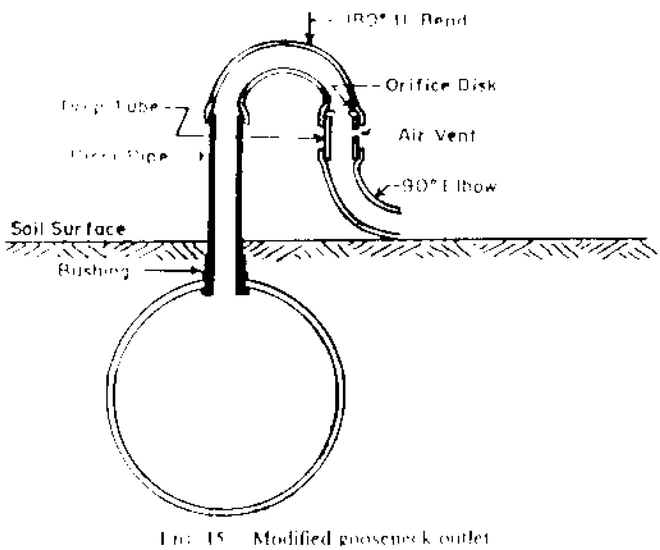


FIG. 15. Modified gooseneck outlet.

Like the gooseneck siphoning outlet, this outlet will also cut off the flow below a given rate. Due to the air vent in the drop tube, the orifice constriction forms the effective outflow end of the siphon. Consequently, the cutoff rate which occurs at a relatively constant flow velocity at the outflow end will vary with the orifice size. The cutoff flow rate will thus be proportional to the flow rate at any given head. This allows some control in setting not only the maximum flow but also the cutoff flow for a soil's infiltration characteristics.

Barrel spigots can be used as outlets for cablegation systems. They are essentially plastic tees through which a capped, slotted pipe slides. When the pipe is rotated, the slot lines up to varying degrees with the leg of the tee, thus adjusting opening area and flow rate. Standard barrel spigots for 19- and 51-mm taps are commercially available. Irrigation outlets of the spigot type such as shown in Fig. 16 are also commercially available in a 25-mm size. They can be attached directly to the pipe with threaded rubber bushings or with the slip-in bushings of the type indicated in Fig. 14. All three sizes can be attached to risers with threaded couplers. Bushings are also available which allow the 25-mm version shown in Fig. 16 to snap into standard rectangular gated-pipe slots. All can be adjusted to any setting. When outlets such as that shown in Fig. 16 have setting markings, they can be set with sufficient precision to attain coefficients of variation of flow that are less than 4%.

For all except wide-open operation, outflow ends of spigot type outlets are larger than the constrictions and the outlet provides some energy dissipation. The amount of dissipation depends on the length and diameter of the outflow pipe. Spigot type outlets redirect the flow 90°, which

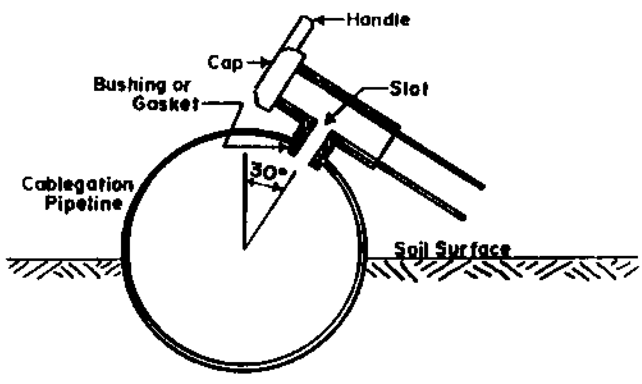


FIG. 16. Barrel-spigot-type outlet (courtesy Aqua Controls, P.O. Box 101, Rupert, Idaho 83351).

directs flow down toward the ground and practically eliminates an effect of the wind on destination of the water.

When spigot outlets are installed at an angle as indicated in Fig. 16 and have a fairly long outflow pipe, they can act as a siphon-type cutoff outlet. However, when elevation difference between the outflow end and the outlet high point is small, the cutoff will be complete only at large openings. At smaller openings, the cutoff head will be above the outlet high point, and the flows will abruptly decrease as air enters the outlet and as the reference elevation switches from the outflow end to the slot, but they will not cut off completely. Rotating the outlet downward (but not below the free-flow water surface) will increase the elevation difference between the slot and the end and improve the cutoff. Rotating the outlet upward to a horizontal position eliminates the cutoff effect.

IV. Models and Design

A. First Approximations

When the minimum slope of the planned cablegation line is known, it is relatively simple to use Eq. (1a) with available pipe diameters to determine which pipe size will carry the desired total supply rate. For reasons depicted in Fig. 3, the pipe should have a carrying capacity Q_c at least 1.18 (= 1.0/0.85) times the maximum anticipated supply rate Q_m.

If adjustable outlets are to be used, the only other essential information needed for design are the maximum and minimum required supply rates to the furrows. The range of outlet sizes required and the water pressure created behind the plug, and thus the need for energy dissipating outlets, are related to the slope of the pipeline and furrow supply rates needed. The interrelations are efficiently and accurately calculated by using the models and design relationships discussed in the following section.

Maximum orifice size needed can be estimated as follows. First, divide the total supply rate (Q in liters/minute) by 0.6 and by the maximum furrow supply rate (q_m in liters/minute) needed. This quotient approximates the number, N, of outlets that will be flowing. Multiplying this number of outlets by the distance between outlets (L in millimeters) and the slope (S) of the pipe gives the elevation difference between the upstream outlet where water has just stopped flowing and the outlet immediately upstream from the plug. Some of this head is dissipated by friction in the pipe section between the outlets. However, when the total supply rate is kept to less than 0.85 of the pipe capacity, about 60% of that head (0.6 ± 0.2) is generally still at the outlet immediately upstream from the plug.

Consequently, the minimum head H_{min} (in millimeters) at the outlet immediately upstream from the plug is approximately

$$H_{min} \doteq 0.6NLS \doteq 0.6(QLS/0.6q_m) \doteq QLS/q_m \qquad (4)$$

The maximum head on a system (H_{max}) may also be estimated using Eq. (4) by replacing q_m with the minimum furrow supply rate anticipated at the outlet immediately upstream from the plug *and* considering whether there will be occasions when only every other furrow will be supplied with water and therefore the distance (L) between flowing outlets will be doubled. A form of Eq. (3), written explicitly to determine the maximum outlet orifice areas, i.e.,

$$A_{max} = 119q_{max}/(C_d H_{min}^{0.5}) \qquad (5)$$

can be used to estimate the maximum outlet area (in square millimeters) needed.

If the maximum head at the plug (H_{max}) exceeds 400 mm, outlets providing energy dissipation and/or redirection of the water are recommended. If more precise design parameters are needed they can be obtained from the following calculator and computer models.

B. Models

1. *Purpose*

A mathematical cablegation model was developed to provide predictions of outlet flow rates as a function of total water supply rate, pipe size, type and slope, outlet size and spacing, plug speed, and time. It is also used to provide visual displays of the relationships such as those shown in Figs. 2–4. The model has been experimentally verified (Goel *et al.*, 1982, and numerous unpublished studies by the authors). Inputs of specifications such as pipeline slope(s), total water supply rate(s), outlet spacing, furrow supply rates, etc., into the model enable potential installers of cablegation systems to predict how the system would work before making major investments.

The model, and expansions thereof, have also played a major role in the development of cablegation system improvements. For instance, the bypass concept for minimizing end effects, discussed in Section V, was evaluated by, and eventually incorporated into the design model.

2. *Developments for Handheld Calculators and Computers*

a. Hydraulics Analysis. The schematic diagram (Fig. 17) of a cablegation pipe with outlets placed near the top shows the relationship of the energy gradeline and hydraulic gradeline to the pipeline and outlet elevations. The piezometric head is measured from the center of the outlets. Friction losses are computed based on full pipe flow.

The energy equation is used to determine the difference in piezometric head, $h_{i+1} - h_i$, between two adjacent outlets. Thus,

$$h_{i+1} - h_i = SL - h_f - h_0 + (V_i^2 - V_{i+1}^2)/2g \tag{6}$$

where V_i is the velocity in the pipe, immediately upstream from the ith outlet, in meters/second; g is the gravitational constant, 9.81 m/sec^2; S is the slope of the pipeline between the two outlets; L is the outlet spacing, in millimeters; h_f is the loss of head due to friction between the two outlets, in millimeters; and h_0 is the loss of head due to branching flow at the ith outlet, in millimeters.

The friction loss, h_f, in millimeters is calculated by the Hazen–Williams equation previously discussed as Eq. (1).

b. Outlet Discharge. The discharge, q, from an outlet is given by Eq. (3). The orifice discharge coefficient is usually assumed constant. However, laboratory studies showed that C_d for outlet orifices cut into the side of cablegation pipes is not constant but is dependent upon the ratio of the piezometric head to the velocity head. In a cablegation system, the flow condition near the plug is low velocity combined with high piezometric head. Moving upstream, the velocity increases as the piezometric head approaches zero and the C_d value decreases appreciably.

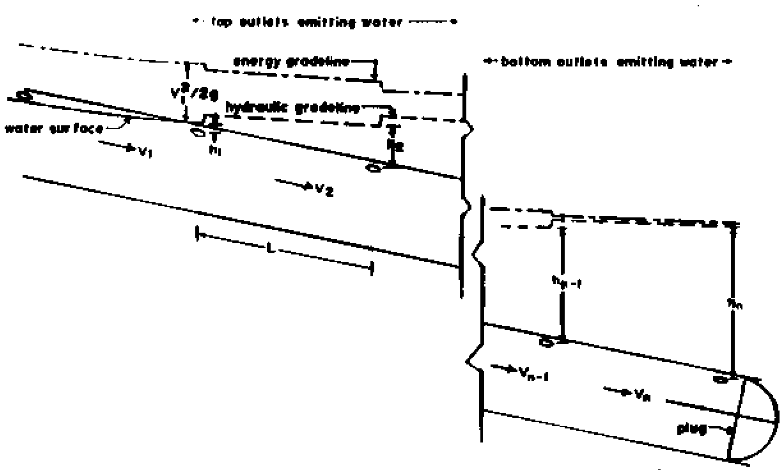


FIG. 17. Hydraulic parameters used in the cablegation model.

The ratio, r_h, of piezometric head to velocity head is

$$r_h = h/(V^2/2g) \quad (7)$$

The discharge coefficient begins to decrease appreciably when $r_h < 10$ (Kincaid and Kemper, 1982). The following empirical relationship was derived from data collected in the hydraulics laboratory and was used in the calculator model:

$$C_d/C_{d0} = 1.03/(0.40 + r_h) \quad (8)$$

For outlet holes in the side of pipe, $C_{d0} = 0.65$ is the value of C_d as the water velocity in the pipe approaches zero. Other types of outlets have been calibrated in terms of the effective area with $C_{d0} = 0.65$ (USDA-ARS Kimberly Staff, 1985).

Equation (8) fits the measured data for $r_h > 0.05$. For values of $0 < r_h < 0.05$ Eq. (8) may not be accurate. However, this region represents such a small portion of the outflow distribution that inaccuracies in this region do not affect the results appreciably.

Equation (8) does not hold for outlets such as are shown in Figs. 14–16, where the constriction is not at the surface of the pipe. Constant C_d values are often assumed for these types of outlets.

3. *Operation of Computer and Calculator Models*

a. Midsection Flow. When water flow is from the pipe midsection (not flowing from the first or last outlet of the pipeline), inputs to the model are pipe inside diameter, roughness, and slope(s); outlet size(s) and spacing; and system supply rate(s). The supply rate may vary with time but should be limited to 0.85 of the flow capacity of the pipe. As shown in Fig. 17, the hydraulic head, which is measured from the center of the outlet, becomes zero at some point upstream from the plug. For the case of constant outlet size and spacing and uniform pipe slope, the distribution can be calculated directly by starting at the upstream end where the head is known ($h = 0$), and calculating outlet flows downstream until the accumulated outlet flows exceed the supply rate. This method is simple to program and operate and has been adapted to both programmable calculators and microcomputers.

When outlet spacing or size or pipe slope change, the point of zero head relative to the change is unknown, so a successive approximations procedure is used to determine the hydraulic gradeline. Starting at the downstream end, a value is assumed for the piezometric head, h_n, at the last flowing outlet. The outlet discharge and pipe flow are computed, and the changes in head are computed from downstream to upstream. When the piezometric head becomes zero, the total accumulated flow is compared with the known inflow rate. If supply rate exceeds the sum of the outlet flow rates, the assumed head h_n is increased; or, if the supply rate is less than the sum of the outlet rates, h_n is decreased and the process is repeated until the sum of the outlet flow rates is within 1% of the supply rate. This iterative version of the model runs much more slowly and has only been used on minicomputers.

Predictions of outlet flow rates using this model are shown in Figs. 2–4 and in Kemper *et al.* (1981), Kincaid and Kemper (1982), and Goel *et al.* (1982). Figure 18 indicates the degree of agreement of outlet flow rates predicted by the model with those measured in the original cablegation system. Deviation of experimental points from the predicted line were shown (Goel *et al.*, 1981) to be associated with deviations of outlet elevations from the designed grade.

b. Startup Models. For the initial or startup period, the procedure must be modified. Three modes of operation are described for startup as shown in Fig. 19. In modes 1 and 3 a constant rate of supply, Q_{max}, is provided, as is the case in most irrigation supply systems. Mode 2 is used when elevation of water in the distributory is only slightly higher than the highest area to be irrigated.

Mode 1: Constant inflow. The plug is held stationary just beyond the *i*th outlet for a specified time, t_i, and then allowed to move at a constant rate. Supply rate, Q, is constant from time zero. Initial outlet flow rates are constant until the plug begins to move and then decrease slowly to zero.

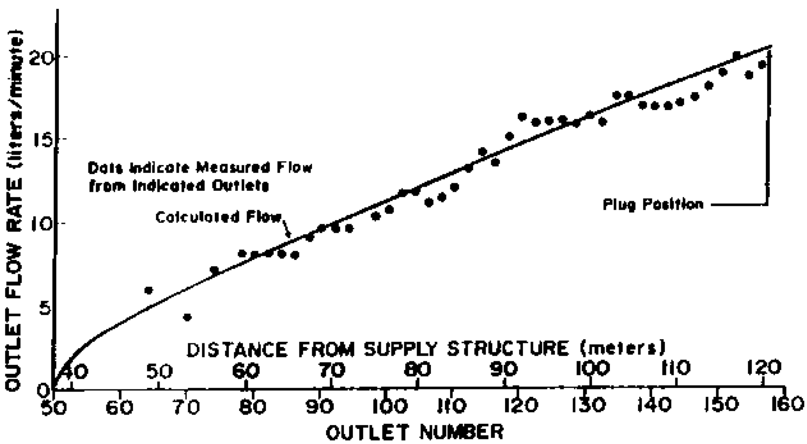


FIG. 18. Measured flow rates at outlets along a pipe compared to those predicted by the model.

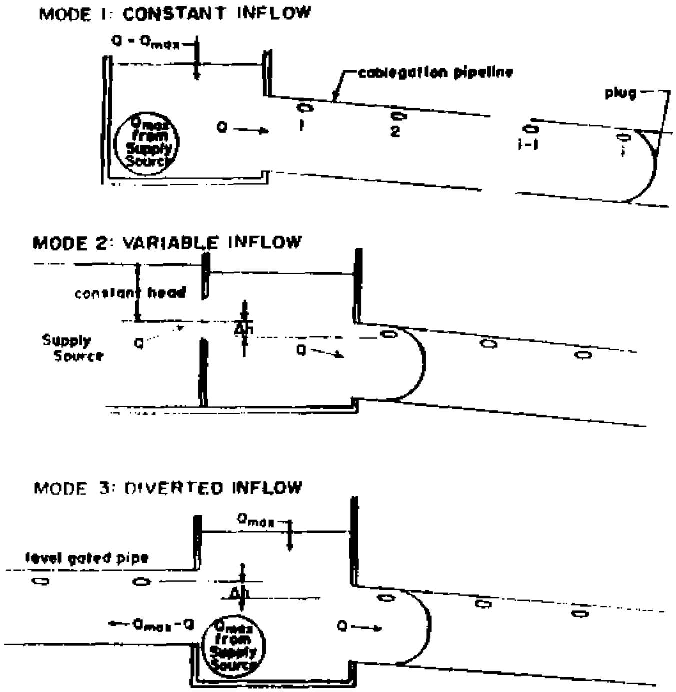


FIG. 19. Modes of operation on startup.

To obtain adequately high flows from outlets near the supply structure, these outlets must generally be larger than those farther down the line. For details on outlet modifications to help compensate for different supply times on the end sections, see Kemper *et al.* (1981).

Mode 2: Variable inflow. The plug starts moving at the first outlet from time zero. Supply rate is initially equal to the flow rate from the first outlet and supply rate gradually increases as the plug moves, opening additional outlets, until a maximum specified flow is reached. The head at the first outlet gradually decreases to zero. The supply rate is controlled by an orifice of specified area which allows water into the supply box under constant upstream head as shown. Head in the supply box decreases as additional outlets open until the water surface is lower than the first outlet.

Mode 3: Diverted inflow. The plug moves from time zero as in mode 2. Initially, the full supply rate is diverted to a level gated pipe of large diameter at an elevation slightly higher than the top end of the cablegation line. The level pipe extending to the left of the inlet box comprises an

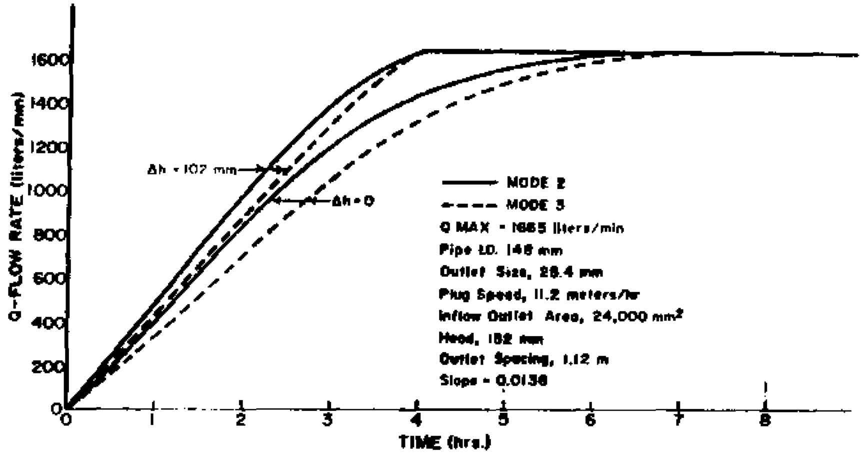


FIG. 20. Time distribution of rate at which cablegation lines take water for startup modes 2 and 3.

initial set. As the plug moves, the flow into the cablegation pipe increases until all flow is diverted to the cablegation side. The total area and elevation, *h*, of the outlet(s) in the level pipe are specified. Figure 20 shows an example of the time distribution of supply rate to the cablegation line assuming modes 2 and 3.

For all startup modes, the calculation procedure is as follows. The piezometric head for the first outlet is assumed, the inflow rate is determined, and calculation proceeds downstream to the plug. If the calculated accumulated flow is larger than the inflow rate, head assumed at the first outlet is decreased or vice versa. The inflow rate is then recalculated, and the procedure is repeated until the flows balance. As the plug moves down the pipe, the head at the first outlet decreases and finally becomes zero. At this time the calculation procedure is switched to the previously described method for the midsection.

c. Completion Modes. When the plug reaches the end of the pipe, there are at least three ways of completing the irrigation:

1. Inflow continues at the same rate after the plug reaches the end of the line until a desired gross or net application has been applied at the last furrow. It is difficult to obtain uniform net application with this method because the intake opportunity time for the last furrow is less than for furrows farther upstream. Outlet sizes may be increased at the lower end to produce rapid advance and increase the wetted perimeter which will minimize the final set time required. At the top end of this final set,

decreasing the orifice size can decrease the tendency for excess irrigation on these furrows, which are supplied with water for a longer time period (for more details on orifice size adjustments, see Kemper *et al.*, 1981; Kincaid and Kemper, 1982).

2. Begin decreasing supply rate when the plug reaches the end. The inflow rate is decreased linearly to zero over a time period equal to the width of the flow distribution divided by the plug speed. This method simulates the transfer of flow to a second cablegation line (operating from the same inlet box but at a lower elevation (e.g., in the Klompein system described in Figs. 71–73 of Kemper *et al.*, 1985) in which the plug in the second line starts to move when the plug reaches the end of the first line. This method allows more uniform outlet and stream sizes and results in water supply to the bottom end furrows of the first line and top end furrows of the second line similar to that provided in the midsection.

3. When the plug reaches the end, the outflow rate past the plug is allowed to increase slowly from zero to maximum rate, simulating the transfer of flow to a second plug system downstream. This transfer can be accomplished by letting the plug move into a standpipe at the tail end of the first line which is connected to a downstream cablegation line and allowing the flow to back up behind the plug in the second line, which then controls the flow.

The foregoing methods consider the startup and completion phases separately. The plug bypass methods described in Section V effectively eliminate furrow supply deviations at both top and bottom ends.

d. Incorporate Soil Infiltration Characteristics, Furrow Flow, and Runoff in the Computer Model. An expanded model developed by Kincaid (Kincaid and Kemper, 1982) incorporates infiltration characteristics of the soil and requires a computer. Given an infiltration-rate-versus-time equation for the soil, this model predicts runoff (as in Fig. 21) and infiltration at different locations in the furrow-irrigated field. This expanded model also allows prediction of runoff as a function of delivery system characteristics. The limiting factor on the accuracy of these predictions is the accuracy and variability (and common unavailability) of the infiltration-rate-versus-time equation.

C. Development and Use of Relations Between Relevant Factors Combined in Dimensionless Parameters for Performance Prediction and Design

Kincaid (1984) used the computer model to develop and evaluate equations involving dimensionless variables which enable individuals without access to a computer to develop designs for cablegation systems.

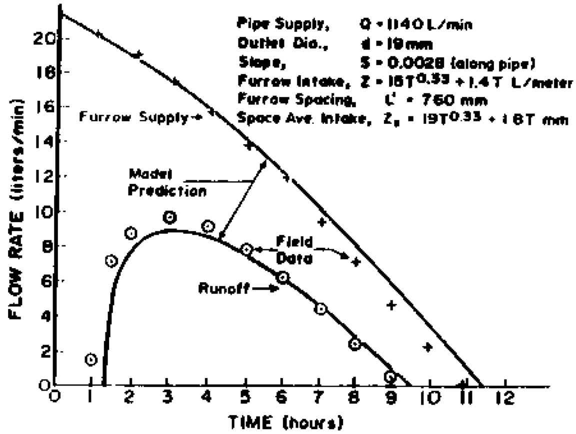


FIG. 21. Computer model predicted inflow and runoff rates of midfield furrows compared with measured rates (average of eight furrows).

1. *Reasons for Use*

The design of cablegation systems using the mathematical model is partially a trial-and-refinement process. The pipe size is easily determined for the given pipe slope and total flow. A trial outlet size is specified. The outlet flows and heads are calculated beginning at the upstream end, or first flowing outlet, and continuing until the maximum head and flow at the plug are determined. The resulting stream sizes are input to the intake-furrow-advance program, and the distribution of infiltrated water and runoff are determined. If the stream sizes and infiltration distribution are not as desired, the outlet size is changed in the direction needed and the process repeated. The computer goes through these iterations fairly quickly. However, it saves the designer time if he can specify the furrow length and intake characteristics, determine the stream size(s) required to obtain an acceptable intake distribution, and calculate the outlet size directly without calculating the entire distribution. The relationships between dimensionless parameters discussed in this section enable this direct determination and provide a simplified design procedure. The parameters are made dimensionless as far as possible to reduce problems of converting units and to generalize the solutions. The relationships were derived through empirical correlation of the dimensionless parameters using output from the computer model.

The analysis is presented in two parts, the delivery system (pipe flow distribution) and the infiltration distribution.

2. Scaling Factors in the Delivery System

There are six independent variables that must be considered in designing cablegation systems: the pipe slope; S; pipe inside diameter, D; total flow rate, Q; Hazen–Williams pipe roughness parameter, C; and outlet spacing, L. Two dependent variables, the piezometric head at the plug, H_p, measured from the top of the pipe, and the distance, X, along the pipe in which outlets are flowing, are incorporated into dimensionless parameters by dividing them by the pipe diameter, D. The outlet area, A, and spacing, L, are combined in one dimensionless parameter, A/LD, which is equal to the ratio of the width of an equivalent continuous-slot outlet to the pipe diameter. The other dimensionless parameters are the pipe slope, S; the ratio of the total flow to the pipe flow capacity, Q/Q_c; and the pipe-roughness ratio, $C/150$, where $C = 150$ is the value used for most PVC pipe. The flow capacity can be determined by Eq. (1a).

Dimensionless equations for the head, H_p, at the outlet nearest the plug and distance, X, were developed by inputting many combinations of the dependent variables into the computer model. Ranges of the variables used were pipe sizes from 100 to 400 mm, slopes from 0.001 to 0.05, C values from 110 to 150, and flow ratios Q/Q_c from 0.5 to 0.95. Outlet areas ranged from 20 to 8,000 mm² except that outlet size was limited to less than 30% of the pipe diameter. Outlet spacing ranged from 0.3 to 1.5 m. The following dimensionless equation predicts the maximum outlet head within ±15% when the dependent variables are within the above specified ranges:

$$H_p/D = 12.1(C/150)^{0.76}S^{1.09}(Q/Q_c)^{0.46}(LD/A)^{0.56} \qquad (9)$$

A similar equation predicts the outlet flow distance X within ±10%:

$$X/D = 8.3(C/150)^{0.44}(Q/Q_c)^{1.1}(LD/A)^{0.6} \qquad (10)$$

For Eqs. (9) and (10), the same units of length must be used for H, D, A, and L within any of the dimensionless parameters. After the head has been determined, the maximum outlet flow rate, q_m, can be determined within ±7% by Eq. (3).

The number of flowing outlets is $N = X/L$, and the average stream size is $q = Q/N$. The ratio of the average to the maximum stream size, q/q_m, gives an indication of the shape of the flow-distribution curve. A ratio of 0.5 indicates a linear decrease (similar to the curves in Fig. 3 where $Q/Q_c > 0.8$), while higher values of q/q_m indicate that the flow rate decreases slowly initially and then decreases rapidly to zero.

Equations (9) and (3) can be combined and the head eliminated to yield an equation for outlet area, A, as a function of maximum furrow supply rate, q_m, as follows:

$$A = 246q_m^{1.38}\{(150/C)^{0.76}/[D^{1.56}L^{0.56}S^{1.03}(Q/Q_c)^{0.46}]\}^{0.694} \tag{11}$$

where D and L are in millimeters, A is in square millimeters, and q_m is in liters/minute.

Equation (11) can be used to determine the outlet size required to produce a desired maximum stream size. The cable tension, f, is given by

$$f = 7.7 \times 10^{-6}D^2(H_p + D/2) \tag{12}$$

where $H_p + D/2$ is the head in millimeters at the outlet nearest the plug, measured from the center of the pipe.

These equations can serve as the basis of a simplified design method for cablegation systems where the desired stream size(s) are known or have been determined by the method outlined in the following section. They can be used separately or in conjunction with the computer model to reduce the trial-and-refinement process in outlet-size determination.

3. *Dimensionless Relationships to Predict Spatial Infiltration Distribution*

Furrow infiltration can be modeled reasonably well by the time-based function

$$z = aT^b \tag{13}$$

or in the rate form

$$\partial z/\partial t = abT^{b-1} \tag{14}$$

where z is the equivalent depth of intake in millimeters or liters/square meter based on gross field area, T is the time in hours since the beginning of wetting, and a and b are constants.

A parameter characterizing the average initial rate of application per unit area is q_m/EL', where q_m is the initial furrow supply rate, E is furrow length and L' is furrow spacing. This is divided by the intake rate, $\partial z/\partial T$, at 1 hour, which is ab, to obtain the dimensionless parameter, $q_m/(EL'ab)$. The gross depth of water application, G, is total volume of water delivered to the furrow divided by the area, EL', served by the furrow. The value G is divided by the 1-hour intake depth, a, to obtain the dimensionless parameter G/a. The percentage of runoff is a third dimensionless parameter. Surface storage was ignored in the volume balance-type surface hydraulic model, so specific effects of furrow parameters, such as furrow slope, roughness, and shape, are not considered.

The shape of the furrow supply hydrograph is relatively constant. The ratio q/q_m is related to the ratio Q/Q_c. Values of Q/Q_c of 0.9 and 0.5 give values of q/q_m of about 0.5 and 0.6, respectively. Thus the maximum furrow supply rate, q_m, and desired gross application, G, which determine the plug speed, completely characterize the inflow distribution. The plug speed is given by the equation

$$P = Q/EG \tag{15}$$

where, when Q is in liters/minute, E is meters, and G is millimeters, then P is in meters/minute.

The series of computer runs used to develop the following application-intake relationships used values of q/q_m of about 0.5. The relationships shown in Figs. 22–24 were developed for the intake parameter, b, having values of 0.3, 0.5, and 0.7, respectively. The solid lines were computed from cablegation simulations with decreasing furrow supply rates. The dashed lines were computed for a constant furrow supply rate equal to the average flow rate provided by the cablegation system. These figures can be used to estimate the initial (or constant) stream size required for a specified percentage runoff and gross application, given the length of furrow and intake characteristics of the soil.

Predicted water absorption at the bottom end of the furrow divided by that at the top is plotted in Fig. 25 against percentage runoff for a soil with intake rate defined by Eq. (14). Since the value of a in Eq. (14) is charac-

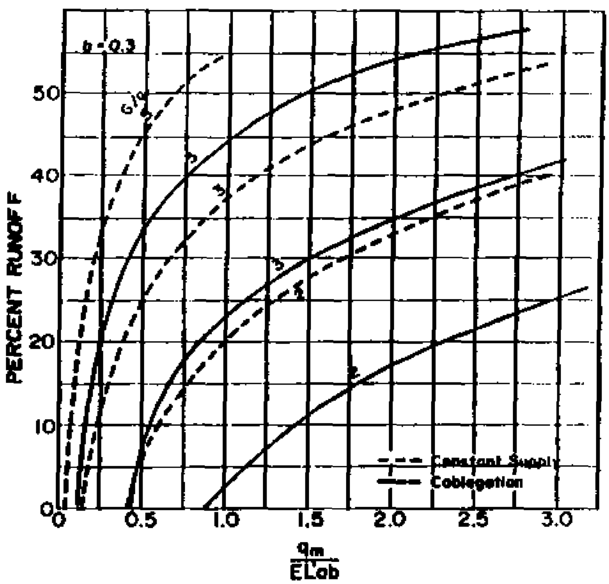


FIG. 22. Cablegation design curves for soils with intake characteristics of $z = aT^{0.3}$.

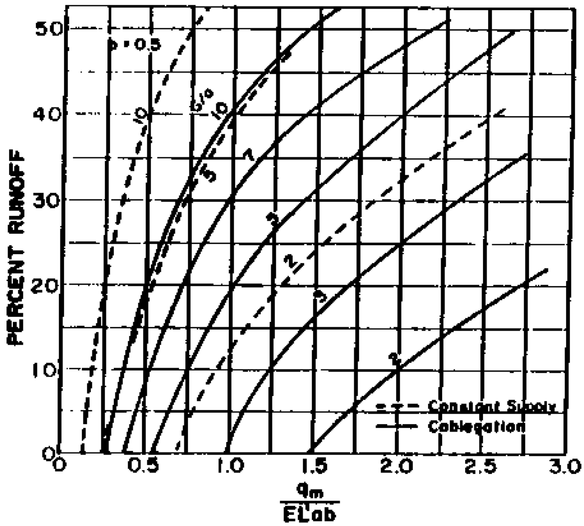


FIG. 23. Cablegation design curves for soils with intake characteristics of $z = aT^{0.5}$.

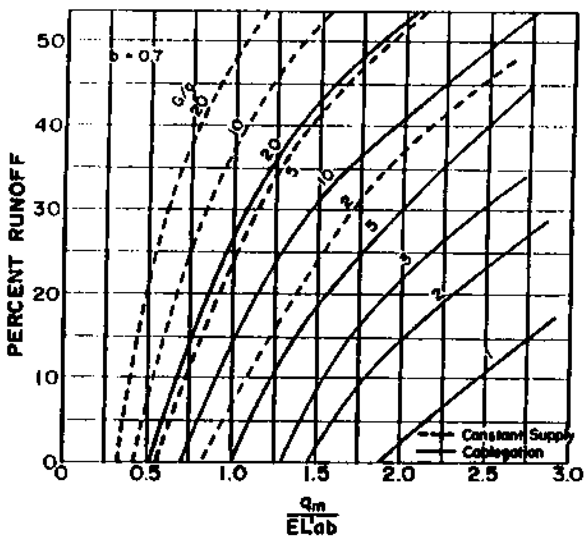


FIG. 24. Cablegation design curves for soils with intake characteristics of $z = aT^{0.7}$.

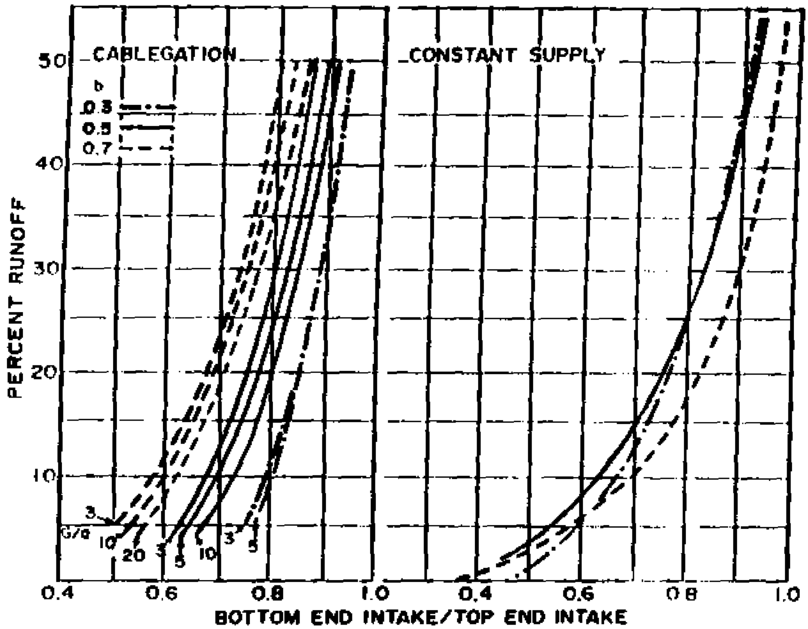


FIG. 25. Association of infiltration uniformities with percentage runoff.

teristic of a soil, increasing values of G/a represent proportionally increasing amounts of water supplied (or slower plug speeds on the cablegation systems). Different values of G/a for the constant furrow supply system had little effect on these curves, so the single lines on the right of Fig. 25 are reasonable estimations for all values of G/a. The distribution becomes more uniform as the percentage runoff or gross application increases. The infiltration rate, as characterized by the value of b, has a marked influence on the ratio of intakes at the bottom and top ends.

4. *Use of Dimensionless Equations and Figures to Design Cablegation Systems*

As an example of how to use these equations and figures, consider the following set of parameters describing the features of the land for which a system is to be designed.

For values of $b = 0.5$ and $G/a = 5$, Fig. 25 shows that 15% runoff would give a bottom end/top end intake ratio of 0.74, which is acceptable. Using Fig. 23 with 15% runoff, the value of $q_m/EL'ab$ is found to be about 0.9. Thus, the maximum furrow supply rate, q_m, is estimated as $0.9/EL'ab$, or

Parameter	Value
Slope along headline, S	0.003
Water supply rate, Q	2,200 liters/min
Distance between furrows, L'	762 mm
Length of furrows, E	300 m
Intake after 1 hour, a	0.03 m/hour
Intake time exponent, b	0.5
Gross (average) application, G	0.150 m

$q_m = 0.86(300)(762)(0.03)(0.5) = 3000$ liters/hour = 50 liters/min. Equation (1) is used to determine pipe size and flow capacity. At this slope and with $C = 150$, Eq. (1) shows that pipe with inside diameter of 248 mm (nominal 10-inch diameter plastic gated-pipe size) can carry $Q_c = 2{,}780$ liters/min. The flow ratio is $Q/Q_c = 0.79$. Equation (3) is used to calculate the outlet size, 750 mm^2. The maximum outlet head is calculated by Eq. (9), $H_p = 147$ mm. The flow distance, X, calculated from Eq. (10), is about 66 m, and the number, N, of flowing outlets is 86. From Eq. (15), the plug speed, $P = Q/EG = 2{,}200/300 \times 0.15 = 49$ mm/min, or about 0.05 m/min. According to Eq. (12) the cable tension, f, will be about 130 N.

V. Arrangements to Improve Application Uniformity

A. Furrow Supply Variance at the Top and Bottom Ends of the Pipe

1. *The Problem*

Most canal or pump supply systems provide a constant rate of water supply. Cablegation systems are easily designed to accept this constant rate when the plug is in the main midsection of the line. However, if the plug is started near the inlet, the few flowing outlets cannot dispense the full supply rate, so the water level will rise in the inlet structure until it is near the supply level. If the supply level is higher than the top of the inlet structure, over-topping of the inlet structure may occur.

To avoid this incapacity to accept part of the full water supply, the plug can be started at a position down the cablegation pipeline which is equal to about two-thirds of the length of line (X) from which the outlets are normally flowing. If the inlet structure has sufficient free board, the water level therein will increase until the constant supply rate is being dispensed through two-thirds as many outlets as flow normally. To adequately irrigate the top end furrow, the plug can be held in this position until sufficient intake opportunity time has elapsed and then it can be started moving at its normal speed. However, this provides the rows which were immediately upstream from the plug's initial position with greater intake opportunity time than it does the furrows near the inlet structure.

When the irrigator has adjustable outlets he can help compensate for this disparity of intake opportunity times by decreasing the opening area, stream size, and consequent wetted perimeter of furrows immediately upstream from the initial position of the plug. He can also increase the outlet openings near the inlet which increases the advance rate and wetted perimeters of those furrows and allows adequate infiltration in a shorter time.

There are similar problems at the bottom ends of the field. Outlet adjustments can improve the application uniformity at the ends of cablegation systems to levels better than those commonly observed in most surface systems (i.e., Kemper *et al.*, 1981). However, need for such adjustments complicates the design and operation of the system and better application uniformity can be achieved by the bypass approach discussed below.

2. *Bypass Systems*

a. Bypass Lines. A bypass pipeline at the top section of the cablegation line (Fig. 26) can provide improved furrow supply patterns at both

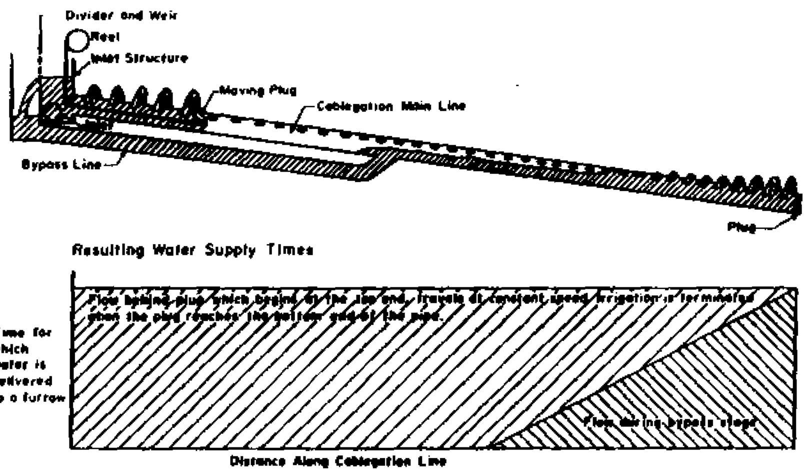


FIG. 26. Bypass pipeline to reduce supply time deviations at top and bottom ends of cablegation lines.

ends of the line. The inlet structure and weir are made as indicated at the top of Fig. 26. The lower end of the main line is closed with a plug or cap. The system is started with the plug at the upper end of the main line and the total flow going into the bypass line. This flow goes to the lower end of the main line and starts irrigation at that part of the field. As the plug moves, it starts flow from the outlets at the upper end of the main line, and the flow in the bypass line decreases. As the plug progresses, more of the water flows into the main line at the top end, and the water supply through the bypass to furrows at the lower end of the main line tapers off. Finally, all the flow goes directly into the main line, and irrigation ceases in the bottom section of the line until the plug gets there to complete the water application. When the moving plug reaches the end of the line, each outlet has had water supplied to it for the same length of time, and irrigation is complete. No water is lost from the end of the pipe system, and more uniform distribution is achieved. Several installations involving bypass systems have utilized weirs designed by the computer program discussed by Kincaid and Kemper (1984). These weir sizes provide practically equal flows from all outlets from the pipe.

Plan and elevation views of a weir and bypass pipe are shown in Fig. 27. The bypass flow goes over a weir, through a parallel pipe, and enters the cablegation line at distance X from the inlet structure. The bypass pipe may be the same size as the main pipe but can sometimes be one size smaller. The bypass flow is controlled by an overflow weir at the inlet structure. The weir width is designed so that the head at the plug remains nearly constant as the plug migrates down the cablegation line. The weir

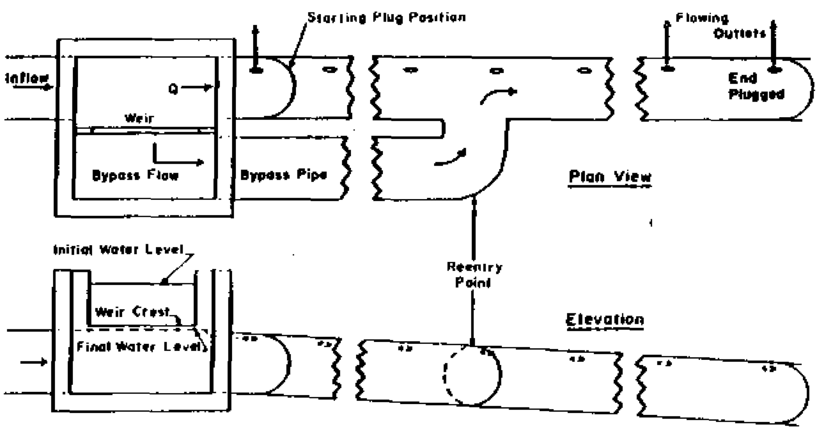


FIG. 27. Plan and elevation views of a bypass pipe and weir.

crest is placed at an elevation above the first outlet equal to the velocity head in the main pipe with full supply. Ideally, the weirs should have curved sides; however, rectangular weirs provide a flow distribution close to those desired and practically eliminate differences in supply rates and times at end sections compared to midsections (Kincaid and Kemper, 1984).

b. Bypass Plugs. The bypass function can also be achieved using a flow-through plug which initially bypasses most of the flow and closes slowly while it travels the first set length (X). Design and construction details of these plugs are given by Kincaid and Kemper (1984) and Kemper *et al.* (1985). While a few farmers are using them, bypass plugs are still in the developmental stage.

B. Intake Variability at the Top and Bottom Ends of Furrows

1. *The Problem*

Intake of water by a section of the furrow is primarily dependent on intake rate of the soil, wetted perimeter of the furrow, and time for which water remains in that section of the furrow. A design objective of cablegation systems is to improve intake uniformity. To some extent, more uniform intake times are achieved by high initial flow rates of cablegation systems which advance water quickly to the bottom end of the furrows and minimize differences in intake opportunity time between the top and bottom ends.

The inherent cutback flow of the cablegation system reduces runoff. However, when furrow supply rates decrease below the infiltration rate, water begins to recede from the bottom ends of the furrows. This decreases application uniformity. For instance, in the system depicted in Fig. 21, water is not reaching the ends of most of the furrows after 9.5 hours, and water added after that time is absorbed by upper reaches of the furrow, which have already had longer intake opportunity time than the bottom end.

If water intake rate by the soil remains relatively high throughout the full period of normal cablegation delivery to the furrow, water ceases to reach the tail end of the furrow at an earlier time and final intake rates are high, so nonuniformity due to tail-end recession is appreciable. However, if the soil has a high initial intake rate and that rate declines rapidly to lower and lower values, water continues to reach the end of the furrow till near or after the end of the supply time, and distribution uniformity is not significantly decreased.

2. *Benefits Derived from a Sharp Cutoff of Furrow Supply*

Uniformity of intake opportunity time is improved if the inflow to each furrow is cut off when the runoff from that furrow ceases. Figure 28 shows the furrow inflow and runoff rates calculated when the supply is via normal cablegation, via cablegation with cutoff outlets, and via gated pipe or siphon tubes (constant supply rate). For the cutoff flow case, the cutoff flow rate (21 liters/min) was selected so that the cutoff occurred at about the same time that runoff ceased. The size of the cutoff outlets was reduced in order to obtain about the same percentage runoff (19% on the cablegation-supplied systems). Gross application was 150 mm in all cases. The initial stream size was slightly smaller, and the beginning of runoff was delayed, as shown, for the cutoff compared with the regular cablegation system. Figure 29 shows the effect (calculated using the computer model) of cutoff outlets on intake along a furrow when intake rate is $7.3T^{-0.3}$ mm/hour and T is the hours for which water is in that section of the furrow. This example shows a case of severe tail-end recession due to high b and extremely high Q/Q_c values.

Figure 30 shows the effects of cutoff outlets on intake along a furrow when intake is $28T^{0.4}$ mm. The initial intake rates are higher for this intake function than for that used in Fig. 29, but after about 6 hours, the intake rates are lower than in the previous example. The relative improvement of the distribution because of cutoff is less than that shown in Fig. 29, where the infiltration rate was higher when flow ceased to reach the end of the furrow.

In general, cutoff supply, as provided by siphon outlets of the type shown in Figs. 14 and 15 (and to some extent by spigot-type outlets as in

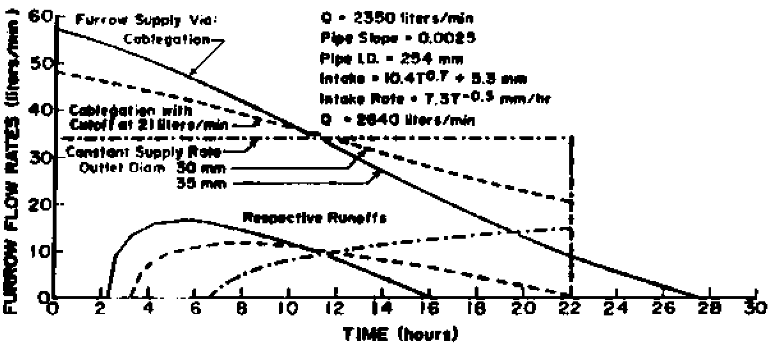


FIG. 28. Inflow and runoff rates for the three modes of furrow supply.

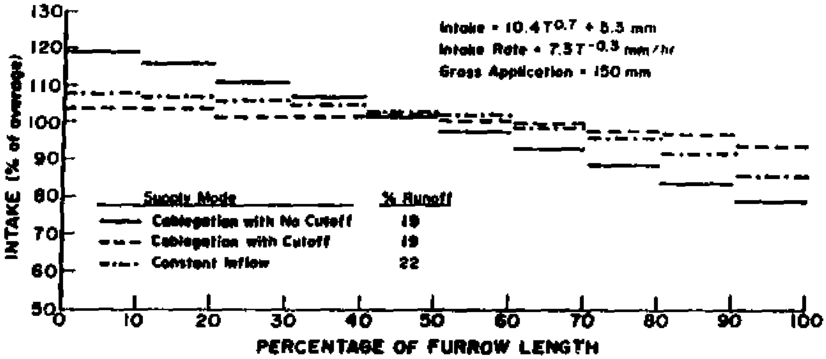


FIG. 29. Intake along a furrow as affected by supply mode when rate of water intake by the soil is relatively sustained.

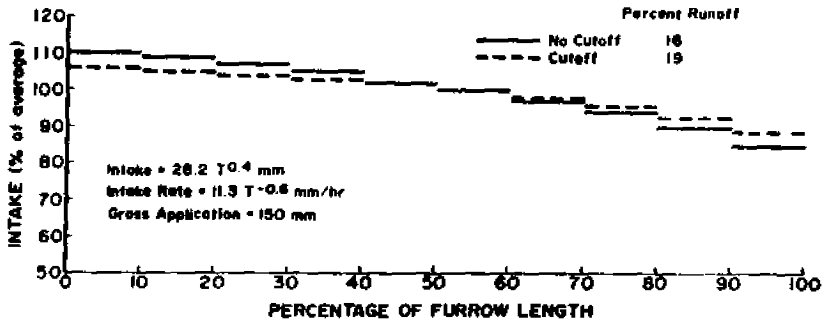


FIG. 30. Intake along a furrow when supply is from cablegation with and without cutoff outlets and rate of intake by the soil decreases rapidly.

Fig. 16), significantly improved intake uniformity when intake rates are sustained but has little effect when intake rates diminish rapidly, or $Q/Q_c < 0.6$.

VI. Installation

A. Preliminary Design and Cost Estimate

When deciding whether to install a cablegation system, a preliminary cost estimate is needed. Normally, the pipe is the major portion of the cost. Length of pipe required is usually the length of the previously used supply ditches or pipes at the head of the field. Specific information essential to choosing pipe size includes the maximum rate of water supply which must be carried by the system and the minimum slope that will be encountered along the line. In calculating minimum slope, it should be remembered that some head loss will occur at inlet structures, trash cleaning structures, etc., at the top of the line.

The cost of the pipe increases rapidly with size, and required pipe size decreases as minimum slope increases. Grading along the headline to make the slope more uniform can often increase the minimum slope and may reduce the pipe size and cost. The second factor affecting pipe size, the required water supply rate, can be adjusted downward on some farms by dividing large supply rates into two or more systems.

In addition to the cost of the pipe, there will be costs for the control system, inlet structure, outlet gates, trash screens, engineering, grading, and installation. The control system, cable, and plug will cost between $300 and $1,000 (1986 dollars) depending on size and sophistication. Grading and installation will depend upon earth movement requirements, but will generally be less than $3.00/m. A rough first approximation is that total costs may be about double the pipe costs.

In some cases, farmers may have the equipment, training, and experience to design and/or install their own systems. In the United States, Department of Agriculture Soil Conservation Service and Extension personnel are qualified to help. For farmers with limited time and who do not have the equipment or surveying skills needed, commercial installers are available in some areas to provide these estimates and the installation. Commercial installers with laser- or wire-guided trenchers can install cablegation pipe to a precise grade.

B. Fitting the System to the Farm

1. *General Information Needed*

The primary prerequisite for a cablegation system, in addition to the normal soils and topographic requirements for surface irrigation, is an available hydraulic grade along the proposed pipeline of at least 0.002 m/m. This grade is least expensively provided by a uniform ground slope across the top of the field, although grade can be created by land movement or the use of outlets on risers. The water supply elevation must also be higher than the top end of the proposed pipeline.

If the field has been surface irrigated before, these prerequisites probably exist. Information on previous irrigation practices, including number of furrows irrigated per set and total supply rate, provides good first estimates of required flow rates. If the field has not been surface irrigated before, irrigation practices on nearby fields are another source of the first estimates. Soil Conservation Service soil maps and irrigation guides provide surface irrigation design parameters for many agricultural areas in the United States.

A primary purpose of automated systems is to reduce the labor input and frequency of inspections needed to provide proper distribution of the water. This cannot be achieved if water entering the cablegation line carries significant amounts of trash, which can block or partially block outlets. Turbulent flow "self-cleaning" screen systems have been designed which will remove the trash. They require 150 mm or more of head for proper operation (Bondurant and Kemper 1985). If this amount of head is not available, electric-powered screens (e.g., Humpherys, 1985) can be installed if the power is accessible.

2. *Specific Elevations Needed*

The first field data required to design a cablegation system are the elevation of the water supply at the inlet to the field and a profile of elevations along the edge of the field where the proposed pipe will be placed. Shots should be taken and elevations should be determined relative to a fixed benchmark at 10- to 20-m intervals and the locations staked for future reference.

The profile is used to determine whether cut or fill will be needed along the headline to provide the desired uniformity of grade and whether the water supply elevation is high enough to serve the system. Where possible, it is advantageous to lay the pipe on a constant slope. However (as discussed by Kemper *et al.*, 1985), changes in slope can be accommodated. Increases in slope result in increased pressures in the line near the plug and consequently must be accompanied by decreases in outlet size to keep flow rates and times uniform. Near the transitions, the slope on one side of the transition affects pressure on the other and intermediate outlet sizes are needed to achieve delivery rates and times reasonably similar to those above and below that transition. The optimum outlet sizes at such transitions change if total supply rate to the pipe or the desired outlet flow changes. Although the computer model can calculate these optimum patterns, in practice, adjustable outlets allow farmers to set them as required and to provide the desired furrow flow rates.

If the outlets need to be lower than the existing ground level, cuts along the pipeline may be needed in those reaches. Downfield slope should be checked in those reaches to determine how far the cut must extend into the field to ensure that water will flow away from the pipe outlets. Generally, the downfield slope of this cut area should be no less than 0.002 m/m. Where fill is needed under the pipe to maintain the desired slope it is not generally necessary to extend the fill into the field, but some protection of the soil against erosion may be needed.

While the primary factor determining the slope of the pipeline will be the slope of the land, head losses in structures and connecting pipe often use substantial portions of the elevation difference between the supply and the tail end of the system. Consequently, the structures and connecting pipes and their associated head losses must be planned before the final pipe grade is determined.

3. *Supply Pipes, Connectors, and Associated Head Losses*

a. When Supply Head Is Not Limiting. In some cases water supply elevations are high enough above the highest corner of the field to provide the desired head at the top end of the cablegation line and accommodate intervening head losses. If sufficient supply head is not available, a complete bypass operation will not be possible. To determine whether the supply head is limiting, it should be compared to the elevation of the highest corner of the field plus the planned head in the orifice next to the plug, plus the following set of possible head losses (indicated in Fig. 31A).

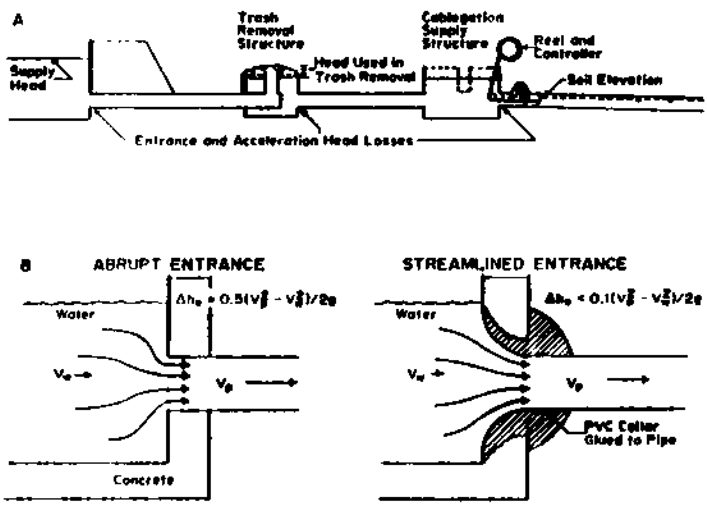


FIG. 31. (A) Head losses commonly encountered. (B) Effects of streamlining on entrance losses.

1. Friction loss in the pipe or ditch carrying water from the supply source to the cablegation input structure.

2. Head loss at the screen structure which removes trash from the water.

3. Head loss at a structure which allows water measurement or provides power for the cable-speed-control system (in some cases these functions are not needed and this head loss will be zero).

4. Head loss, h (meters), through the cablegation supply structure which is due to the dissipation of velocity head at the expansion into the structure, and the need to contract the flow and restore its velocity as it enters the cablegation line.

Piezometric head loss required to accelerate the water—which is traveling at velocity, V_w, in the structure back up to its pipeline velocity, V_p—and to achieve its contraction into the pipe is estimated from the equation

$$h = (1.0 + j)(V_p^2 - V_w^2)/2g \qquad (16)$$

where g is the gravitation constant (9.82 m/sec^2) and j is the contraction loss coefficient. The contractional loss is dependent on the shape of the entrance, and its coefficient, j, can be reduced from about 0.5 to 0.1 by rounding the entrance (Fig. 31B).

As an example of the magnitude of the acceleration and contraction head losses, consider that water in a structure has an average velocity of about 0.1 m/sec and that it accelerates as it enters the pipe to 1.2 m/sec. The acceleration head loss according to Eq. (16) will be 0.08 m, and a nonstreamlined entrance (j = 0.5) causes an additional 0.04 m of head loss. If these losses are incurred at all three of the pipe entrances indicated in Fig. 31A they can result in a total of 0.36 m of head loss. Streamlining the entrances would reduce the loss to about 0.24 m.

The maximum head required at the first outlet from the cablegation pipe is greater if the pipeline has considerable slope and if a bypass line and weir (as indicated in Fig. 26) are being used to maintain the same flow pattern from equal-sized outlets all along the line. During the early portion of the bypass stage, velocity of flow into the cablegation line is slow, so acceleration and entrance head losses to the cablegation line are negligible.

b. When Supply Head Is Limited. Many irrigation supply systems are built with operating levels in the distributaries less than 300 mm higher than land which they are to serve. Under such conditions, the following alternatives will often adapt a cablegation system to the situation. As indicated in the previous section, streamlining all entrances to pipes from structures will reduce head loss. Larger pipelines reduce transmission head loss. If electric power is available, an electric-powered screen (e.g., Humpherys, 1985) at the takeoff from the supply lateral can practically eliminate head loss used in trash removal. In some cases it has been relatively inexpensive to plane the top corner of the field to a lower elevation to reduce the required head.

The head required to push the desired furrow supply from the first outlet is a function of the outlet size. When adequate head is available to keep the size of that first outlet equal to the other outlets (h_p at the first outlet), calculation of the height and width of the bypass weir is relatively simple. However, if the supply does not have that much head, the first set of outlets can be opened larger than the others, and the initial head can be reduced by widening the bypass weir. On cablegation lines with steep slopes, this can reduce head required at the supply structure from as much as 1 m above the top of the cablegation line to as little as 0.1 m. This reduction in head required at the cablegation supply structure may reduce the size of that structure. The computer model can be used to compute the required weir width and outlet sizes near the inlet for a given available supply head. The outlet sizes can then be decreased linearly across the first set (i.e., the distance X). The farmer generally invests some time during his first use of such systems to refine the weir and outlet settings.

Where supply head has been extremely limited, startup mode 2 indicated in Fig. 19, with no bypass, has been used effectively. In this mode, when the irrigation starts, only one outlet is flowing, head losses are negligible, and the head at the outlet is essentially equal to the supply head. As the plug moves down the cablegation line, the water level in the supply structure decreases and supply flow rate increases until head losses in the structures and pipelines balance the available head. Using this startup mode, the supply head required is equal to the initial head at the first outlet.

4. *Final Design*

Once the head loss that will occur in the structures and connecting pipes is determined, the elevation plan should be plotted. This should show elevation of water at the supply, head loss in connecting pipelines, head loss at the structures, cablegation pipeline grade(s) and diameters, and original soil surface and needs for cut or fill along the cablegation line.

The final design should also include plans to accommodate other factors related to specific field shape, water delivery, drainage, etc. Many such options are described in the section "Modifications and Innovations to Meet Special Requirements" and Appendixes A–D, F, H, and J of Kemper *et al.* (1985).

C. Field Work

This discussion has been abbreviated since it is assumed that most readers will not be practicing installers. Installation procedures are detailed in a cablegation manual (i.e., Kemper *et al.*, 1985).

1. *Preparing the Bed for the Pipeline*

The most critical prerequisite for a cablegation system to perform effectively is having the outlets of the system on a precise gradeline. This can be accomplished by laying the pipeline roughly to grade and then putting the outlets on risers that are cut to precise lengths needed at each point on the pipe. Most outlets, such as the regular gates on gated pipe, are attached directly to the pipe. When using such directly attached outlets it is essential to lay the pipe to within $\pm 4000S$ mm of the designed grade, where S is the slope of the pipeline. Wire or laser-controlled equipment can be used to construct pads and trenches to these grade tolerances on lines with slopes as low as 0.002. Manual touch-up along with surveyor's level readings are required when using other types of trenchers on these minimal slope lines.

2. *Installation of Supply Structures*

Supply structures at the head of the cablegation lines can be installed while beds for the pipelines are being prepared. They can be as simple as the T-structure, shown in Fig. 32, which can be constructed from a saddle and pulley and coupled into existing pipelines in a few minutes. Structures of the type indicated in Fig. 33 can be fabricated from sheet metal, corrugated pipe, or concrete pipe, or formed in place from concrete. A male

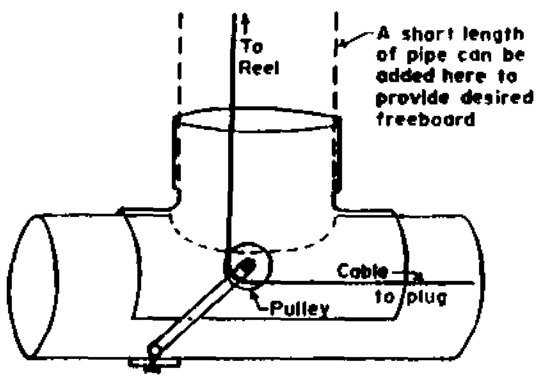


FIG. 32. Low-cost supply structure which minimizes head loss.

starter nipple for the cablegation pipe should be attached to the structure. A pulley or other cable guide must be located in line with the reel and pipe.

In some areas where there is adequate rain for germination and early season growth, farmers like to move their gated pipe and cablegation lines out of the way of their harvesting, land preparation, seeding, and cultivation operations. Consequently they remove their pipe along with their supply structures after harvest in the fall and stack them in their farm yards. After their land is prepared, the crop is seeded, furrowed, and cultivated, and they smooth the pipe bed and replace their cablegation lines and supply structures. Supply structures for these systems must be portable such as those shown in Fig. 32 or 34. Note that the structure shown in Fig. 34 has an adjustable weir and provision for a bypass line.

Examples of several other types of supply and special needs structures are given by Kemper *et al.* (1985).

3. *Pipeline Installation*

When the outlet structures are in place and the pad and trench prepared to desired slope(s), pipe can be installed. Male ends should be directed downstream, to reduce the possibility of catching the plug or sharp-

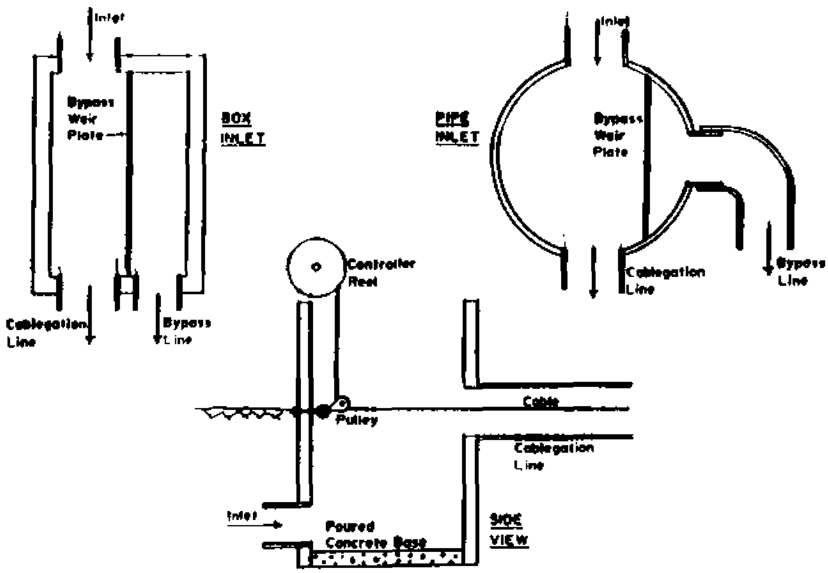


FIG. 33. Types of supply (inlet) structures commonly used for cablegation lines.

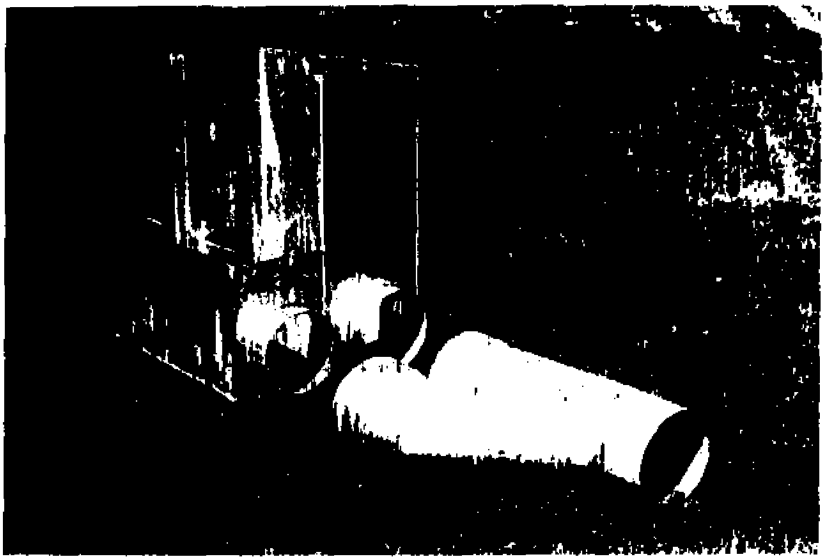


FIG. 34. Portable supply structure with adjustable weir provision for a bypass pipe and reentry joint.

pointed debris in the joints. Both rubber-gasket and glue-joint types of plastic irrigation pipe can be used in cablegation systems.

According to PVC manufacturers, the coefficient of thermal expansion of PVC pipe is about 0.000065 m/m per degree Celsius. Using this coefficient and anticipating that the temperature may increase as much as 20°C after installation, a 12-mm gap should be left at each joint of 9.1-m (30 ft) pipe. Achieving the desired gap is facilitated by measuring the length of the bell, subtracting the width of the desired gap, and then making a mark at a distance from the male ends of all the pipes equal to the remainder.

When the glue-joint type pipe was used, the pipe was assembled quickly by lubricating the male end with vegetable shortening and slipping the joints together as described above. Because of the low pressures in the pipe, cement is not needed. Expansion couplers are not needed along the length of the pipe if the joints are not glued and the required gaps are left at the joints.

4. *Outlet Installation*

Unless preslotted gated pipe is used, holes for attaching outlets must be cut in the pipe. The outlet locations along the pipe are determined by measuring along the top and marking distances to correspond, to the spacing of the closest spaced corrugates to be used in the planned crop rotation. The approximately 30° offset from the centerline of the top of the pipe may be quickly determined with a short carpenter's level and a jig.

Round outlet holes can be cut with electric drills or hole saws powered by portable gasoline generators. A router and jig can be used to make rectangular slots. A gated-pipe style of PVC pipe is available with factory-cut rectangular holes that fit many of the commercially available slide gates.

If flow adjustment is not required, outlet holes cut in the pipe are all that is required. Otherwise, commercially available inserts or gates are fitted into the holes in the pipe to allow adjustment of the outlet size. Cablegation outlets need not seal or close completely since water in the pipe does not normally flow above the outlet level. The outlet fittings should not project more than 12 mm into the pipe, or they may interfere with the passage of the plug.

Recent development of plugs which will pass regular gates allows cablegation users to select from the broad spectrum of commercially available gates designed to adjust flow rates from gated pipe. Other gates have been designed to achieve additional functions found desirable for cablegation systems such as energy dissipation, redirection of the water, and automatic cutoff (i.e., Figs. 14–16).

5. *Specific Location Requirements*

In some locations transitions from one pipe size to another may be needed. Varying elevation of the water supply may cause undesirable supply rate variations. Water supply may carry sufficient coarse sediment to partially fill the pipe with sand and interfere with the plug movement. Discussion of solutions to these and other specific problems is beyond the scope of this article. Solutions to many such problems are discussed in Kemper *et al.* (1985) and subsequent yearly updates based on cablegation workshops held annually at the Snake River Conservation Research Center, Kimberly, Idaho 83341, and are available from that location.

VII. Operation

A. Water Supply Requirements

Cablegation has been used with supply rates in the range from 200 to 6,000 liters/min. While most systems are designed for constant supply rates, interruption of the supply is tolerable if the waterbrake type (Fig. 11) or electronic type of controller is used.

When system supply rates increase, a greater length of the pipe fills with water, increasing the average head at the outlets and the number of outlets flowing. This tends to increase the rate and time of supply to furrows. The waterbrake controllers allow the plug to move faster when supply rate increases. However, the increase in plug velocity only partially compensates for the greater number of furrows flowing, and time of furrow supply is approximately proportional to the square root of the system supply rate.

Trash, such as weeds, grass, crop residues, and paper products, in the water supply blocks outlets of gated pipe systems or siphon tubes. Monitoring and cleaning outlets and restarting siphon tubes often consume large amounts of labor and the interruptions in furrow supply prevent some crop rows from getting adequate water. Screening systems to remove trash from water supplies are a good investment even when the water supply is carrying only a few pieces of trash per hour (i.e., Kemper *et al.*, 1986). Since major objectives of cablegation are to allow the farmer to attend to his other work (or get some well-earned sleep!) and uniformly supply water to the furrows, it is even more critical that trash be removed from the water supplies before they enter cablegation systems.

Bondurant and Kemper (1985) and Humpherys (1985) provide construction details for screens which will remove trash. Since screen woven with 12 wires/cm will remove most weed seeds in addition to the trash, this fine mesh is recommended for use in these screening systems if weed seeds in water are a problem.

B. Labor Requirements

The cablegation operator winds the cable onto the reel, attaches the plug to the cable, inserts the plug in the cablegation line, turns on the water, and adjusts the controller so the plug moves at the desired speed. These operations constitute the primary labor involved in irrigating a field with a cablegation system. However, the conscientious irrigator will return after a few hours to determine whether his initial settings of the outlets and plug speed are providing (1) sufficient water to reach the ends of the furrows in the desired time, (2) no more runoff than is needed (since excess furrow supply increases erosion and wastes water), and (3) sufficient intake opportunity time on a sufficient proportion of the furrows to satisfy crop needs till the next irrigation.

If furrow supply rate is not adequate for water to reach the ends the operator can increase it slightly by increasing the total water supply rate. If he needs increases in furrow supply rate of more than 20% he will need to increase the opening on each of the outlets. If his total supply rate is fixed and this is a first irrigation following tillage, he may not want to spend the time needed to open all the outlets wider (approximately 2 hours to adjust 500 outlets) because he suspects he will need to close them down again during the next irrigation. Increasing furrow supply rates might also cause unacceptable erosion. Another option is to reduce the intake rate on the already wetted portion of the furrow by interrupting (surging) the flow. This can be done by sending the plug down the line at high speed so each furrow receives water for only long enough to advance the water part way down the furrows. If at least 60% of the furrow is wetted initially and the interruption reduces the intake rate over that length by at least 30%, in an immediately following irrigation the water will advance to the end of the furrow. If this irrigation continues for several hours, total intake in the bottom half of the furrow will often be as great as in the top half. The extra labor involved in this flow interruption includes unhooking the plug from the cable after its high-speed trip, returning it to the supply structure, reeling in the cable, hooking the plug to the cable, reinserting the plug in the top end of the pipeline, and adjusting the controller to the slower speed (about ½ hour). Interrupting flow generally consumes less time than changing the outlet openings.

If water is inexpensive (or can be reused) and the irrigator's time is at a premium he may open the outlets wide for all irrigations and allow a major part of the water to run off the tail end. Thereby he saves the time that would have been used in setting and resetting outlets, interrupting the flow, etc. The disadvantages of the "wide-open" labor-saving approach are the loss (or recirculation cost) of the water and the probabilities of substantially increased furrow erosion.

Overall, the labor required per hectare using a cablegation system is a small fraction of that needed to set siphon tubes or outlets on gated pipe. This fraction is even smaller if the siphon or gated pipe irrigator tries to reduce runoff by reducing furrow supply when water has reached the ends. An important difference between the labor required to monitor and operate cablegation irrigation and that required for conventional surface irrigation is that while conventional irrigation requires scheduled field visits to change sets which often occur, or, at least should occur, at inconvenient times, cablegation field visits can occur whenever convenient to the operator. The operator becomes more of an irrigation water manager and less of a laborer.

C. Maintenance

1. *Pipeline*

One of the most critical requirements for maintaining uniform furrow supply (USDA-ARS Kimberly Staff, 1986) is keeping the outlets on grade. In a few systems frost action has caused changes of a few centimeters in elevation of the pipeline. Water may continue to flow from outlets in sections which have sagged and in sections immediately upstream from sections which have raised, when the plug is no longer influencing water elevations in those sections. A quick and simple way to check for such deviations from grade is to supply water to the pipe at near its designed capacity and walk the line. If any outlets are flowing, check the height of water in the pipe section downstream from the flowing outlets. If the water level in that section of the pipe is low, the pipe is high in that section and needs to be lowered. Otherwise, raising the pipe in the section where outlets are flowing is the solution. If the pipeline is on or near the surface, an hour or two of shovel work can usually bring the line back to within the designed grade tolerances. If the line is buried deep, with risers bringing water to the surface, there is less possibility that elevations of outlets will change as a result of frost action. If they do, it is generally easier to lengthen or shorten the few risers involved than to excavate and regrade the pipe. Generally less than 10% of the permanently installed pipelines have required regrading.

Some farmers remove their pipelines each fall to get them out of the way of their harvesting, land preparation, and seeding operations. They then lay the pipelines back on the surface after these operations are finished. A higher percentage of these pipelines will probably need some "touch up" on the grading each year.

Smoothness of the inside of pipe plays a significant role in its carrying capacity [Eq. (1)]. A variety of mossy materials either grow on, or attach to, the inside of pipe, and sediment often becomes entrained therein. In one case in which NH_4OH was distributed via the pipeline, $CaCO_3$ deposits occurred on the walls of the pipeline. Some of these materials are rubbed off as the cablegation plug comes through the line during each irrigation. However, if dribbling of outlets upstream from the normal set of outlets begins, it is possible that the pipeline needs cleaning. Scrubbers made of burlap bags or coconut fiber mats have been effective in cleaning pipelines when the scrubbers were constructed to press firmly against the pipe walls and were pulled downstream through the pipe with the detached cable while water was flowing in the pipe. This is a two person operation, with one person pulling on the cable and the other dragging the emerging cable back up the pipeline where it is wound back on the reel.

To date, less than 5% of the cablegation lines have required such scrubbing. Transmission lines bringing water to the supply structures are not subjected to the regular rubbing action of cablegation and significant decreases in their carrying capacity are more common.

2. *Weed Control along Permanently Installed Pipelines*

A common method of weed control along irrigation ditches is burning. This is not recommended along PVC pipelines because of the low melting point of PVC. Herbicides such as Roundup have been used to keep vegetation down. However, in some cases in which the pipeline is on an elevated pad, or erosion can otherwise be a problem, good sod has been needed and 2,4-dichlorophenoxyacetic acid sprays and a short grass have been a satisfactory solution.

3. *Controller Maintenance*

Electric-powered controllers have operated with reasonable success without shelter in low-rainfall areas. However, they and the other controllers with moving chains, sprockets, etc., last longer if cover is provided to keep them dry.

The basic waterbrake controller has no parts which are susceptible to damage by water and consequently needs no cover. However, the water inside the water race should be mixed with $CaCl_2$ or ethylene glycol to prevent it from freezing, or it should be drained before the first frost in the fall. Water may leak from the valve stems of waterbrake controllers when solar radiation heats the race and raises the internal pressures to the equivalent of nearly 1 m of head. Since the speed of the waterbrake controller increases and its braking torque decreases as water is lost, it is prudent to check the water level in the race and keep the race half full of water. Clean water must be used to refill the race because the valve openings in the baffle plates are relatively small and susceptible to plugging.

4. *Cables and Plugs*

The twisted polypropylene and braided Dacron cables used to date are resistant to biological decay and can last several years. Long exposure to sunlight reduces the flexibility of these materials and thus cable life will be extended by shading the reel. However, the cost of the polypropylene cables is so low that most farmers do not shade their reels and routinely replace the cable every 2 years.

Plugs with gaskets made of flexible, compressible PVC have only been used for about a year and their longevity and maintenance requirements are not known. They are constructed so the gaskets, which cost less than half as much as the plug, can be easily replaced. The plugs should be stored between irrigations and during the winter in a manner so the gaskets are not distorted. Distorted gaskets allow more leakage past the plug.

5. *Outlets*

Polyethylene is the most common plastic used in construction of outlets. It is resistant to biodegradation, but is somewhat subject to deterioration by sunlight. Most outlets are designed to last for at least several years under normal operating conditions. The main problems encountered to date with outlets on cablegation systems is a tendency for old gated-pipe outlets to slide when the plug passes them because the clip has lost its strength and the gasket material has become hard and has lost its ability to adhere to the pipe. For this reason, when old gated pipe is being converted to cablegation, any old gates which slide exceptionally easily should be replaced.

VIII. Evaluation

A. Supply Variability from Furrow to Furrow

Furrow supply rates were measured on 30 fields being served by regular gated-pipe systems or siphon tubes in southern Idaho and on a few fields in the Grand Valley in Colorado (Trout and Mackey, 1985). When regular fixed-set gated-pipe systems were being used, one-third of the gates flowed at least 25% more or 25% less than the average flow, i.e., the coefficient of variation was 25%. One of the potential advantages of cablegation systems is that, because the gates do not have to be opened and closed with each irrigation, more effort can be spent setting them evenly, thereby providing more uniform applications of water. Because cablegation pipe is laid on a uniform grade, each outlet is subjected to the same pressure sequence. Consequently, outlets set to the same size will emit the same total amount of water. There is generally a gradation of pressures along regular gated pipe so the irrigator chooses between uniform-sized openings, which he knows provide differences in flow, or adjusts each gate "by eye" to what appears to be reasonably uniform flows. Measurements were made on several cablegation systems to find out whether this potential improvement in application uniformity is being achieved. At a specific time, furrow supply rates decrease as one moves upstream from the plug in the manner indicated in Fig. 35. Deviations of the flow rates from the best-fit line are a measure of supply uniformity

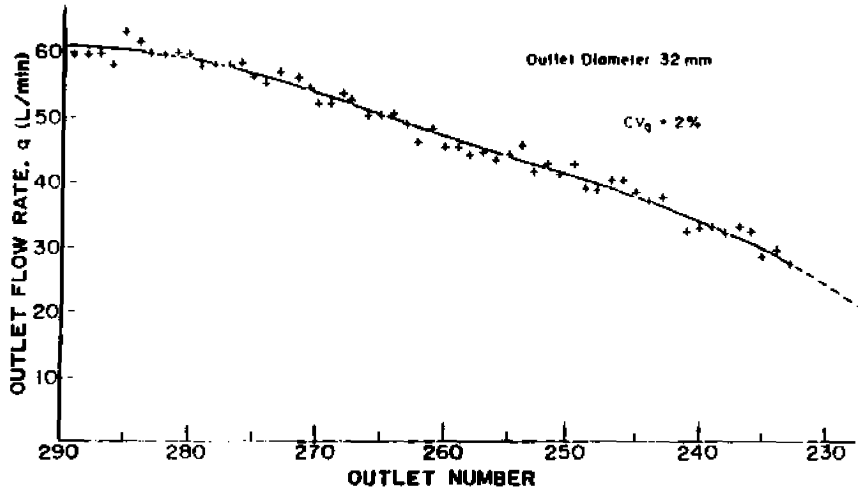


FIG. 35. Flow from fixed-size round hole outlets in a cablegation line at a specific time.

similar to deviations from the means in the gated-pipe and siphon-tube systems.

Figure 35 shows the outlet flow from a section of the Hood cablegation system (which is described in detail by Kemper *et al.*, 1985). The outlets on this system are 32-mm-diameter holes drilled directly in the pipe. The coefficient of variation of the measured outlet flow rates is only about 2%. This means that measured flow rates of two-thirds of the outlets are within 2% of the line on the figures. These flow rates were measured by timing the rate at which a bucket is filled and the coefficient of variation of this measurement method is 2 or 3%, so there is essentially no measurable variation in outlet flow. This excellent uniformity is one of the reasons that early cablegation systems were installed with outlets consisting of simple uniform-sized holes drilled in the pipes.

However, soil infiltration rates vary widely over the season and from year to year and consequently most users feel they need adjustable outlets to do a consistently good job of irrigating.

Figure 36 shows the outlet flow rates from another cablegation system in which gated-pipe slide gates were set "by eye." The coefficient of variation of these flow rates was 14%, which is better than the 25% which was the average measured on conventional fixed-set gated-pipe systems, but is not as good as it could be. The primary problem was that the outlet gates were not set evenly.

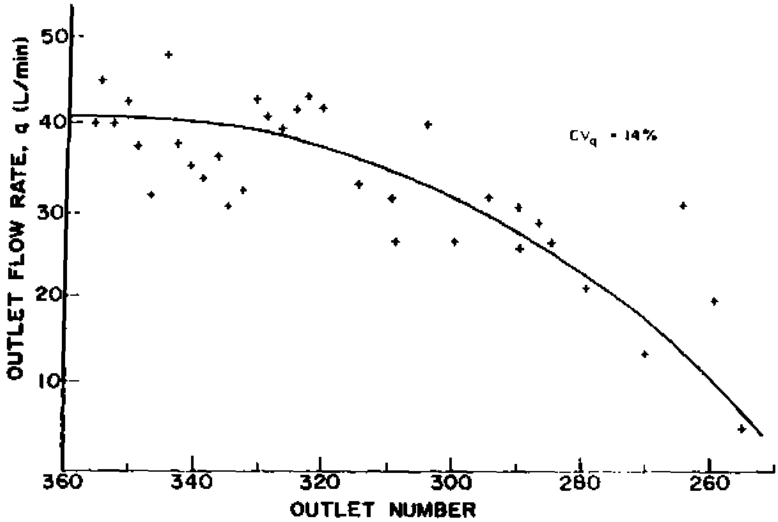


FIG. 36. Flow from slide gate outlets in a cablegation line when flow rates were set "by eye."

Figure 37 shows outlet flow rates for the same pipeline during another irrigation when the gate openings were set with a wedge. The wedge used to help set the gates on this system is shown as an inset in Fig. 37. It has an adjustable stop which is set to the opening width desired. The gate is opened, the wedge is pushed in the gate slot until the stop meets the pipe wall, and then the gate is closed against the wedge. Using this wedge, to set the gates more evenly, the coefficient of variation of furrow supply rates was reduced to 4%. Note that, due to the higher supply rate being used in Fig. 37, compared to that in Fig. 36, the supply rate is close to the carrying capacity of the pipe, producing the predicted dribble flow in outlets 200 through 160. Reduction in total supply by 15% would eliminate most of this dribble flow (i.e., see Fig. 3).

Figure 38 shows outlet flow rates from a section of the Glenn cablegation system which uses barrel-spigot-type outlets (as shown in Fig. 16). The measured coefficient of variation is 4%. These outlets have graduated marks on the sleeve surrounding the swiveling spigot so that pointers on the spigots can be set at the same positions, which helps improve opening uniformity. The flow tends to cut off at about 20 liters/min. At the setting used, cutoff was not complete and four outlets continued to flow after the cutoff at a reduced flow rate. About 1% of the total application occurred after this cutoff.

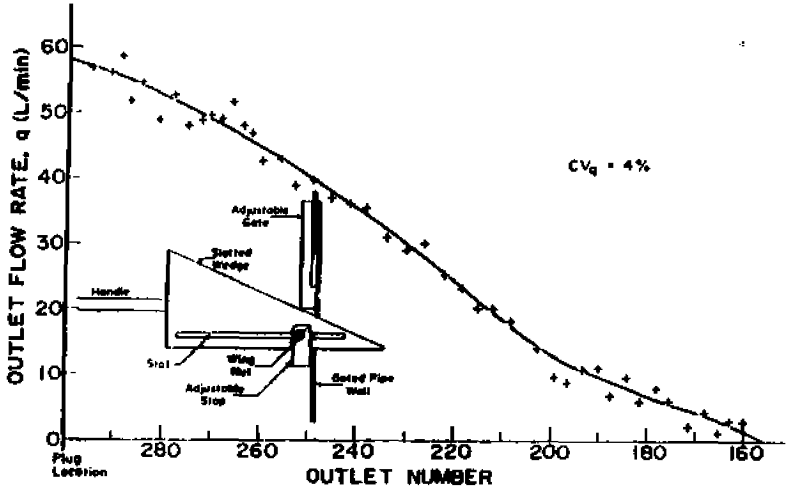


FIG. 37. Flow from slide gate outlets in a cablegation line after they were set with the indicated wedge.

Siphon outlets of the type shown in Fig. 14 were also tested in the field to determine whether their fixed-size orifices would further reduce the coefficient of variation of furrow supply rates. However, since they emit water in the bottoms of furrows, it was not possible to catch the flow in a container and flow measurements had to be made using flumes. The coeffi-

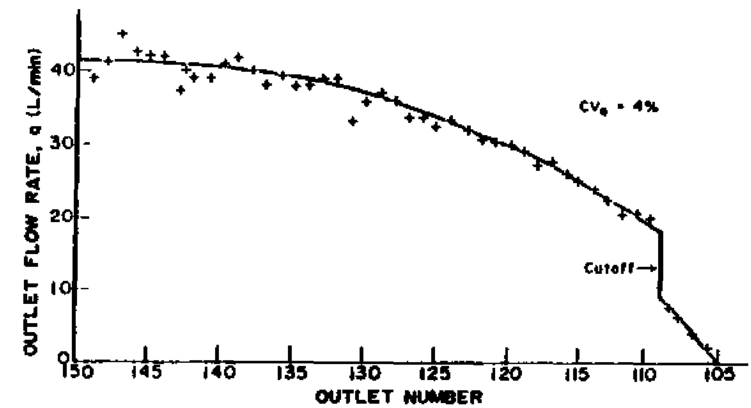


FIG. 38. Measured furrow supply rates from a cablegation line using graduated spigot-type outlets.

cient of variation of the flume measurements was more than 4%, so assessment of coefficients of variation of supply rate from the siphon-orifice outlets was not possible.

Figure 39 shows elevation-induced outlet flow rate variability due to pipe having heaved above and settled below grade. This line has fixed 32-mm-diameter holes for outlets. When the pipe elevation was checked with a surveyor's level it was found that flow rates higher than the line were associated with the pipe being below designed grade, and flow rates lower than the line occurred where the pipe was above designed grade. This points out the importance of installing cablegation lines on a uniform grade, checking the grade every few years to see whether their elevations may have changed and adjusting elevations, if needed, to keep the pipe on a uniform grade.

Figure 40 shows the predicted supply to furrows from outlets above or below a designed grade of 0.005. When an outlet is 25 mm too high, the relative effect on the flow rate is fairly small near the plug where the head is high because the relative variation in head is small. But as you move along the hydrograph and the pressure in the pipe decreases, the relative error increases. Outlets 25 mm lower than designed grade will flow about 1.35 times as long as outlets 25 mm higher than designed grades and will apply 1.4 times as much water. The deviation from designed furrow supply due to deviation of outlet elevation from designed grade is shown in Fig. 41 for a 254-mm-diameter cablegation pipeline as a function of pipe-

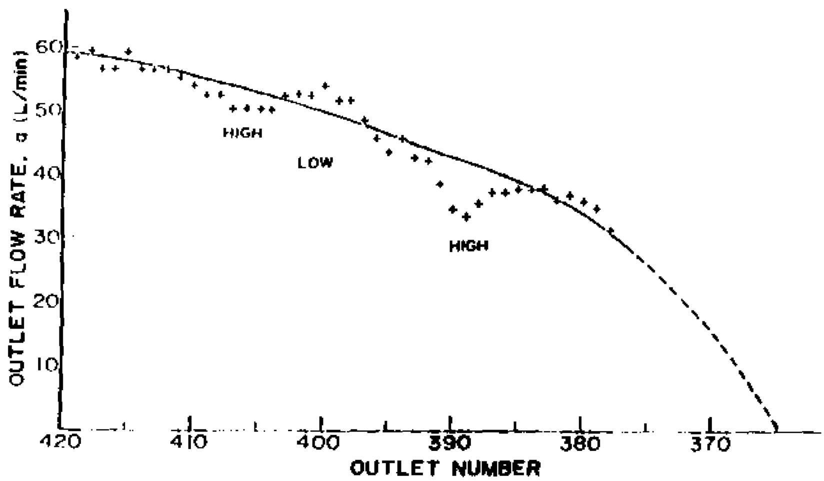


FIG. 39. Supply rates to furrows on a section of a cablegation line where elevations of the pipe had departed from the designed grade.

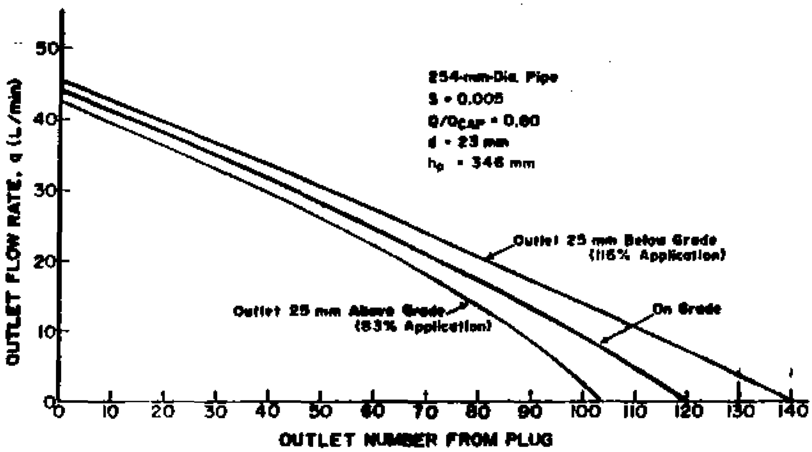


FIG. 40. Effect on furrow supply rate when outlets are 25 mm higher or lower than the designed grade.

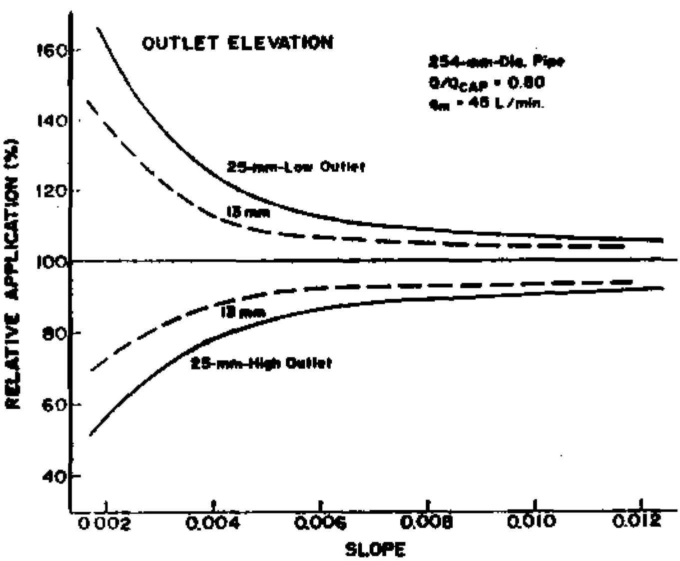


FIG. 41. Deviation from designed furrow supply due to deviation of outlet elevations from designed grade.

line slope. The solid and dashed lines in Fig. 41 show the relative flows from outlets which are 13 or 25 mm high or low from the designed elevation of the outlets. Figure 41 illustrates the importance of precision grading of cablegation lines which are laid on slopes of less than 0.005 and the difficulty of providing uniform furrow supplies with cablegation lines on slopes less than 0.002.

B. Intake as Affected by Intake Rates, Furrow Supply Rates, and Time

Intake rates (IR, in millimeters/hour) by furrows (data provided by the Soil Conservation Service, USDA), in a Nebraska cornfield during the second and seventh irrigation, decreased with time (T, in hours) according to Eqs. (17) and (18), respectively.

$$\mathrm{IR} = 13.7T^{-0.28} \tag{17}$$

and

$$\mathrm{IR} = 16.8T^{-0.63} \tag{18}$$

The volume-balance computer model previously described can predict performance of cablegation systems on soils with infiltration rates described by relationships such as given in Eqs. (17) and (18). The relatively high initial intake rates result in slow initial progress of the water down furrows and in intake opportunity times shorter at the bottom ends of furrows than at the top. This difference in intake opportunity time commonly results in lower intake at bottom ends compared to top ends of furrows. A measure of furrow intake uniformity is the ratio of the bottom end intake to the top end intake.

To get water to the bottom end more quickly and thereby increase uniformity, initial furrow supply rates should be high. However, if they remain high, runoff and erosion will often be unacceptably high. Consequently, it is commonly recommended that high initial furrow supply rate be followed by a decreased or cutback supply rate. This is labor consuming and is often difficult to do in conventional siphon or gated-pipe application systems for which system supply rate is usually constant, unless the irrigator can divert the water not used in the latter part of each set to storage or some other use. Cablegation systems provide an initially high furrow supply rate that subsequently decreases.

The ideal surface application rate sequence would be high while the flow advances to the bottom end of the furrow, and would then decrease, at a decreasing rate to match the decreasing average infiltration rate of the furrow. Cablegation furrow supply curves (e.g., Fig. 35–39) are somewhat convex in shape and do not precisely match this ideal concave supply pattern. However, as indicated in Fig. 42, major reductions in runoff are achieved as a result of having the decreasing cablegation-type furrow supply rate compared to a constant furrow supply rate equal to the initial cablegation supply rate.

The computer model was also used to predict runoff for a supply rate that was constant and equal to the average cablegation supply rate. As indicated in Fig. 42, this reduced constant supply rate resulted in runoff which was only about 10% more than with the cablegation supply. However, it also increased the time required for water to reach the bottom ends of furrows, so the bottom ends of furrows receive less water.

Runoff from rows with a constant water supply rate equal to the average cablegation supply rate, during the time prior to runoff, was also calculated and is indicated in Fig. 42. Resulting runoff was still more than double that occurring with the cablegation supply.

Achieving high-efficiency water use requires minimizing runoff and maximizing intake uniformity. Inherently, these are competing objectives, so the irrigator is generally forced to accept a compromise. Cable-

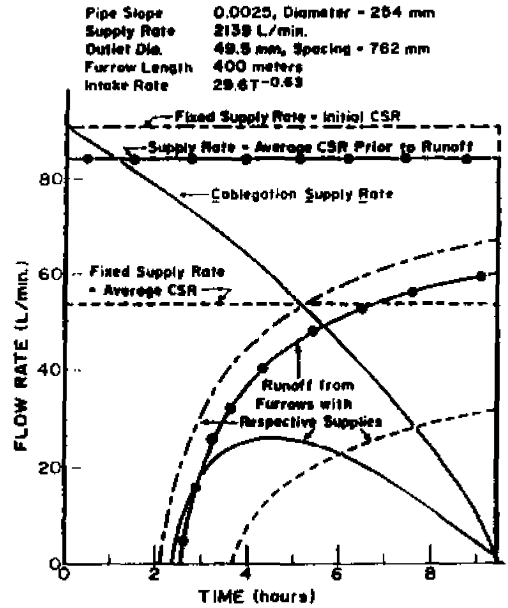


FIG. 42. Runoff from furrows with cablegation supply rates (CSR), fixed-rate supplies equal to initial and average CSRs and average CSR prior to runoff.

gation systems allow irrigators to attain a compromise that is better than that attainable with fixed supply rate systems. How much better performance can be achieved using the cablegation supply is a function of how the intake rate changes with time. Figure 43 shows the computer model predicted percentage runoff and bottom/top end intake when the intake functions are those given in Eqs. (17) and (18). For both intake curves, runoff is decreased by increasing the plug speed, but the rate of runoff decrease is greater when the intake rate decreases faster. In general, decreasing furrow supply rates provided by cablegation are most beneficial when intake rates decrease most rapidly.

Furrow runoff from fixed-set furrow irrigation commonly ranges from 30 to 50% of the supply. There is no runoff for the initial 1 to several hours after a new set is begun, then flow off the ends begins and continually increases until a new set is made as indicated in Fig. 42. Irrigators are generally able to reuse runoff with relatively constant flow rate, such as occurs from cablegation fields, more effectively that the cyclic flows that result from fixed-set furrow irrigation.

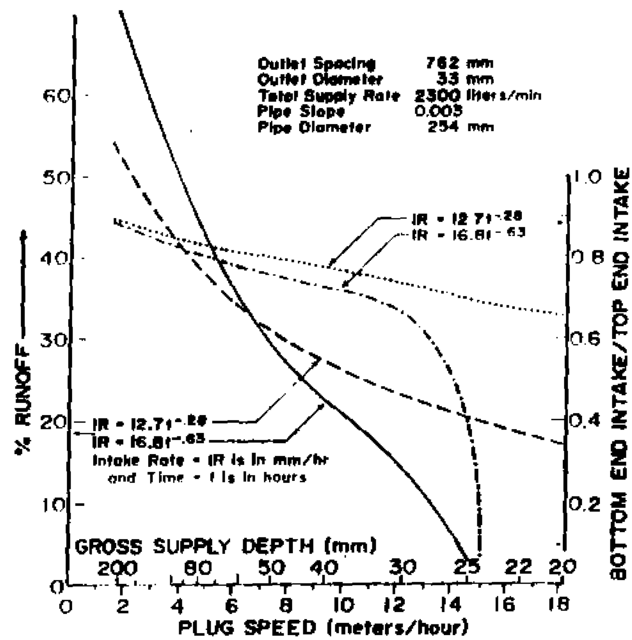


FIG. 43. Intake uniformity and runoff as a function of plug speed when soils have different intakes.

The best plug speeds to optimize intake uniformity and low runoff using the system described in Fig. 43 are between 6 and 14 m/hour. Space-averaged gross supply depths to the area served by the furrows range from about 26 to 62 mm, with 6 to 35% runoff, so water retained ranges from about 20 to 40 mm per irrigation. This is less water than is generally applied in nonautomated irrigations. Applying such light applications, irrigations have to be more frequent. Labor costs for nonautomated irrigation (hand-move or wheel-roll sprinkler; gated pipe or siphon tube) are relatively large and proportional to the number of irrigations applied. Consequently, farmers with nonautomated systems tend to apply water for longer periods of time so they can irrigate fewer times. The cablegation user can apply "heavy irrigations" and avoid excessive runoff by reducing the outlet size and thus flow rate and slowing down the plug. However, using a cablegation system, applying a few extra irrigations usually requires less labor than adjusting outlets. An additional advantage of frequent light irrigations is less likelihood of deep percolation that sends water and nitrates on past the root zone into the groundwater. In some of the well-managed cablegation systems used in Colorado, Washington, and Nebraska, frequent light irrigations have been used and deep percolation has been nearly eliminated.

While intake rates change somewhat throughout the irrigation season [e.g., Eqs. (17) and (18) are for the second and seventh irrigation] the largest differences are generally between the first irrigation following tillage and the second irrigation. Soils during the first irrigation following tillage commonly have from 20 to 200% higher intake rates than during later irrigations. Accommodation of such differences requires that outlets be opened wider prior to the first irrigation and closed back to about the original size prior to the second irrigation.

Interrupted, or surge, irrigation has reduced intake rates by the factors needed (e.g., Bishop *et al.*, 1981; Kemper *et al.*, 1985, p. 124) to get them back down to where the outlet opening used the previous year will provide flow rates high enough to get water to the end of the furrows. While the desired rate of intake rate reduction does not always occur, it does often occur in uncompacted furrows in freshly tilled soils, which is where it is most needed. One flow interruption is normally adequate, but as many as three to consolidate the wetted perimeters may be used. This can be achieved with cablegation by passage of the plug through the pipeline on from one to three fast runs, during which each furrow is wetted for only an hour or two during each passage. If the supply is not interrupted during or after the time when water is advancing through the bottom section of the furrow, this section will generally retain a higher intake rate than will the upper end. This higher intake rate persisting in the bottom section helps compensate for shorter intake opportunity time at the bottom end. The amount of labor needed to provide these flow interruptions using fixed-set siphon tubes or gated pipe is so great that it is not commonly done. Instead, the farmer commonly increases the flow rate, often moving substantial amounts of topsoil from the top end to the middle or bottom reaches of the fields and greatly increasing runoff. This topsoil movement has substantially decreased top end productivity on many furrow-irrigated fields (i.e., see Carter *et al.*, 1985).

Another method of avoiding the large differences in intake due to recent cultivation is to avoid cultivation. No-till or minimum-tillage irrigation farming, wherein furrows are cleaned out as needed, but weed control is primarily by chemicals, appears to be a viable option in many situations. Furrow intake rates still vary with time to some extent as crop residues accumulate, weeds grow, worm burrows intersect the wetted perimeter, etc. However, small variations can often be handled by increasing or decreasing total supply, or increasing or decreasing plug speed when the supply is fixed, or by setting the outlet sizes to handle the highest intake rates and tolerating considerable runoff when intake rates are low.

In many areas supply systems for surface irrigation are designed to reuse runoff or tail water by bringing it back into the supply system by gravity or by pumping. In such areas farmers are given supplies considerably in excess of crop needs and relatively high rates of runoff are tolerated because most of this water is not lost. Operators of cablegation systems in such areas tend to follow local practice, setting furrow supplies high to assure that water gets through all furrows and reducing the time that they have to spend adjusting their system.

In other areas (e.g., in Nebraska and California) the law requires that irrigation water be retained on the farm. This commonly requires pumping systems which take tail water back to supply lines. Such pump-back systems not only save the water, but also save fertilizer nitrogen and other chemicals that the farmer may be applying with his water, which could otherwise become a contaminant in downstream water. The lifts and energy required in such pump-back systems are usually relatively low and again farmers commonly find that the economically logical decision is to save labor by providing relatively high furrow supply rates, pumping more tail water, and reducing time spent adjusting the system. Most of the Nebraska cablegation systems serve furrows with less than 0.5% slope where furrow erosion is not a problem and energy required to pump water back to the pipelines is minimal.

One factor which cablegation systems are unable to completely compensate for is furrow-to-furrow variability in intake rate. The primary cause of furrow-to-furrow intake variability is tractor wheel compaction of part of the irrigated furrows. Kemper *et al.* (1982) found that intake rate on wheel-compacted furrows averaged about 60% of that on uncompacted furrows. When cablegation systems provide highly uniform applications, decreases of intake rate by factors such as wheel compaction become strikingly apparent. On an initial overnight application to every second furrow with one of the first cablegation systems, water was furnished to 93 furrows. Water in 31 furrows (every third irrigated furrow) had failed to reach the end of the field, while water in the other 62 had reached the end. The 62 furrows in which water had reached the end were all wheel compacted and the other 31 had not been compacted. Providing round orifices 16 mm in diameter on outlets to serve the uncompacted furrows and 13-mm-diameter orifices to serve the wheel-compacted furrows resulted in water reaching the bottom end of every furrow in this field, solving the apparent problem. However, the real problem was that the two crop rows drawing water from each uncompacted furrow were being supplied over 50% more water than the two rows next to each wheel-compacted furrow. The major portion of this intake rate difference persisted through the three irrigations of the season.

The only way to compensate for such differences in intake rate and achieve uniform intake is to provide water for longer periods of time to wheel-compacted furrows than to uncompacted furrows. Irrigators using siphon tubes or gated pipe could make such adjustments in supply time but do not because of extra time involved. Cablegation systems can provide water for different times to compacted and uncompacted furrows by closing outlets to compacted furrows and irrigating the uncompacted furrows, then closing outlets to uncompacted furrows, opening outlets to compacted furrows, and irrigating again for a longer time period.

For both the manual and cablegation systems, the additional labor and complications involved in selectively extending supply time to compensate for compaction-induced lower intake rates are practically prohibitive.

The problem of nonuniformity of furrow intake rates due to irrigating in wheel-compacted and uncompacted furrows is getting worse rather than better, as most manufacturers have ceased making three-wheeled tractors. The three-wheelers were used effectively to seed, cultivate, and furrow six rows in preparation for irrigation. If the irrigator was irrigating every other furrow he could choose to irrigate in the three wheel-compacted or in the three uncompacted furrows. If he irrigated every furrow, each crop row had a wheel-compacted furrow on one side and an uncompacted furrow on the other. It is practically impossible to fit the four wheels of the large tractors, which cultivate 8 to 12 rows, into patterns where the farmer is not serving water to some crop rows via wheel-compacted furrows, while others are served via uncompacted furrows, with attendant under- or oversupply.

Since cablegation systems can supply water with coefficients of variation of the order of 4%, the most pressing complementary need is management to reduce variation of furrow intake rates which have coefficients of variation in excess of 25%. Resulting improvements in uniformity of water application, attendant savings of water and nitrate, and increases in yield quality and quantity could be worth over $\$10^9$ to farmers in the United States each year.

C. Installation, Operation, and Maintenance Costs

Cablegation lines have been installed for costs ranging from \$150 to \$650 per hectare. The upper level of these installation costs, when combined with \$250/ha for land leveling, results in system costs near those for purchasing hand-move sprinkler systems, which are the lowest cost sprinkler systems. One operator recently installed cablegation systems and a hand-move sprinkler system on his farm. Longevity of the large underground pipeline, which was the major cost component of his cablegation system, should exceed that of the hand-move sprinklers. Annual operation and maintenance costs of his hand-move sprinkler system are about \$184/ha; for the cablegation system costs are less than \$50/ha.

Because cablegation utilizes a single line for both conveyance and distribution of the water and because pipeline costs are the main cost of automated surface irrigation systems, cablegation is generally the least expensive type of automated surface system.

IX. Applications

A. Range of Soil Types Suitable for Cablegation

The lower the intake rate of the soil, the lower the cost of cablegation systems, because furrows can be longer and smaller pipelines can be used. Cablegation on low-intake-rate soils has been described as the low-cost trickle system. When crop canopy covers the furrows its water use efficiency is nearly the same as that of trickle systems.

Soils with exceptionally high intake rates have historically been a problem for the surface irrigator because intake at the supply end becomes excessive before adequate water reaches the tail end. One solution to this problem has been bordered strip irrigation in which closely planted crops such as small grains or alfalfa are planted on a flat surface and small dikes are constructed to confine the water into relatively narrow strips. High rates of flow delivered to the top ends of such strips push water quickly through the bordered strip and often accomplish acceptably uniform application. Cablegation is suited to provide the frequent set changes needed on such bordered strip systems on high-intake soils.

B. Range of Slopes on which Cablegation Systems Will Work

Cablegation systems have worked successfully where slope along the cablegation line was as high as 2.2%. As long as the outlets provide for energy dissipation and direction of the water to the furrows, there is no upper limit to slopes along the pipeline that can be handled by these systems. Slopes along the furrow are limited to those in which flow rates required to reach the end of the furrow do not cause unacceptable erosion.

The minimum grade on outlets from cablegation lines that is recommended (for reasons outlined in discussion of Figs. 40 and 41) is 0.002. There are substantial acreages of surface-irrigated lands where the supply end of the field does not have this much slope. In some cases the limited existing slope has been complemented by laying the supply end of the pipeline on top of the soil surface and progressively trenching the pipe into the soil, so that at the tail end of the pipeline the outlets are at the soil surface. When 300-mm-diameter pipe is being used, this can provide nearly half of the elevation difference needed to achieve 0.002 slope on a line 300-m long. Other means of complementing the existing soil slope to achieve the minimum recommended outlet grade are to build an elevated soil pad at the supply end, or to put the outlets near the top end of the line on risers. In both cases here is a need to dissipate the energy of the water, as it falls from the outlets 100–400 mm above the field surface, so erosion will not occur. Low-cost corrugated polyethylene tubing of about 30-mm diameter has been used effectively on such elevated outlets to practically eliminate erosion problems.

When water is supplied to fields via pipelines, adequate pressure is usually available to achieve the heads needed at the supply ends of cablegation lines. However, if water is supplied via open channels in flat areas, additional head may be needed. Some of the most trouble-free methods of removing trash from irrigation water can also be incorporated into the system if 200 mm of excess head is available. Low-head, high-volume pumps can provide the heads needed at relatively low energy costs. Such pumps, combined with elevated pads or outlets on risers, can adapt cablegation to flat lands.

References

Bishop, A. A., Walker, W. R., Allen, N. L., and Poole, G. J. (1981). Furrow advance rates under surge flow systems. *J. Irrig. Drain. Div., Am. Soc. Civ. Eng.* **107**(IR3), 257–264.

Bondurant, J. A., and Kemper, W. D. (1985). Self cleaning nonpowered trash screens for small irrigated flows. *Trans. ASAE* **28**, 113–117.

Booher, L. J. (1974). Surface irrigation. *FAO Dev. Pap.* (95).

Carter, D. L., Berg, R. D., and Sanders, B. J. (1985). The effect of furrow irrigation erosion on crop productivity. *Soil Sci. Soc. Am. J.* **49**, 207–211.

Goel, M. D., Kemper, W. D. Worstell, R. V., and Bondurant, J. A. (1982). Cablegation: III. Field assessment of performance. *Trans. ASAE* **25**, 1304–1309.

Humpherys, A. S. (1985). Mechanized wheel and belt screens for farm irrigation turnouts. *Trans. ASAE* **28**, 1933–1939.

Kemper, W. D., and Bondurant, J. A. (1982). Turbulent flow self-cleaning trash screens. *Annu. Tech. Conf. Proc. Irrig. Assoc.* pp. 75–84.

Kemper, W. D., Heinemann, W. H. Kincaid, D. C., and Worstell, R. V. (1981). Cablegation: I. Cable controlled plugs in perforated supply pipes for automatic furrow irrigation. *Trans. ASAE* **24**, 1526–1532.

Kemper, W. D., Ruffing, B. J., and Bondurant, J. A. (1982). Furrow intake rates and water management. *Trans. ASAE* **25**, 333–339.

Kemper, W. D., Kincaid, D. C., Worstell, R. V., Heinemann, W. H., Trout, T. J., and Chapman, J. E. (1985). Cablegation systems for irrigation: Description, design, installation and performance. *USDA Agric. Res. Serv.* **ARS-21**.

Kemper, W. D., Bondurant, J. A., and Trout, T. J. (1986). Irrigation trash screens pay. *J. Soil Water Conserv.* **41**, 17–20.

Kincaid, D. C. (1984). Cablegation: V. Dimensionless design relationships. *Trans. ASAE* **27**, 769–772, 778.

Kincaid, D. C. (1985). Cablegation: VI. The waterbrake controller. *Trans. ASAE* **28**, 1957–1960.

Kincaid, D. C., and Kemper, W. D. (1982). Cablegation: II. Simulation and design of the moving-plug gated pipe irrigation system. *Trans. ASAE* **25**, 388–395.

Kincaid, D. C., and Kemper, W. D. (1984). Cablegation: IV. The bypass method and cutoff outlets to improve water distribution. *Trans. ASAE* **27**, 762–768.

USDA–ARS Kimberly Staff (1985, 1986, and 1987). Cablegation updates. Available on request from USDA–ARS Research Center, Kimberly, ID 83341.

Trout, T. J., and Mackey, B. E. (1985). Furrow inflow and infiltration variability. *Am. Soc. Agric. Eng. Winter Meet.* Paper No. 85-2588.