Design of Recirculating Irrigation Systems

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THE reuse of runoff water is becoming an integral part of the farmer's irrigation operation, especially where water costs are relatively high. Reuse of runoff water collected by recirculation systems from one or more fields decreases the amount of water that needs to be pumped or delivered to the farm and can improve water-application efficiency on individual fields. It also reduces contamination of natural streams by stopping the surface flow of silt and any nutrients that may be contained in the runoff water.

The economic value of the runoff water will usually be the deciding factor in installing recirculating irrigation systems. In areas of limited water supply or where water is relatively expensive, such as water pumped from wells, reuse of runoff water may result in more economical farm operation. Water is often used as a substitute for labor, thus causing an increase in runoff. This is particularly true on farms using surface irrigation systems. Reuse of irrigation runoff water, particularly with furrow irrigation, may be more economical than the use of additional labor to accomplish efficient irrigation. If runoff is reused, a larger percentage of the diverted or pumped irrigation water will infiltrate the soil.

In some irrigated areas, runoff from both surface and sprinkler irrigation is prohibited by law and return of runoff water to the supply is mandatory. In other areas, farmers may be more concerned about the actual loss of water and soil. Whether a recirculating irrigation system is installed for economic, social or legal reasons, there exists a need for a functional analysis of such systems, for better methods of obtaining the data necessary for design and for a better design procedure.

A survey of recirculating systems in southern Idaho showed that many were installed haphazardly and could have benefited from better design (1)*. Many of these systems were not functioning in a manner that provided maximum economy and efficiency in the reuse of collected runoff water.

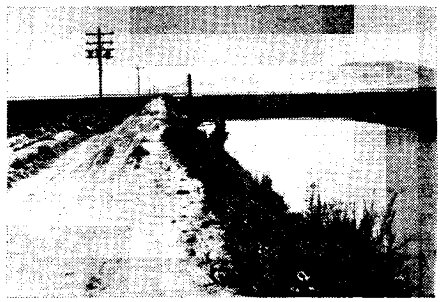

FIG. 1 Sequence-type return system with reservoir, pump and short return pipe. Stored water collected from an upper field is used as a separate supply and is pumped across the road to lower lying field.

Functional Analysis

The recirculating irrigation system must collect runoff water from one or more fields and return it to some point in the farm distribution system where it may be used effectively and efficiently. A study of different methods of handling runoff water showed that the system should function in the following manner to accomplish its design purpose:

1 Runoff water should be applied to a different field or portion of the field than that on which runoff occurs. Recirculating runoff to the same irrigation set that is generating runoff results only in temporarily storing water on the field. This will not increase the infiltration rate, but will increase the rate of runoff and will probably increase erosion in the furrow.

2 When computed over the time interval required to irrigate the area contributing to the recirculating system, runoff water will have to be returned to the system at the same rate that it is accumulated if all runoff is to be reused. If temporary storage is provided, stored runoff will eventually have to be recirculated at a rate equal to storage accumulation to prevent loss by overflow.

3 Maximum improvement in total water use on the farm will result from using stored runoff water to achieve a reduced stream size for cutback irrigation; i.e., stored runoff water is pumped to increase the stream size during the advance period and pumping is stopped after the field has started to produce runoff. This reduces deep percolation and runoff so that a minimum amount of water must be recirculated. Runoff water collected from one irrigation set is returned to the head ditch and applied with the normal inflow on the next irrigation set. A volume balance for such a system is:

$$V_s = c_1 V_a + (n-1)(c_2-c_3) V_a \quad \ldots\ [1]$$

where

V_s = volume of runoff water in storage after any irrigation set
V_a = volume of water applied per set
n = number of irrigation sets
c_1 = ratio of amount of runoff to amount of applied water, for the first irrigation set
c_2 = ratio of amount of runoff to amount of applied water, for subsequent irrigation sets
c_3 = ratio of amount of water pumped from stored runoff to amount of applied water

Since the rate at which water is pumped from storage must be determined, equation [1] may be restated in terms of flow rates:

$$V_s = c_1 q_o t_a + (n-1)(c_2-c_3)(q_o + q_p r_1) t_a \quad \ldots\ [2]$$

where

q_o = rate at which water is diverted from external sources (canal, well, etc.)
q_p = rate at which water is pumped from stored runoff
r_1 = ratio of time stored runoff water is pumped to total time of application
t_a = total time of application

The rate at which water is initially applied to the field for the second and succeeding sets is:

$$q_a = q_o + q_p = q_o(1 + c_4) \quad .\ [3]$$

where c_4 is the ratio q_p/q_o and is determined from field trials or analysis of existing irrigation practice.

The volume of water pumped from stored runoff is:

$$V_p = q_p r_1 t_a \quad \ldots\ [4]$$

The volume of water applied during the first set will be less than that applied on succeeding sets and the area irrigated will also be less if the same stream size is used. Thus:

$$V_a = V_o \ (n = 1) \quad \ldots\ [5]$$

$$V_a = V_o + V_p = q_o t_a + q_p r_1 t_a \ (n > 1) \quad \ldots\ [6]$$

where V_o is the volume of water, per set, delivered from the primary source – canal, well, etc.

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Having V_p and V_a, c_3 may be determined as:

$c_3 = V_p/V_a$ . . . . [7]

For example, analysis of the irrigation practice for a given field, 660 ft long, 3-ft-row spacing, and an initial stream size of 10 gpm per row, has shown that irrigation with unreduced stream size produces 20 percent runoff and irrigation with the stream reduced 20 percent after one-fourth of the total time of application produces 10 percent runoff. Designing to achieve this reduction in stream size by pumping from stored runoff:

$c_4 = 20\%/(100\% - 20\%) = 0.25$

Assuming 1.00 ac-ft (1.00 cfs for 12 hours) diversion, from the canal for all sets, the runoff from the first irrigation set would be:

$c_1 V_a = 0.20 \times 1.00 = 0.20$ ac-ft (acre-feet)

For the second set:

$q_a = 1.00 (1 + 0.25) = 1.25$ cfs
$q_p = 0.25$ cfs

The volume pumped from stored runoff would be:

$V_p = 0.25 \times 1/4 \times 12 = 0.75$ ac-in. $= 0.0625$ ac-ft

The total volume applied:

$V_a = 1.00 + 0.063 = 1.063$ ac-ft

The volume of runoff per irrigation set ($n > 1$):

$c_3 V_a = 0.10 \times 1.063 = 0.106$ ac-ft

This leaves a net gain of 0.043 ac-ft per set accumulating as stored runoff.

After five sets, the first applied to two acres at the 1.0-cfs rate and succeeding sets applied to 2.5 acres at the 1.25-cfs rate with cutback irrigation, 12.0 acres would be irrigated, 5.00 ac-ft would have been diverted from the canal and 0.37 ac-ft (0.20 + 4 × 0.043) stored as runoff at the end. If the runoff had not been stored and reused, 6.00 ac-ft would have been diverted from the canal in six sets and 1.20 ac-ft wasted as runoff. A further savings of water and a reduction in runoff storage capacity can be obtained by diverting the amount needed to be pumped from storage to effect the cutback irrigation directly into storage before the first irrigation. All sets would then be irrigated at the higher efficiency and the resulting stored runoff after five sets would be 0.28 ac-ft (0.063 + 5 × 0.043).

If, in the above example, a cutback stream was not used and all runoff from the first five sets was collected, 1.00 ac-ft would have been stored. This could be used as a separate supply to irrigate the last set and the total water diversion from the canal would be 5.0 ac-ft with 0.20 ac-ft remaining in storage. This system, however, would require repumping more water, a larger reservoir and a larger pump and pipeline; therefore, the total operating cost would be greater.

Analysis of surface irrigation practice shows that if the amounts of water stored in the soil and lost by deep percolation are constant for each set, and if all runoff returned to the distribution ditch, then the amount of water that needs to be diverted to the field is independent of the percent of runoff. However, when nonreduced streams are used, increasing the stream size results in an increase in runoff and a decrease in deep percolation. Thus, the diversion requirement can be reduced by using larger irrigation streams and recirculating runoff water. Maximum nonerosive streams should not be exceeded, however.

Description of Systems

Recirculating irrigation systems can be classified according to the method of handling runoff water. If the water is returned to a field lying at a higher elevation, it is usually referred to as a return-flow system; if the water is applied to a lower lying field, this is termed sequence use. A sequence system with a reservoir is shown in Fig. 1. Systems may also be classified according to whether or not they accumulate and store the runoff water. Systems storing collected runoff water are referred to as "reservoir systems." Systems which immediately return the runoff water require little reservoir capacity. These usually have automatically cycled pumping systems and are termed "cycling-sump systems." One or more types of systems may be applicable to a given farm.

The sequence system generally will have a pump and only enough pipe to convey the water to the head ditch of the next feld. With planning and some land leveling, it may be possible to create enough elevation difference between fields to apply the runoff water to a lower field in sequence by gravity.

A reservoir system collects enough water to be used as an independent supply or as a supplement to the original supply to provide a cutback stream. Reservoir size will depend on whether collected water is handled as an independent supply, and, if not, on the rate water is pumped for reuse. A smaller reservoir is required if this system is used for cutback irrigation.

The cycling-sump system consists of a sump and a pump large enough to handle the expected rate of runoff into the sump. Pump operation is controlled automatically by a float-operated or electrode-operated switch. These systems are similar to drainage pumping installations. Some storage can be obtained by enlarging the collecting ditch.

The recirculating irrigation system will normally consist of three parts:

1 System for collecting and storing of runoff water

2 Pumping unit for returning water to irrigation system

3 Pipeline or other method for conveying water back to irrigation system.

Under certain conditions, neither pump nor pipeline may be necessary.

The size, capacity, location and selection of equipment for these systems are functions of the main irrigation system, the topographic layout of the field or fields, and the farmer's irrigation practice and desires. The collection system will usually consist of ditches conveying runoff water to a central location. The pumping part of a system will usually consist of a pump, motor-drive equipment, starter for electrical systems, valves, and a sump.

Design Data

The design data needed for any given farm are the topographic features of the farm and an estimate of the amount of runoff water to be handled. Generally, by the time a farmer installs a recirculating irrigation system, he has irrigated the farm and the point of runoff collection is known. Some field leveling may be necessary to channel runoff waters to a common collection point. Reservoirs should be located so that the most economical conveyance to the point or reapplication is obtained. On flatter lands, all runoff usually can be picked up at one point. The situation, however, may lead to a system requiring the most pipeline to return water to the head ditches. On steeper slopes and on rolling and hilly land, runoff collection points probably will not be as far from the point of reapplication as on flatter land, because irrigation runs will not be as long.

Determination of the amount of runoff water to be handled by a recirculating system is of major importance. The amount of runoff, and in some instances the rate of runoff, is needed to determine the size of reservoir, pump, and conveyance system, all of which are major cost factors in the recirculating system. The expected runoff can be determined by measurement or by estimation. Measurement of runoff from the total land unit over a period of time will yield the best data for design. Lacking this, measurement of one or more irrigation sets under the farmer's normal practice will yield a reasonable estimate.

The amount of runoff can also be estimated from analysis of field conditions and the farmer's irrigation practice. One technique, outlined by Willardson and Bishop (2), requires data

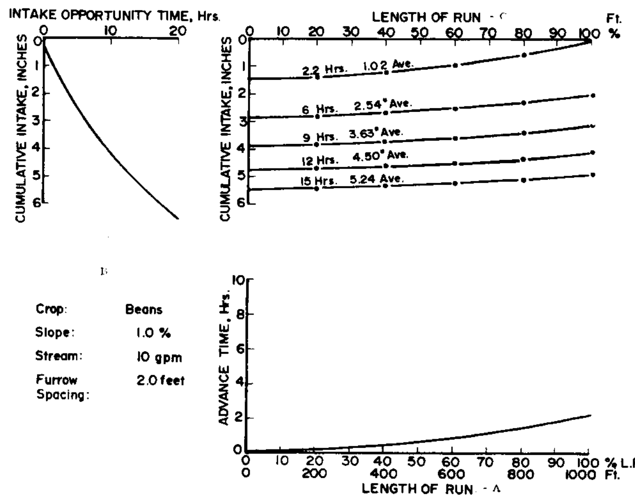

FIG. 2 Stream advance, cumulative intake function and cumulative intake curves.

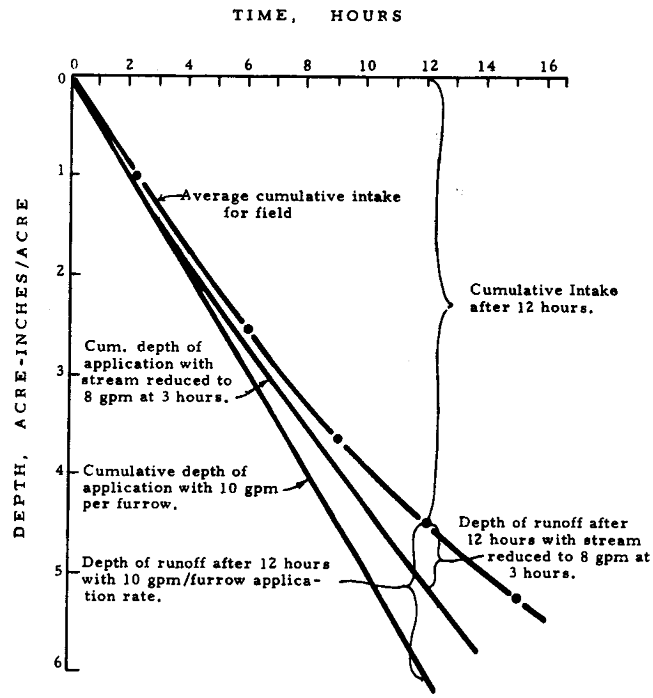

FIG. 3 Plot of average cumulative intake and cumulative application depths with and without cutback stream.

on the intake rate of the soil, the rate of advance of the furrow stream down the furrow, the design depth of irrigation and the physical dimensions of the field. Their analysis shows that, if a single (or nonreduced) stream size is used, a minimum of about 20 percent runoff can be expected for most intake rates with stream advance to total irrigation time ratios approximating 0.20.

The amount of runoff to be expected can also be computed quickly by the graphical technique shown here. This method also requires data on intake rate and stream advance for the particular field. The advance data (Fig. 2A) is used to obtain intake opportunity times at various distance intervals along the length of run. Cumulative intake curves for the field at any given time are then computed using the intake curve (Fig. 2B) and are plotted in Fig. 2C. Average cumulative intake values are plotted in Fig. 3.

Using the mass balance concept, the amount of runoff is the difference between cumulative depth of application and average cumulative intake for the fields as shown in Fig. 3. The average cumulative-intake curve and the application rate are used to obtain the rate of runoff. The average intake rate for the field at any time is the slope of the average cumulative intake curve and can be determined by drawing a tangent to this curve at the desired time. The rate of runoff is the difference between the application rate and the average intake rate, or the slopes of the two curves, at the given time. In the example, Fig. 3, the application rate is 10 gpm per furrow and the average intake rate is 8 gpm per furrow after 3 hr, leaving a runoff rate of 2 gpm per furrow.

When designing cutback streams, the net effect of reducing the stream size can also be determined by this method. This example shows that by reducing the applied stream size to match the average intake rate at 3 hr results in 0.6 in. of runoff at the end of 12 hr of irrigation. If the stream was not reduced, 1.5 in. of runoff would have occurred after 12 hr. The effect of reducing the application rate at other times can be tried to determine the maximum reduction in runoff. The effect of returning water to the field at different rates can also be evaluated. If the designer is familiar enough with the area and irrigation practices, design runoff quantities may be estimated. Where the water supply is reasonably constant over the season, such as pumped supplies or continuous deliveries from a canal, the amount of runoff expected from a given farm will probably be quite uniform. With a variable water supply, the amount of runoff may also vary. The amount of runoff may also vary over the irrigation season because intake rates change. In most areas, intake rates are relatively high in the spring and after cultivations. Later in the season they usually decrease and runoff percentages increase unless application rates are changed.

Design Procedure

The procedure for designing recirculating irrigation systems is similar to designing any other type of pumping system. The design and operating conditions are determined, fixed costs and annual operating costs are computed, and finally the total annual cost is determined. The following information is needed to design the system:

Rate and quantity of water diverted to the farm

Irrigation practice analysis

Reservoir size

Pumping rate for returning water to the system

Total operating head, including both elevation and friction head

Pipe diameter and type

Pump type, size and efficiency

Motor size and efficiency.

The total hours of operation are determined from the number of hours per irrigation and the number of irrigations per year that may be expected.

The rate at which water is diverted to the farm from external sources may be changed if the runoff is recirculated, since most systems are designed to use a specific flow rate. The total amount of water diverted to the farm can be decreased by the amount of runoff saved. This is the amount of runoff which occurred under the previous practice and not necessarily the amount recirculated because some water may be recirculated more than once.

The amount and rate of runoff to be handled can be determined by analysis of the farmer's irrigation practice as previously discussed. These data are used to determine the reservoir capacity necessary for the proposed method of handling the runoff. Reservoir size will be smallest if the runoff is pumped back at the rate it occurs, and largest

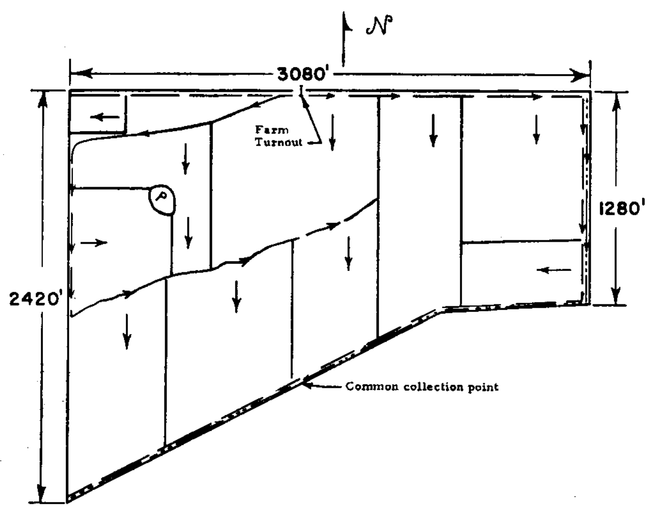

FIG. 4 Plan view of example farm showing direction of irrigation of fields and flow of runoff water.

TABLE 1. WATER-USE RECORDS FOR EXAMPLE FARM

	Applied, acre-feet	Runoff, acre-feet	Runoff, percent
May	38.42	3.30	8.6
June	15.18	1.19	7.8
July	92.34	7.45	8.1
August	84.53	12.41	14.7
September	64.22	9.11	14.2
October	6.55	1.38	21.1
Total	301.24	34.84	11.6

if the the runoff is stored and handled as a separate supply. The smallest quantity of water will be handled and equipment costs will be least if the runoff is used to effect a cutback in irrigation.

Fixed costs include the cost of the pumping plant (including pump, strainer, fittings, starter, wiring), structures, reservoir, and pipeline. The annual fixed costs are determined using an amortization factor based on the design life and the interest rate paid for borrowed money. The annual operating costs include the power cost and maintenance for the given pumping installation. The total annual cost for a given design is the sum of the annual fixed costs and the annual operating costs. Since the fixed costs and the operating costs are not entirely independent, analyses should be made with different rates of pumping and pipeline sizes to determine the minimum total annual cost.

If the different factors involved in the total annual cost can be expressed as a function of pipe diameter, total dynamic head and flow rate, then a minimum cost can be obtained by partial differentiation and simultaneous solutions of the partial derivatives. An example of this for gravity-irrigation pipelines has been given by Horn (3). Pipeline costs for a given gage pipe can usually be expressed in terms of cost per linear foot per inch of diameter. Some irrigation power rates can be expressed as a function of head, flow rate, and pumping hours, but it is difficult to find pump prices which have a mathematically describable relationship to head, capacity and efficiency.

Design Example

A southern Idaho farm of 105 irrigable acres, obtaining water from a demand canal system, is used as an example. The farm layout (Fig. 4) shows that the water enters the farm at the high point and is distributed along the north side of the farm and down both the east and west sides to irrigate lower lying fields. All runoff water drains into the central point indicated. This central point or reservoir location lies 750 ft from the lower distribution ditch, which is level and can be supplied from either end, and about 1,500 ft from the farm delivery point. The slope of the land is one percent giving 15 feet elevation difference between the collection point and the farm delivery point.

The measured water use on this farm for 1964 is given in Table 1. These data are given by months since the power rate structure for irrigation pumping in this area is on a monthly billing basis. Three hundred ac-ft of water were applied during the year, with almost 35 ac-ft or 11.6 percent runoff. Assuming that this 11.6 percent runoff can be saved, the diversion to the farm can be reduced by this amount. An allowance for seepage and evaporation from the reservoir may have to be made.

Cost analyses for delivering water to the lower ditch and to the farm delivery point for different pumping rates and different pipe sizes are shown in Figs 5 and 6, respectively. These are total annual costs for electric pumping plants having wire-to-water efficiencies of 60 percent. Prices were based on 14-gage, welded-steel pipe and side-suction centrifugal pumps. A 15-year expected equipment life and a 6 percent interest rate were used for computing fixed annual costs. If the water is pumped the 750-ft distance, the most economical pipe diameter for 0.2 cfs pumping rate is 3 in. with an annual cost of about $160. This most economical pipe diameter increases with pumping rate to 8 in. and an annual cost of about $245 for pumping 1.0 cfs. If the water is returned to the farm-delivery point, the minimum-cost pipe diameters are also 3 in. for 0.2 cfs and 8 in. for the 1.0-cfs pumping rate. Total annual costs are increased since more head and a longer pipe are involved. Corresponding total annual costs are $225 and $400, respectively. The linear increase in total annual cost after the minimum pipe diameter is reached is the effect of a minimum power charge which in this case is equivalent to a 3-hp installed demand charge. In the example area, it is cheaper to connect to the normal farmstead system if the installed horsepower is 2-hp or less and operating time is less than 500 hr a month.

The recommended design in the above example would be to pump 0.2 cfs with provision to return the water to both the original delivery point and the lower lying distribution ditch. The annual cost of this system will be about $2.10 per acre. This system could be used either to effect a cutback irrigation or provide a separate supply for smaller sets. The reservoir size is determined from the average runoff and should store about 15 percent runoff for a 24-hr irrigation. With an aver-

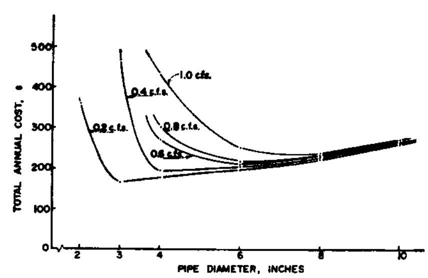

FIG. 5 Total annual cost as a function of pumping rate and pipe diameter for a 750-foot pipeline.

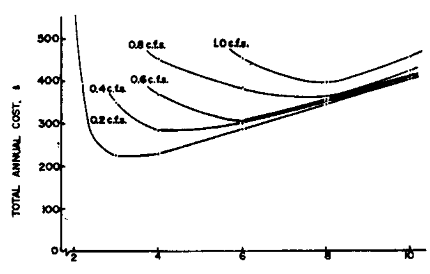

FIG. 6 Total annual cost as a function of pumping rate and pipe diameter for a 1600-foot pipeline.

age inflow of 1.0 cfs, this is approximately ⅓ ac-ft of storage. If the farmer planned his irrigation sequence so that all of the collected runoff could be used on the lower field, the pipeline cost could be reduced.

The effect of pump efficiency on system annual cost should be closely evaluated. For the example given, comparative costs were computed using 30 and 60 percent efficient pumps. To maintain the same total annual cost at a 0.4-cfs pumping rate, a 30 percent efficient pumping unit would have to be purchased at a first cost equal to only 25 percent of the 60 percent efficient pump. At a 1.0-cfs pumping rate, the extra operating cost of a 30 percent efficient unit is more than the fixed annual cost of a 60 percent efficient unit. In other words, at this pumping rate a 30 percent efficient pumping unit obtained free would still have a higher total annual cost than would the system using a 60 percent efficient pump purchased at a normal price.

Summary

Recirculating irrigation systems consisting of a runoff collecting system, storage unit, pumping installation, and return pipe are being used increasingly to reduce total water use on the farm. These systems improve irrigation efficiency in two ways: (**a**) by saving runoff and thereby decreasing overall diversion requirements, and (**b**) by providing the means of altering management practice so that deep percolation losses are reduced.

These systems can be most effective in improving irrigation practice when they are used to achieve a cutback or reduced stream flow. This allows the farmer to obtain efficient irrigation by surface methods, reusing runoff water with minimum investment and operating cost. A cutback system will return collected runoff water to the supply system at a rate calculated to give the required stream size during the advance period and as adequate stream size for a cutback stream when pumping of stored water ceases. A method for determining rates and amount of runoff and time and size of a cutback stream is presented.

After the total diversion is decreased by the amount of runoff saved, there will be only small differences in the amount of water used due to the method of handling the runoff water in the farm system. The method of using runoff water will affect the rate and amount of runoff handled and this will be reflected in the cost of owning and operating the system. Close attention should be given by designers to selection of efficient pumping units, since the total annual cost varies greatly with the efficiency of the pumping installation.

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