PHYSICAL AND OPERATIONAL IMPROVEMENTS THAT AID MODERNIZATION OF IRRIGATION DELIVERY SYSTEMS

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ABSTRACT

Because many irrigation systems throughout the world are well into the late years of their economic design life, efforts presently are toward their rehabilitation and modernization. Modernization is widely recommended over simply rehabilitating to the original status. Several goals of modernization include providing flexible water delivery service that is responsive to modern, on-farm irrigation systems, such as drip, sprinkler, level basin, and surge. To adopt many of these technologies implies that the farm unit can control the water supply by being able to start and stop the delivery at will, or at least negotiate or specify start and stop times. This often is well served by canal automation, a tool that will play a prominent role in improving the operation of delivery systems. Automation techniques are still under development and may still be prohibitively costly for many applications. However, there are a number of structural and management changes that can be considered that require only limited automation, or no automation, and can still provide significant flexibility of irrigation delivery to the farm unit. These measures include combinations of canal level-control structures, field outlet structures, strategically placed off-line reservoirs, low-cost measurement devices, and canal operating procedures. How to retrofit these useable features into an existing system as part of the rehabilitation and modernization scheme is the major emphasis of the paper. These features usually improve the convenience of irrigation applications and can encourage better irrigation efficiency.

INTRODUCTION

Many of our world irrigation systems are well into the late years of their economic design life. Project reconstruction efforts are currently emphasizing rehabilitation and modernization. Modernization (upgrading to new performance criteria) is widely recommended over simply rehabilitating to the original operating condition (Burt, et al., 1997). The possible meaning for modernization of irrigation delivery systems covers a wide spectrum, ranging from simple mechanization to full automation of system operations. The specific form that modernization activity should encompass appears to be very site-specific. The decision is based, among other things, on a combination of economic, social and educational structures.

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Most system modernization and rehabilitation projects involve canal delivery systems, and less frequently involve pipeline distribution systems. Infrequently, the project may involve changing from a canal distribution system to a pipeline distribution system. Sometimes the work will involve either a hybrid system where parts of the old project are converted to pipelines and the remaining canals are refurbished in some manner. By far the majority of projects will involve upgrading canal distribution systems without any type of conversion to pipelines.

BACKGROUND AND SCOPE

Several goals of modernization include providing flexible water delivery policies that are responsive to modern, on-farm irrigation systems, such as drip, sprinkler, level basin, and surge. The needs of these systems obviously differ. Drip systems benefit from a low delivery rate on almost a continuous basis. Sprinklers operate with medium, steady flow rates over extended periods. Level basins work well with large flow rates that may last a few minutes to a few hours. Surge irrigation systems need special variations of flow rate at the field level, but, as with most all systems, benefit from nearly constant delivery rates furnished to the farm. Serving these various farm needs simultaneously usually exceeds the capabilities of the canal delivery system.

Providing tools to projects that would enable improved delivery capability and thus the ability to offer flexible delivery policies is challenging. It usually implies that the farm unit can control the water supply by being able to start and stop the delivery at will, or at least negotiate or specify start and stop times. This in turn often requires automation of the delivery system for physical implementation. Efforts are growing to make automation economical, reliable, and practical. Canal automation is a tool that will play a prominent role in improving the operation of delivery systems. Several of these automation techniques are still under development and may still be prohibitively costly for many applications, (Clemmens, et al., 1997).

There is, however, a middle ground between simple rehabilitation and full automation. That middle ground involves the structural and operational changes that might be beneficially imposed during a partial rehabilitation that would serve the purposes of modernization. Often these changes can be economically implemented to offer immediate operational benefits and still allow further mechanization and automation. Here, mechanization is defined as the mechanical follow-through of a stimulus initiated manually. Automation, on the other hand, may use the same mechanical follow-through, but is self initiating, that is, it requires no manual initiation to function, once installed. Currently, canal automation of more than individual structures, for the most part, implies computer control.

Supporting the idea that a manual system should be capable of later automation is desirable in the reverse sense. That is, it should be operational, in some fashion, if the automation fails. The inconvenience of no planned manual backup to an automated system was brought painfully to the forefront by the failure of the Denver Airport's train that stranded thousands in the Spring of 1998. No manual backup existed, not even a pedestrian walkway. Thus, automation of an irrigation project should include planned manual operation as backup insurance. This backup will probably mean temporary reversion to a non-flexible delivery service because some delivery techniques are too difficult to do without computer control.

There are a number of structural and management changes that can be considered that require only limited automation, or no automation, and can still provide significant flexibility of irrigation delivery to the farm unit. Retrofitting these changes into an existing system as part of the rehabilitation-modernization scheme is a major emphasis of this discussion. Most of the items to be discussed are known to veteran irrigation technologists. However, the lack of general application indicates a gap between general knowledge and field practice. It is this gap that this paper also addresses.

PREPARATION FOR AUTOMATION

What to Do until Automation Arrives

Several questions come to mind. What can be done when limited funding efforts allow only small amounts of annual work? What can be done with manually operated systems when automation is not forthcoming in the immediate future? How can these changes be implemented without jeopardizing future automation? A partial list of the control concepts, structural changes, and operational changes that need addressing includes:

- Flow measurement
- Priority for flow measurements
- Control concepts
- Isolating canal subsystems
- Selection of appropriate hydraulic control for the delivery function
- Improved operating function of check structures, or cross-regulators
- Operational management of check structures
- Application of canal level-control structures
- Use of reservoir and other storage possibilities
- Sediment transport considerations

Flow Measurement

The importance of flow measurement as a means for achieving flow control in canal systems has been generally supported by irrigation technologists and was specifically documented in a case study by Palmer, et al. (1991). Instilling a local interest in the flow measurements already available appeared to have a positive effect on water control, even without new structures. That study reinforced the premise that modernization and efforts to improve water control, even before automation arrives, depends heavily on water measurement.

For canal systems, long-throated flumes have emerged as the device of choice because of their accuracy, ease of construction and related costs, flexibility in size and channel-matching shapes, and small required-head drop, which allows their use in relatively flat canals. Design and selection procedures are described in Bos, et al. (1991); Replogle, et al. (1990); and USBR (1997). Computer modeling to obtain accurate calibration equations for almost any geometric shape of a long-throated flume is given in Clemmens, et al., 1993. This includes rectangular, triangular, trapezoidal, circular, parabolic, or complex cross-sections. More recently, small rectangular flumes with adjustable throats in a variety of sizes with flow rates up to about 1 m^3/s have become commercially available (Replogle, 1998). Because water measurement is well treated by these other sources, no attempt is made here to repeat or even summerize those efforts.

Priority for Flow Measurements

For most irrigation delivery systems, management is most convenient when canals can be controlled and monitored at all desired points. This is usually impractical. Thus, priority measurement and control points should be determined. High priority is usually at the headings of all canals, but these headings also have a priority. The main canal can usually be operated to meet criteria based on maintaining a certain flow depth, (e.g., full). If a constant and known delivery is provided at the head of secondary canals, it may be practical to subdivide the flow among two or more tertiary canals and sometimes practical to subdivide on down to the farm units with sufficient accuracy. Thus, secondary canals are first priority for flow measurement. Farm deliveries are usually considered the next priority, followed by measurements at the heading of the main canal and finally at intermediate points in the main canal. Automation schemes may alter these priorities.

Control Concepts

Canal operators throughout the world use several different hydraulic procedures and concepts to operate their systems. We will review some of these operational methods in terms of hydraulic theory and accuracy. The discussion is primarily directed to canal systems where the delivery to farms is through adjustable orifice gates that may be intentionally varied from irrigation to irrigation. Although this discussion is mostly qualitative, numerical examples are presented to illustrate limitations of some concepts. Specific limitations and actual operating procedures for selected canal systems are frequently developed through experience, or by using one of the newer canal modeling techniques (Clemmens, et al., 1997).

Two general canal control concepts available to a canal operator are *upstream control* and *downstream control* (Clemmens and Replogle, 1989). These designations are based on whether for a particular control structure or gate, the upstream or the downstream flow level is used to determine a response to adjust the structure or gate. Upstream control is the method most commonly used by canal operators. Upstream control can be implemented with manual, remote, or automatic gates; with oblique weirs and duckbill weirs; or with combinations of these (Walker, 1987). Most canals contain a series of check structures that the canal operator manipulates to control the water level at specific places in the canal. Alternately, rate of flow could be used if an appropriate measuring method is available. For most deliveries through irrigation structures, maintaining the level of water also maintains the rate of flow. Canal offtakes (turnouts) to laterals or smaller canals are generally located immediately upstream from the structure and usually depend on this assumption. Downstream control is less common than upstream control because it is more difficult to implement due to the usual need to monitor and control a flow level far downstream from the supply gate.

Isolating Canal Subsystems

It is desirable to isolate and localize backwater interactions between canal subsystems, such as the farm operations on a secondary canal, and the secondary canal operations on the main canal. Passive methods to achieve hydraulic isolation of system components include reservoirs, free overfalls or critical flow devices, long-sloping canals, and high-head orifices. Among active methods of isolation are float, electronic-based, and hydraulic-based control structures.

For example, farm operations far from the head of a secondary canal may not affect the flow rate through the lateral gate, but later when operations are nearer to the gate they may sometimes back water onto the gate and reduce flow rate. A simple overfall structure placed downstream of the gate that slightly raises the water surface so that it exceeds the expected changes in the backwater from farm operations will thus stabilize the discharge rate for all operations on that farm. Figure 1 illustrates a broad-crested weir serving this purpose when it is installed between the field and the gate and causes enough overfall to absorb field operational changes. This type of weir is particularly useful because it has a high submergence limit, which means it will remain insensitive to downstream changes in water level as long as it has more than one or two cm drop in head through it for the usual farm-sized delivery. This helps stabilize the flow in the supply canal and in turns provides more constant delivery to the farm. Note that sharp-crested weirs and high head orifices can be used if a large head drop can be tolerated.

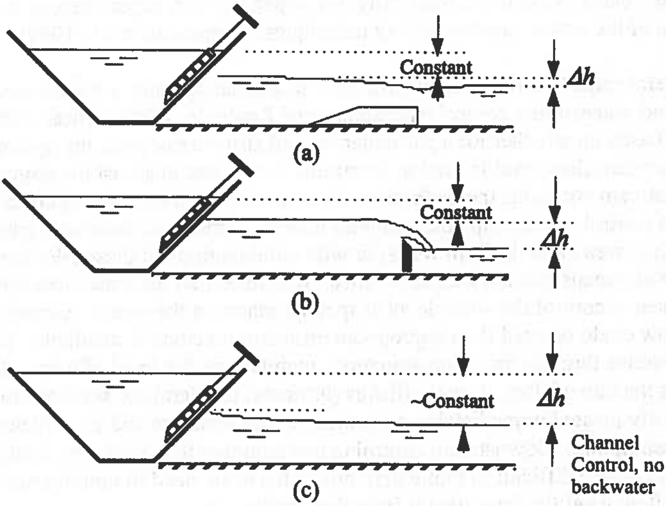


Fig. 1. A Long-throated Control Such as the Broad-crested Weir (A) Can Isolate the Small Canal from its Source Canal with Significantly Smaller Head Loss, *Δh*, than Can a Sharp-crested Weir (B) or an Orifice with a Large Differential Head (C).

Selection of Appropriate Hydraulic Control for the Delivery Function

Canal operations are greatly enhanced when the canal structure is appropriate to the needed function. In general, deliveries to secondary canals and to farms are served well with an orifice type of delivery. This takes advantage of the hydraulics of orifices and allows head fluctuations in the canal to have a small influence on the delivery rate. Structures in a canal that deliver flows further down the canal benefit by using overshot gates (Wahlin and Replogle, 1996) or duckbill weirs (Walker, 1987), to maintain a constant head on the farm delivery orifice. A discussion of the effects of overshot and undershot gates on achieving equilibrium after a change in flow at the upstream end is discussed by Strelkoff, et al., 1998.

Functions that can sometimes be combined, such as measurement and control, usually are best served by separate structures. For example, vertically moveable weirs (Bos, et al., 1991) can control a flow rate and serve to measure that rate. However, it is subject to errors caused by fluctuations in the delivery canal and is best suited to outlets from large reservoirs where the head does not change rapidly. Sometimes flow needs to be divided accurately, such as when it has been measured upstream with a flume at the heading of a secondary canal and must later be proportioned to two farmers. Proportional dividers can be fashioned from overfall or critical-depth weirs with a dividing board (Bos, 1989).

Exploiting Gate Hydraulics: Canal systems are usually operated to maintain a relatively constant level upstream from a cross-regulator, so that there is a constant differential head, Δh, on the delivery gate to the secondary canal or farm unit. Thus, the deliveries are constant. Most canal operators recognize that when the head drop, or differential head, through a rectangular slide gate remains constant for its range of opening (e.g., a free-discharging gate to a small canal from a large canal) each equal increment of gate opening, such as that caused by each revolution of the handle on a screw gate mechanism, adds approximately an equal increment to the discharge. Consider the simple orifice equation,

$$Q = C_d A_o \sqrt{2g\Delta h} \tag{1}$$

in which:

Q = Discharge rate
C_d = A discharge coefficient
A_o = Area of gate opening
g = Gravitational constant
Δh = Differential head.

If Δh remains constant, each complete revolution of the screw handle opens the gate an increment, ΔA. For each turn, the increment ΔQ is added to the discharge without the need to know the total discharge rate. In practice, if the operator knows from calibration procedures that each turn of the screw handle changes the flow by 10 l/s, then for a flow change of 60 l/s, the screw handle must be turned six revolutions to add the desired discharge increment. This same response is required whether the original opening provided 100 l/s or 1000 l/s.

Ignoring small changes in discharge coefficient, C_d, and changes in downstream head, the slide gate, under these special circumstances of constant head, responds linearly to gate opening. If the gate is submerged (backwater on the downstream face) then the gate is likely to respond nonlinearly. If the gate is not free flowing (submerged), then the flow per unit area of opening, is no longer linear. It is now a function of both gate opening and the square-root of differential head, Δh, which may vary with time and discharge.

Improved Operating Function of Check Structures

Large canals are often constructed with rather flat slopes of 0.0001 m/m. Because of their size, the velocities may still exceed 1 m/s, which is usually sufficient to transport moderate amounts of sediment. Check structures, sometimes called cross-regulators, or simply canal gates, interrupt the flow of bed load sediments, and can cause sediment aggradation. Some of the recommendations discussed here will need evaluating in terms of this problem if significant amounts of sediment must be transported.

These check structures can be sluice gates that discharge as an orifice. These and the related radial gates are sometimes referred to as *undershot* gates and their hydraulic response is that of an orifice, albeit with a variable coefficient. Other check structures include vertically adjusted leaf gates, which are basically hinged plates placed across the flow that may have a cable mechanism to lift the downstream edge. These are sometimes referred to as *overshot* gates (Wahlin and Replogle, 1996). These gates respond hydraulically as weirs, again with a variable coefficient. They can be manually operated or automated. If canal levels are to be maintained within a narrow margin, fixed structures that employ the overshot concept, such as long-crested, or duckbill, weirs, can be used (Walker, 1987).

Canal Water Level Control: Electronic-based and hydraulic-based canal water level controllers can provide constant discharge into downstream laterals from a source canal or reservoir with fluctuating flow depth. Many of these are described by Burt (1987), and by Burt and Plusquellec (1990). Float balanced gates, such as the Neyrtec Automatic gates are discussed by Goussard (1987), and the Danadian and DACL controlled-leak (hydraulic-based) controllers, by Clemmens and Replogle (1987), are specific examples of level controllers. Some level of automation can be attained by using these devices, but the response can be very slow because of hydraulic interaction between pools (Rogers and Goussard, 1998).

If a canal lateral is long enough to require several check structures then there are several ways that a canal operator can manipulate these structures. Some of these methods are best suited to "remote-monitored-and-remote-operated" techniques or to full canal automation. Others are also suited to manual control. Also, the delivery policy influences the operating procedure. For example, an arranged policy (Replogle, et al., 1980), where the flow rate and the delivery timing are negotiated between the irrigator and the delivery authority, generally allows a new flow delivery to be requested for a farm at any location from the canal head. This new flow rate must be added to the existing flow rate and passed through, or over, all intermediate check structures. Likewise, when honoring a request to stop flow at a far downstream location, the intermediate gates, as well as the head gate and the specific farm gate may need multiple adjustments.

Operational Management of Check Structures

Primary problems facing the canal operator include starting and stopping deliveries to farms along the canal without significantly interfering with deliveries to other farms, and achieving balance between the inflow into the canal and those deliveries out of the canal, because tail-end spills usually are to be avoided.

There are at least three methods of operations recognized in practice. These are:

Spilling over the gate or adjacent weirs: The lateral canals are constructed so that flows can be passed over weir walls on either side of the slide gate, or over the gate itself. In the overspill case the gate is adjusted so that a portion of the flow passes over the weirs. These overfall weirs can be oblique weirs, duckbill weirs, or when several are in parallel, labyrinth weirs.

The advantage of adjusting the gates to overspill some of the flow is that changes in demand for a downstream destination can be passed through the system with small changes in head at each gate because of the hydraulic characteristics of overspill weirs. This is illustrated later in Numerical Examples 1 and 2.

Operation at Several Centimeters Below Weir Crest: Operating below weir crest elevation is a method suited to automation or to remote operations. In this process the pools being used to make deliveries would be held as constant as practical by frequent gate adjustments, but the pools without deliveries are allowed to fluctuate to provide flow-rate buffering. It thus becomes possible to quickly start or stop a farm delivery anywhere in the entire length of the lateral. It appears practical to be able to start or stop a delivery about once every 3 or 4 hours, depending on the flow travel time for the canal. Several delivery changes, simultaneously, or in close time proximity, would be difficult to handle in this manner. Any new start or stop would require all intermediate gates to be adjusted one or more times. This may not be a problem for an automatic or remotely operated system, but would generate considerable canal-bank travel for a manually operated system. It has the advantage of being able to absorb both immediate shutoff and immediate turn-on conditions within limits of ability to absorb the storage. The system may fluctuate and require much practice for an operator to handle manually.

The pool mismatches can be corrected by changing the discharge from the lateral head at a prescribed rate. For example, it takes a flow rate increase of 10 l/s per meter of canal-surface width to raise the level of a kilometer of canal 1 cm in 1000 s (16.67 min). Thus, replacing 20 cm of water depth in a 1 km reach 3 meters wide, with a flow-rate increase of 30 l/s would require 20,000 s (5.5 hours). Conversely, 30 l/s could be drawn from the same pool for a period of 5.5 hours resulting in a drawdown of 20 cm.

Near-Spill Method: The near-spill method of operating the canal, i.e., operating the canal at nearly the brink of the weir, has been observed. The primary advantage claimed is that it allows the operator to quickly notice small changes in pool level and then make minor gate adjustments. It is possible for the operator to make an immediate start by borrowing from the full pools but does not allow immediate shutoff because the pools are already full. This method requires many gate adjustments for each flow change but does not provide for quick shutoff. Thus, it is more labor intensive than the overspill method and provides little added benefit.

Hybrid Method: The hybrid method has not been observed by the author. The hybrid method would include important canal reaches (pools with active farm deliveries) operated as over-fall pools, and reaches that have no active deliveries operated as buffering pools. Thus, the buffering pools could give up or absorb flow volume to accommodate short notice requests for either delivery or for shut-off. If enough pools exist, the shutoff at the farm and the shutoff at the head of the lateral can be separated in time far enough to allow travel of an operator between the two points. The several intermediate pools would provide the needed buffer.

When canals are steep, ponded storage is limited. Under these conditions, trying to begin or end a delivery to a farm by the operations suggested above may be difficult. Special computations have not been made to quantitatively evaluate the specific limitation for a selected canal. Qualitatively, the flow velocity in these canals is usually high and the elapsed time needed to get a flow delivered to the end of the lateral can be reasonably short, allowing relatively rapid response to requests to start or stop flows by only using upstream control concepts.

Application of Canal Level-Control Structures

Some practical considerations concerning the use of spill weirs as described above are illustrated in the following examples:

Numerical Example 1: Spill weirs might be practical when changing the overspill part of the canal discharge from about 15 l/s to 30 l/s for each meter of weir width. If we assume that these are usually concrete walls about 20 cm thick with 45°, 2.5 cm by 2.5 cm chamfered edges, then for crest depths of less than about 0.2 m, the discharge may be estimated per meter width as a broad-crested weir with a rounded nose, and as a sharp-crested weir for higher flows. The equation for unit-width discharge, q, for the lower flow range is given by Bos (1989) as

$$q = \frac{Q}{b_c} = C_d C_v \frac{2}{3}\sqrt{\frac{2}{3} g}\, h_1^{1.5} \qquad (2)$$

in which:

Q = Discharge, m^3/s

b_c = Width of weir crest, m

C_d = Discharge coefficient, assume to be approximately 0.95

C_v = Velocity Coefficient, assume to be 1.01

g = Gravitational constant, 9.8 m/s^2

h_1 = Head, referenced to elevation of the crest, m (for this example, h_1 is between 0.01 and 0.1 m)

Figure 2 shows an estimate of expected discharges throughout the broad-crested weir range and into the sharp-crested weir range (above about h_1 = 0.2 m). The upper end dashed curve is estimated using a sharp-crested weir equation and is used for freeboard estimates. Dotted vertical and horizontal lines indicate the part of the curve that is used in the Numerical Example.

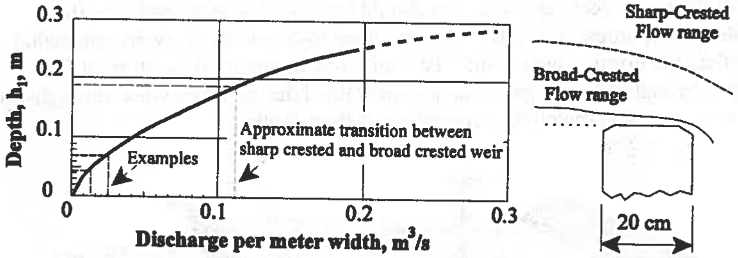


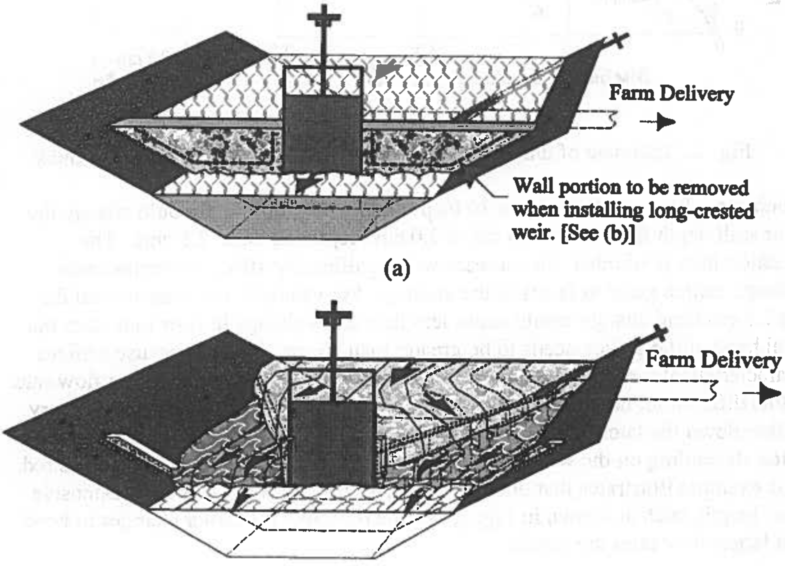
Fig. 2. Estimate of unit-width discharge rates for a weir wall 20 cm thick.

Doubling a flow rate from 15 to 30 l/s per meter of weir width would change the weir spill depth from about 4.5 cm to 7.0 cm (depth increase: 2.5 cm). The question then is whether this increase will significantly affect deliveries made through orifice gates to farms in the vicinity. For example, if it was desired that the 2.5 cm head change would cause less than a 5% change in flow rate, then the total head of the orifice needs to be greater than 25 cm. This is because orifices characteristically require 10% increase in head to cause 5% increase in a flow rate. If this differential head prevails, an effort to accommodate another farm delivery farther down the lateral can be accomplished without changes to the intermediate gates, depending on the widths of the overspill weirs and the flow change desired. This example illustrates that duckbill weirs, or oblique weirs that have extensive crest length, such as shown in Fig. 2, may be desirable if smaller changes in head and larger flow rates are needed.

Numerical Example 2: Assume that an operational goal is to have no more than 5% change in farm delivery discharge due to passing a new flow past the farm gate. Assume that multiple deliveries are in a canal with a maximum capacity of 4.0 m^3/s. What weir width would be needed to bypass another 300 l/s, if the sluice gate is adjusted to cause an overspill depth of about 1.5 cm, and the head drop through the farm gate is 20 cm? What if the over-fall depth is initially 10 cm?

The allowable head change to protect this farm delivery at the ±5% level is 10% of 20 cm, or 2 cm. Thus, the entire flow change must be passed with an increase in head from 1.5 cm to 3.5 cm. From Eq. (2) we find the increase in discharge per meter width to be about 7.7 l/s (Increasing from 3.0 l/s to 10.7 l/s). Thus, we need about 40 meters of oblique weir to accommodate these requirements. This length can be obtained as shown in Figure 3b.

If the overflow depth were initially 10 cm, again with an increase of 2 cm, the increased flow rate per meter width, by Eq. (2) is 16.3 l/s (51.7 l/s to 68.0 l/s), decreasing the required weir width to about 20 meters. This option significantly invades the canal freeboard, and thus should be carefully examined for safety considerations, unless it is deliberately planned to construct the weirs somewhat lower than the original weir walls. This might be an option if the desired flow capacity through the farm gates can be maintained during times when through-flow may be too small to match the original canal flow depth.



(a)

(b)

Fig. 3. A proposed modification to a canal check structure (a) to incorporate a long-crested weir, as in (b). The bypass weirs on either side of the gate are cut out and long weir crests are built at a diagonal upstream. Part of the flow is still passed under the original gate structure. New weir crests are made the same height, or slightly lower, than original crests.

This example illustrates some of the design parameters that may be considered to select options that may not otherwise produce desired results except through automation. Figure 3 shows one option of installing long oblique weirs in an existing canal. Each of the two oblique weirs would be 9.5 meters long, if we choose the deeper overfall-depth option of the above example. The cut-out notches made in the original cross wall need to pass about 625 l/s each (65.9 l/s per meter, 9.5 meters long). This would require each notch to be about 1 m wide and 0.5 m deep. Vertical free fall clearances for the diagonal-weir overfalls of about 2 cm to 5 cm should be added to this cut-out depth. Backwater from downstream structures may control the shape and amount of cut-out needed. Except for considerations of structural integrity, over sizing of the cut-out has no special consequence.

Use of Modified Gates for Canal Operations: Freeboard is frequently specified as 20% of maximum canal flow depth for sub-critical velocities. For a canal that flows 1 m deep, the constructed freeboard would likely be 20 cm. In the above example one option was to increase the flow depth over the weir from 10 cm to 12 cm. This would leave only 8 cm of freeboard, unless the weir crest is moved down. With no lowering, and because the depth is controlled by something as assured as a weir overfall, calculations of the increase in discharge needed to overflow the canal sidewalls would show that at 20 cm of head, the discharge is about 146 l/s per meter width, a total overspill of 2.9 m^3/s, plus any flow through the sluice gate. This is more than two times the flow rate used in the example. A major concern would be that the sluice gate is closed and the canal is presented with a flow of over 2.9 m^3/s to pass. Assuming a canal flowing 1.0 m deep 1:1.5 side slopes, and 1.0 m bottom width, the velocity would be about 1.16 m/s, representing a Froude Number of 0.47. By compromising, and moving the weir crest down half of the overflow depth, or 6 cm, we now can pass a depth of 26 cm, 217 l/s per meter width, or about 4.3 m^3/s, (velocity of 1.7 m/s, with a Froude Number of 0.7). Even though this is near, or in, the unstable region of canal Froude Numbers, it is not likely to occur except possibly for storm flooding.

Thus, a downstream delivery would involve opening the supply gate a prescribed amount, leave intermediate gates alone, and at an appropriate delay for flow travel time, open the gate at the downstream point of delivery. Shut-down would likewise involve closing the supply gate a prescribed amount and after a time delay, close the delivery gate at the farm.

Note that the entire process is upstream controlled and that the farm location in the system determines the time delay. This delay is also a function of total canal flow rate. There is no place near the delivery point to store an emergency shutoff. Emergencies will usually produce an operational spill. For manual operation by a ditch rider, this procedure requires at least one trip from the head gate to the delivery point for each change in flow rate (on or off), but would not require stopping at each gate along the way.

Use of Reservoir and Other Storage Possibilities

Main Canals as Buffer Reservoirs: When lateral canal inflows are automatically controlled, it is feasible to operate the main canal as an extension of the source reservoir. Due to the possibility of trapping water behind canal linings that can cause canal lining failure when the canal is rapidly emptied, most large canals are operated to decrease flow depth by less than 2 cm per hour, but they can be safely filled more rapidly. This change in storage capacity can often be used in lieu of off-line reservoirs. Additional check structures can often increase this reservoir storage. This storage can then facilitate manual operation and enhance future automation when it arrives.

Strategically Placed Reservoirs: Reservoirs can be strategically placed within the system to buffer operational flow mismatches (Marum and Styles, 1997). Usually these reservoirs should be close to the end of the project, but still command enough area to use collected flows. In areas of the world where night irrigation is not desired, these reservoirs would be more numerous and would collect enough flow overnight to irrigate the command area during daylight hours. Farm reservoirs can be used to collect the water delivered by a rigid supply schedule, and then the water can be regulated according to farm needs. An alternative is to place the regulating reservoir further upstream on the canal system, e.g., at the head of a secondary canal, which would isolate this canal and its several users from the rest of the larger system. While installing critical-depth, flow-measuring devices (weirs, flumes) at the head of secondary canals or downstream of all offtake gates on farm canals, can provide sufficient free overfall to isolate the source canal from the receiving canal, they only isolate flow influences in one direction. Automatic gates are particularly useful for maintaining rates at the headings of secondary canals (Clemmens and Replogle, 1987).

Sediment Transport Considerations

Lined canals with a water source from a reservoir usually do not have significant sediment problems. Direct diversions from rivers often have heavy sediment loads that usually are passed down to the farm. Flow control structures usually cause severe maintenance problems for these canals. Before changes are implemented, sediment handling considerations must be addressed.

CONCLUSIONS

Canal rehabilitation and modernization are usually done by a massive reconstruction effort. However, there is merit to including modernization as part of an annual maintenance program. Some of the things that can be accomplished include adding more check structures to shorten canal reaches, adding flow measuring flumes at the heading of each secondary canal, and changing gate handling operations to provide more equitable deliveries to farms far from the main canal. Automation of an irrigation project should include planned manual operation as backup insurance.

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