

# Water Operation and Maintenance Bulletin

No. 233





# In This Issue . .

Canal Water Surface Drawdown - Criteria and Concerns

Concrete Crack Repair and Deck Sealing at the Durango Pumping Plant

Modern Methods for Canal Operation and Control



U.S. Department of the Interior Bureau of Reclamation

This *Water Operation and Maintenance Bulletin* is published quarterly for the benefit of water supply system operators. Its principal purpose is to serve as a medium to exchange information for use by Bureau of Reclamation personnel and water user groups in operating and maintaining project facilities.

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**Cover photograph:** (top) Typical soil saturation behind canal lining. (bottom) Adverse hydrostatic pressure following rapid drawdown.

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# CONTENTS

Page

Canal Water Surface Drawdown – Criteria and Concerns1
Concrete Crack Repair and Deck Sealing at the Durango Pumping Plant5
Modern Methods for Canal Operation and Control

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# CANAL WATER SURFACE DRAWDOWN – CRITERIA AND CONCERNS

by: Darrel Krause and Jim Keith, Program Analysts, Bureau of Reclamation, Maintenance Services Office, 84-57000

# Introduction

For normal, abnormal, and emergency canal water surface drawdowns, the rate of reducing the water level should be given special attention. When reduced at recommended rates, generally the operation is safe, and no impacts are evident to the canal lining. However, during canal incidents or emergency situations, where the canal water surface needs to be reduced more rapidly, damage to the lining system can be a real concern. During such a drawdown, there exists an unbalance in the forces (lower canal water surface inside the canal prism versus saturated soil behind the lining system), resulting in an adverse hydrostatic pressure against the lining system that can result in buckling or other related damage.

Typically, a canal water surface drawdown criteria of 0.5 foot during any 1-hour period and 1 foot during any 24-hour period is recommended as cited in the Bureau of Reclamation's (Reclamation) *Canal Systems Automation Manual* (see excerpt below–pages 47 and 48 of this manual.) These drawdown rates, in most cases, are acceptable for concrete-lined, earth-lined, and membrane-lined canals. Additionally, if available, the canal's Standing Operating Procedures (SOP) or Designers' Operating Criteria (DOC) may specify the drawdown criteria.

For abnormal and emergency operations, which occur infrequently, this predetermined normal drawdown criteria can be relaxed based on engineering judgment. Following any such rapid drawdowns, it is highly recommended that additional monitoring/surveillance and future inspections be conducted on these canals to note any areas of cracking, buckling, sliding, or other signs of movement and the need for remedial measures.

# **Excerpt – Canal Systems Automation Manual**

"Drawdown is the rate of depth reduction at any point in the canal. Drawdown criteria are one of the most restrictive constraints upon canal operation. Rapid increases in water depth are seldom a problem—unless the maximum depth is exceeded. However, rapid decreases can damage the canal even when depths remain within an acceptable range.

### Water Operation and Maintenance Bulletin

Damage will result if hydrostatic forces underneath or behind the canal lining material exceed those forces on the inside of the lining by a large enough magnitude. The difference in hydrostatic pressure required to damage any particular canal is a function of the strength and weight of the lining material and the shape of the canal prism. Sufficient force on the lining's backside will cause buckling, cracking, and bulges in the lining.

Whenever canal embankment soil is saturated with water, hydrostatic pressure will be exerted on the backside of the canal lining. The elevation of saturated soil (called the phreatic line) often will be slightly below the canal water level as shown on Figure 1. The amount of canal embankment saturation varies with the porosity of the canal lining and the permeability of the embankment material. Sometimes, drains are placed behind the canal lining to remove water from the soil and reduce the back pressure. The embankment hydrostatic pressure will vary from one point to another along the canal length, but normally the canal's internal water pressure will be greater than or equal to the back pressure.



Figure 1.—Typical soil saturation behind canal lining.

When the canal lining is relatively impervious and soil behind the lining drains slowly, the water level in the soil will not drop rapidly. If the canal water level is reduced faster than the embankment saturation level, then the net hydrostatic pressure on the lining becomes adverse as shown on Figure 2. The weight and strength of the lining will withstand only a limited amount of adverse pressure before it is damaged.

A maximum acceptable drawdown rate should be established for each canal. Typical drawdown rates permitted in Reclamation concrete-lined canals having 1.5:1 side slopes (horizontal:vertical) are 0.5 foot (150 millimeters [mm]) during any hour and 1 foot (300 mm) during any 24-hour period. These rates are acceptable in most cases for earth-lined and membrane-lined canals. In many instances, higher drawdown rates may prove to be acceptable during operations. More rapid drawdown may be satisfactory in unlined canals, in areas of



Figure 2.—Adverse hydrostatic pressure following rapid drawdown.

well-drained soil, in sections built on fill, and in canals with heavy lining or having drains behind the lining. Usually, the normal drawdown criteria are relaxed for abnormal and emergency operations, which occur infrequently."



# CONCRETE CRACK REPAIR AND DECK SEALING AT THE DURANGO PUMPING PLANT

*by: Rick Pepin, Materials Engineering Technician, Bureau of Reclamation, Materials Engineering and Research Laboratory Group, 86-68180* 

The Animas-La Plata water project included the construction of 280-cubic-footper-second (7.9 cubic meters per second) pumping plant on the Animas River just south of downtown Durango, Colorado, and an underground pipeline to carry water from the pumping plant to an off-stream reservoir, Lake Nighthorse, at Ridges Basin Dam, which is southwest of Durango.

Construction of the pumping plant took approximately 5 years with state-of-theart design and construction practices to monitor, examine, and build the plant. However, even with these programs implemented, construction flaws did occur in the pumping plant concrete deck, which covers some of the pumping plant's electrical control system and computers. Leaks in the deck have been a constant maintenance headache.

An ongoing strategy was developed that uses crack injection with chemical grout and epoxies. This injection process has been used since 2010 and has sealed some of the larger cracks in the concrete, stopping or slowing the water infiltration into the pumping plant.

It was decided in 2012 that an overall sealing of the deck would be beneficial in reducing water migration through smaller cracks in the concrete.



The Bureau of Reclamation's Denver Office, Technical Service Center – Materials Engineering and Research Laboratory (MERL), were asked to conduct the 2012 deck sealing operation. The total cost, including material and 5 days of the crew's time, came to approximately \$40,000.

Four people from the MERL Laboratory traveled to the Durango Pumping

Plant in August 2012 and set up the injections for the few remaining larger cracks that were not completed in previous crack-sealing efforts. Injection ports were used to access the concrete cracks below the top surfaces, and the injected expansive chemical grouts filled and sealed the large cracks.



Once the crack sealing had taken place, surface imperfections were removed by grinding, and the surface was cleaned for the next phase of the project.

By applying sealers, the permeability of the concrete is reduced by up to one order of magnitude. The permeability of concrete is one of the most important factors that will affect the rate of water migration, steel reinforcement corrosion, carbonation, the effects of freeze-thaw cycles, and the overall deterioration of the concrete. The deck was sealed with a type 2b modified epoxy healer/sealer and broadcast quartz sand for slip resistance.

The first consideration with any application is surface preparation. The substrate must be clean and dry as well as free of any grease, oil, dirt, or other contaminants. The texture of the surface should be similar to medium sandpaper, which is best achieved by shot blasting or sandblasting the concrete surfaces.

When applying an epoxy healer/sealer with a broadcast system, it is important to ensure that the surface is smooth and that all the large cracks and irregularities are patched. The Technical Service Center (TSC) crew started preparing the

5,400-square-foot concrete deck by blowing down the surfaces with compressed air to remove dirt and dust. Areas that were contaminated with oil or grease were treated with a solvent, and then it was soaked up with clean rags.

The next step was to use a shot blaster to remove the weak surface layer, or latencies, to open the pore structure of the concrete so that the sealer would



penetrate more easily. The shot blaster had a vacuum recovery system to reduce dusting and to recycle the shot blast medium. Shot blasting took approximately  $1\frac{1}{2}$  days. Any loose steel shot was picked up with a magnet and reused.

Atmospheric conditions can have some effect on the results. Application of the epoxy healer/sealer in directs sunlight or while temperatures are rising can cause pinholes and blisters from outgassing of the concrete. The air in the porous concrete expands during these periods and escapes, potentially causing the blisters or pinholes in the epoxy. The TSC crew applied the epoxy sealers early in the morning and in the late summer to reduce heat buildup and to lessen the chances of pinholes and blisters.

### Water Operation and Maintenance Bulletin

The application of the first modified epoxy healer/sealer coat and broadcast sand took 1 full day. The epoxy healer/sealer is a two-component modified epoxy that is mixed at a 1:1 ratio. Once mixed, it is poured over the application area and then spread over the surface with rubber squeegees, working the material back and forth over cracks to ensure proper filling and coverage. It was important to spread the material to ensure no ponding occurred. In total, approximately 26 gallons of material were applied to the concrete deck area for the first coat. There were areas where the concrete absorbed a great deal resin in a relatively short period of time, and the surface would appear dry. Where this was observed, resin was applied until refusal.



Once the first layer of applied epoxy healer/sealer became tacky, approximately 20 minutes after mixing, a single layer of quartz sand was broadcast over the treated area. Spreading initially was begun with the use of an abrasive blasting pot and hose, but it was found to be too slow, and the coverage was spotty. The switch to drop spreaders allowed ten 100-pound bags of quartz sand to be applied to refusal in a relatively short period of time with very good coverage. The sand was hand applied to hard-to-get-to corners and edges. The sand layer is necessary to protect the modified epoxy healer/sealer from sunlight (UV) degradation and to provide a slip-resistant surface.

The next day, the crew removed approximately 20 pounds of loose sand using a mechanical sweeper. This sand was recycled for the second coat. The crew

### Water Operation and Maintenance Bulletin



began application of the second epoxy healer/sealer coat the following day after the loose sand was cleaned up. Due to the increase in surfaces area created by the application of the quartz sand, a large volume of epoxy, approximately 118 gallons, was needed. Just as with the first coat, once the epoxy became tacky, twenty 100-pound bags of sand was broadcast onto the concrete surface. A total of 144 gallons of epoxy healer/sealer and 3,000 pounds of quartz sand were applied to the concrete deck surface.



Late that afternoon as things were winding down for the day, a thunderstorm graced us with a downpour; fortunately, the epoxy sealer was set, and the rain did not damage or affect the epoxy sealer in any way. The next day, activities included sweeping up 40 pounds of loose sand and disposing of it. The crew performed full site cleanup, and the trucks were packed for the trip back to Denver.

The crack injection and deck sealing will reduce or eliminate the water migration through the concrete deck for years to come.



The finished product after an afternoon thunderstorm – watertight.

**Note**: Since 1946, the MERL has used its capabilities and expertise to inspect and evaluate concrete structures for different degradation mechanisms. Our experience with concrete structures is unique, and we provide a wide variety of services, including troubleshooting construction problems, specification preparations and review, material approvals, onsite inspections, concrete repairs, chemical grouting and other field services, expertise in state-of-the-art construction materials and practices, research on material problems, and training.

# MODERN METHODS FOR CANAL OPERATION AND CONTROL

*by: Tony Wahl, Hydraulic Engineer, Bureau of Reclamation, Hydraulic Investigations and Laboratory Services, 86-68460* 

# Acknowledgments

These course notes are borrowed from a previous set of notes compiled for previous years of this workshop by Dave Rogers and Eric Urban.

# Introduction

In recent years, improved operation of water storage and conveyance systems has become an increasingly important and attainable goal. Enhanced canal operation will improve service to water users, conserve water through increased efficiency, reduce operation and maintenance costs, increase delivery flexibility, and provide more responsive reaction to emergencies.

In years past, water use studies showed that an average of only 44 percent of the water delivered to irrigators' fields on Bureau of Reclamation projects was stored in the root zone for beneficial consumptive use by crops. However, the application of modern technology is beginning to increase irrigation efficiency dramatically and improve canal system management. Improved operation will increase crop yields and make more water available for municipal, industrial, and recreational uses. Therefore, the operation, control, and automation of canal systems are an important topic for today's planners, designers, operators, and managers of irrigation water projects.

Because modern irrigation practices strain the capabilities of conventional canal operating methods, new principles of water distribution, application, and scheduling are being developed and implemented. Canal systems need to respond quickly with greater flexibility to achieve optimum water transfer efficiency [1].

These session notes are divided into two parts. Part I: Canal System Operation and Control deals with general concepts for managing the flow and distribution of water in irrigation water delivery systems. Logically, system operation and control should be addressed early in the modernization process. Part II: Data Collection Sensors contains information on instrumentation for measuring water level and gate position, which are key elements in a modernization effort. Additional information can be found in Reclamation's publication *Canal Systems Automation Manual, Volumes 1 and 2* (references [1] and [2] in the Bibliography) and in the information provided with sessions on Flow Measurement.

# Part 1 CANAL SYSTEM OPERATION AND CONTROL

# Canal System Operation and Control Operation Fundamentals

# **Principles of Operation**

# Definition

The canal system operation transfers water from its source(s) to one or more points of diversion downstream. Operations deal with the movement and behavior of water in a canal system and are dependent on the principles of open channel hydraulics. The primary function of operation is to manage the changes in flow and depth throughout the canal system. The term, "operation," refers to the hydraulic reaction in the canal pools which results from control actions.

# **Objectives**

Basically, canal systems are built for the purpose of conveying water from one place to another. The most prevalent reason for water transfer is to irrigate farmlands, with the objective of helping farmers increase crop yields. Canals also convey water for (1) municipal and industrial (M&I) use, (2) storm and snowmelt runoff to natural drainage channels, (3) collecting water from several independent sources into a single supply, (4) electrical power generation, (5) fish and wildlife, and (6) recreation.

The objective of building and operating a canal system is to serve the above purposes as efficiently and economically as possible. To do this, canal operations should be tailored for each canal system to meet that system's specific requirements. But the requirements imposed on canal systems are steadily becoming more complex. Modern irrigation practices require greater delivery flexibility and increased efficiency. The higher cost of water, power, and construction decreases the feasibility of wasting water from canals or building oversized canals to obtain additional in-channel storage. The use of intermediate storage and wasteways may be restricted by environmental concerns. Because of these and other factors, canal systems need to respond quickly to flow changes. Overall canal operations must be improved to provide this capability.

Canal system automation should not be thought of as an end, but rather as a means to accomplish the desired canal system operations. The true goal should be to achieve the most efficient and beneficial operation possible. Modernization through expanded control system capabilities is one of the best methods to economically reach this goal.

# **Balanced Pool Operation**

The length of canal between check structures is called a canal pool. Occasionally, an in-line pumping plant may serve as a pool boundary instead of a check structure. When total flow out of the canal pool equals total inflow, the pool operation is balanced. Referring to figure 1, a balanced pool operation exists when:

$$QC1 = QTO1 + QC2$$

where:

QC1 is the pool inflow QTO1 is the turnout deliveries from the pool QC2 is the outflow at the pool's downstream end



Figure 1.—Balanced pool operation.

# **Conventional Operation**

Traditionally, canals have been sized to convey the maximum design flow, with freeboard added as a safety factor against excess water depths. Canals of this design usually have been operated in the "conventional" manner. Figure 2 illustrates some of the characteristics of conventional operations.

An important characteristic of conventional operation is the attempt to maintain a constant water depth at the upstream side of each check structure. When flow changes occur, the water surface profile within each canal pool essentially pivots about this constant depth at the downstream end of the pool. Conventional operation has had such widespread use for so many years because (1) construction costs can be minimized by sizing the canal prism only large enough to convey the maximum steady flow, and (2) canal system operation can be successfully accomplished using local manual control. Most Reclamation canals were designed for conventional operation.



Figure 2.—Conventional canal operation.

# Supply and Demand

Canal operation concepts are based on whether the water schedule priorities are supply or demand oriented. Supply refers to the quantity of water that is available or being provided from an upstream source. The upstream operational concept applies to canal systems that are primarily supply-oriented. A supply-oriented system, therefore, must be operated to satisfy upstream requirements. One example of this is a storm drainage system.

Demand refers to water needed or being delivered at points downstream in the canal system. The downstream operational concept applies to canal systems that are primarily demand-oriented. These systems must respond to downstream conditions, and the water supplied from upstream is a function of downstream demand. A municipal water system is an example of a demand-oriented system. Water users at downstream ends of the system take water without restriction, and the operation responds only to downstream conditions.

# **Prediction Versus Reaction**

Some canal systems only react to circumstances after they happen, while others are operated by anticipating situations in advance by predicting the future demands on the system. Automatic controls are purely reactive, responding to present or past information. However, prediction often is used in manually controlled systems to enhance the operation; it also can be used in automated systems which include manual input.

The more common application of canal operation using prediction is in scheduled delivery. Operations scheduling is based upon water orders being turned in by

water users in advance to the actual delivery. Anticipation also can be based on historical data, daily or weekly trends, meteorological information, or agricultural data such as soil moisture content.

The downstream operational concept applies to canal systems that are primarily demand-oriented. These systems must respond to downstream conditions, and the water supplied from upstream is a function of downstream demand. A municipal water system is an example of a demand-oriented system. Water users at downstream ends of the system take water without restriction, and the operation responds only to downstream conditions.

# **Canal Systems**

A canal system can be classified according to its principal objectives as a delivery system, collector system, or connector system. Certain characteristics of each of these types of canal systems will affect operations. In addition to the different priorities associated with supply and demand, physical differences exist which needs to be considered. The typical irrigation system is a delivery system and is discussed below.

A delivery system has a large capacity at the upstream end and gradually decreases to a small capacity at the downstream end—sometimes branching into successively smaller lateral canals. Water is turned out at various points along the length of the canal as it tapers to the final turnouts at the extreme end(s). This decrease in capacity amplifies the effects of a flow mismatch as it moves downstream.

For example, consider a canal having a 20-cubic-meters-per-second  $(m^3/s)$  capacity at the upstream end which tapers to a 4-m3/s capacity in the downstream pools. If a 1-m<sup>3</sup>/s mismatch in flow occurs at the upstream end, this is only a 5-percent error. This amount of error may be normal and acceptable without creating significant problems in the upper pools. But as the 1-m<sup>3</sup>/s mismatch is passed downstream, it will become significant in the downstream pools, where it will be a 25-percent flow error.

Water users at the downstream end of delivery systems, referred to as "tailenders," often will suffer from too much or too little water. Surplus water must normally be supplied at the headworks to prevent water shortages to tail-enders. Oftentimes, the surplus is wasted at the downstream end of the system. Typical waste in a conventionally operated canal system is about 5 to 10 percent of the total inflow [3].

# Water Schedule

The water schedule for a canal system is the flow versus time relationship. This can range from nearly constant flow—for a canal with little flow change—to a complex schedule of flow rates that change frequently at numerous points throughout a large canal system. Every canal has a water schedule, but a variety of ways to predict, create, and implement the schedule exist [4, 5, 6]. Usually, the water schedule is predicted or arranged in advance and then adjusted during implementation. The flexibility to adjust the water schedule can vary widely from one canal to the next.

Schedules often are addressed in conjunction with delivery. Delivery refers to release of water from the canal system to the water user. Usually, this release occurs at some type of turnout structure. A delivery schedule is the quantity of water to be transferred to a user, as a function of time. Scheduled delivery is the primary type of delivery concept used for Bureau canals. Rotation and demand delivery systems also exist in the United States. Delivery concepts are discussed later in these notes.

# Water Transfer Procedure

In a conventional canal system, the ditchrider adjusts the check gates to satisfy the water schedule. First, the ditchrider must determine the new canal check gate openings required for the flow changes. An experienced ditchrider is able to predict the relationship between gate opening and flow with reasonable accuracy. Usually, the ditchrider begins to implement the new water schedule in the early morning by changing the flow at the head of the reach. The headgate opening is adjusted to obtain the new total flow, QC1. Then, the ditchrider follows the flow change downstream to make the required adjustments at canalside turnouts and the successive check gates sequentially.

The check gates usually are adjusted to maintain a desired depth on the upstream side of the check structure. This is the upstream control concept. This helps to achieve steady flows through gravity turnouts which are located just upstream of the check structure. As the flow change progresses downstream through each canal pool, the ditchrider will attempt to achieve a balanced pool operation.

Figure 3 shows a flow increase progressing downstream through the pool. When the flow change reaches the turnout, the turnout flow will be adjusted to the scheduled value. The remaining portion of the flow change will proceed past the turnout to the next downstream check gate, Check n+1.



Figure 3.—Flow increase progressing downstream.

When the flow change arrives at Check n+1, the check gate opening is adjusted to transfer the flow mismatch (between the upstream canal pool inflow and turnout outflow) into the next downstream canal pool. If Check n+1 is adjusted properly, pool inflow and outflow will be balanced and the Check n+1 upstream depth, Yu, will remain relatively constant. A new steady-state flow is established as shown in figure 4.



Figure 4.—Downstream gate adjustment to transfer flow change.

The sequence for making flow changes and balancing the canal pool operations then continues downstream until all turnout flow changes have been made according to the water schedule. To manually correct flow imbalances with just a single gate adjustment at each check structure is difficult. Realistically, regulation is more difficult than it appears in this idealized example. Hence, only one trip down the canal by the ditchrider is often insufficient. Typically, subsequent gate adjustments are required to balance flow conditions. The above procedure is one example to illustrate some of the details in transferring water through a canal system. It is a typical procedure for many conventionally operated canals. Other water transfer procedures will be used for canal systems that are operated and controlled by different methods.

# **Canal Hydraulics**

# Flow Types

Depending upon how the flow depth in a canal changes with respect to distance and time, the flow can be classified into several different types.

- Changes with respect to distance are referred to as varied flow.
  - Gradually varied flow, if the depth changes gradually over a long distance.
  - Rapidly varied flow, if depth changes are abrupt over a short distance.
- Changes with respect to time are referred to as unsteady flow.
- If the depth does not change with time, the flow is steady (steady-state).

All flow types can be summarized as follows [7]:

Steady Flow

- Uniform flow
- Varied flow
  - o Gradually varied
  - o Rapidly varied

Unsteady Flow

- Uniform flow
- Varied flow
  - Gradually varied
  - Rapidly varied

These flow types are described in more detail in the *Canal Systems Automation Manual* [1, 2].

Steady, uniform flow is characterized by a constant depth in each pool. The condition exists at maximum design flow with all check gates wide open. Steady

uniform flow is also called flow at *normal* depth. With steady uniform flow, the friction force on the sides and bottom of the canal prism is exactly balanced by the component of force due to gravity acting in the direction of flow. The normal depth in a canal depends upon the flow boundary roughness, canal geometry, and flow rate. For a given roughness and geometry, the normal depth in a canal pool can be determined as a function of flow as shown on figure 5. Usually, the design normal depth determines the target operating depth of a canal.

Unsteady, gradually varied flow results from flow changes. For example, a gate movement produces changes in flow and in adjacent depths as shown on figure 6. A flow change that is initiated by changing the check gate opening takes the form of traveling translatory waves. A translatory wave is a gravity wave that propagates in an open channel and results in displacement of water particles in a direction parallel to the flow [7].



Figure 5.–Normal depth relationship in a canal.



Figure 6.—Flow change due to gate movement.

For example, if a check gate is opened a small increment, as shown on figure 6, flow into the downstream canal pool will increase, generating a positive translatory wave which will travel downstream. Simultaneously, a negative translatory wave is generated upstream of the check gate; this wave travels upstream. Translatory waves also are generated when the check gate closes.

However, in this case, a negative translatory wave progresses in the downstream direction and a positive wave progresses upstream. Figure 7 is a schematic of a translatory wave profile.



Figure 7.—Translatory wave profile.

The amplitude (height) of the translatory waves is a function of the magnitude of flow change and canal prism geometry. Friction forces will attenuate or decrease the height of the wave front as the wave transverses the entire canal pool. Theoretically, the translatory wave has the following features:

- The successive positions of the wave front at different times are parallel.
- The wave velocity, or *celerity*, is greater than the mean water velocity.
- The wave configuration travels at a constant velocity, but the mean water velocity may vary from section to section.

The translatory wave velocity is:

$$Vw = \frac{Qu - Qd}{Au - Ad}$$

where:

a
area

From a practical viewpoint, the translatory wave changes shape because the wave's leading edge travels at a velocity that is also a function of the canal prism geometry. The velocity of the leading edge of the wave front is given by:

$$Vl = Vm \pm C$$

where:

Vl	=	velocity of leading edge of wave
Vm	=	mean flow velocity = $Q/A$
Q	=	flow rate
А	=	canal prism cross sectional area
С	=	wave celerity = $(gD)^{1/2}$
g	=	gravitational constant
D	=	hydraulic depth = $A/T$
Т	=	wetted prism top width

A positive sign is associated with waves moving downstream and a negative sign with waves moving upstream. The leading edge of the translatory wave travels much faster than the final wave velocity. Depending upon the value of the hydraulic depth, the wave velocity may be as much as 10 times the mean water velocity.

The velocity of the translatory wave is an important operating criteria; it determines when the effects of a flow change at one point in a canal will reach other points. For instance, a common assumption is that a flow increase (at a canal headwork) will travel downstream at the flow velocity in the canal, and that flow increases at canal-side turnouts cannot be accomplished until this additional water arrives. In reality, flow will begin to increase at points downstream as soon as the leading edge of the translatory wave front arrives, which is much sooner than would be predicted from the average flow velocity in the canal.

The water surface behind the translatory wave slowly approaches the steady, gradually varied flow profile. The amount of time required to fully achieve the steady profile is a function of initial and final flows, channel properties, check structure spacing, and initial and final water depths.

# **Canal Storage Considerations**

As noted previously, the velocity of translatory waves is a function of canal water depth. Thus, operation of a canal system is enhanced when water depths are maximized. A more important consideration, however, is the change in storage relative to the change in canal flow. With a relatively small backwater effect in a canal, the difference between water surface profiles for different flows is almost rectangular as shown on figure 8. The shaded area shows the volume of water that must be added to increase the flow from one steady-state flow to another. A negligible backwater effect condition exists when the control structure spacing is large relative to the channel slope.



Figure 8.—Storage with negligible backwater effect.

By increasing the number of check structures, backwater effect causes the difference between water surface profiles to become wedges which are nearly triangular. Figure 9 shows how this can greatly reduce the storage volume between two different flow rates.



Figure 9.—Wedge storage effect.

In examining wedge storage, it is evident that check gate spacing has a significant effect on the volume of water required to change to a new water surface profile. Doubling the number of check structures in a canal will approximately halve the volume change needed to establish a new steady-state flow. This can be seen, on figure 10, where the shaded area represents the reduction in wedge storage that would result from placing a check structure in the middle of a pool.



Figure 10 – Effect of added check structure.

When flow at a canal headwork is changed, the time needed for the associated translatory wave front to reach any given point in the canal downstream can be determined from wave speed. However, steady state will take longer to achieve. The time required for a new steady state flow to be established can be estimated as:

$$Ts = \frac{\delta V}{\delta O}$$

where:

Ts	=	time to achieve new steady-state flow
δV	=	change in storage volume between previous steady-state
		and new steady-state conditions
δQ	=	change in flow

Therefore, flow changes can be accomplished more quickly when check structure spacing; and, hence, the wedge storage volume is reduced.

# **Methods of Operation**

# **Pool Operation Alternatives**

Several methods are available which can be used to convey water downstream through a series of canal pools. The method of operation—sometimes referred to as method of pool operation—determines how the water level varies in a canal pool to satisfy the operational concept. The method of operation is tied closely to the check gate operating technique being used.

The method of operation is based on the location of the canal pool water surface pivot point. The pivot point is the location within a canal pool where the depth remains constant while the water surface slope varies. The methods of operation are:

- **Constant downstream depth**—The pivot point is located at the downstream end of the canal pool (figure 11-a).
- **Constant upstream depth**—The pivot point is located at the upstream end of the canal pool (figure 11-b).
- **Constant volume**—The pivot point is located near the midpoint of the pool (figure 11-c).
- **Controlled volume**—The pivot point can move within the canal pool (figure 11-d).



Figure 11.—Methods of operation.

The basic method of operation should be identified for a canal system before control alternatives are evaluated. The location of the pivot point is particularly important when selecting a control method; i.e., local manual, local automatic, or supervisory control.

# **Constant Downstream Depth**

Constant downstream depth method of operation—where the water depth at the downstream end of each canal pool remains relatively constant—is used in most canal systems. This method is associated with "conventional" operations and with local manual control. The primary reason why this method is so prevalent is that a canal can be sized to convey the maximum steady flow; steady-state water depths should never exceed the normal depth for the design flow rate. The canal prism size and the freeboard can be kept to a minimum—reducing construction costs.

With a constant downstream depth, major turnouts usually are located near the downstream end of the canal pools. This allows turnouts to be designed for a maximum and relatively constant depth in the canal; this also prevents problems in water delivery to users caused by low or fluctuating water depths.

Wasteways, if any, also will be located at the downstream end of pools. Sidechannel spillways and overflow weirs in the check structures can be set slightly above the maximum normal depth to prevent excessive depths.

When a constant depth is maintained at the downstream end of canal pools, the water surface profile will essentially pivot about this point as the canal flow changes (see figure 11-a). A storage wedge between different steady-state flow profiles is created. When flow increases, the water surface gradient and the storage volume must also increase. Conversely, storage volume must decrease for a reduction in steady-state flow.

Because of these storage considerations, the constant downstream depth method of operation is particularly effective when combined with the upstream operational concept (supply-oriented operation). A natural tendency exists for a flow change that originates at the upstream end of a pool to create the change in storage that is needed to keep the downstream pool depth constant.

Figure 12 shows how a flow change at the upstream end of a pool causes the pool storage to change in a manner compatible with the constant downstream depth method of operation. When pool inflow increases (figure 12-a), an additional volume of water enters the pool. This additional volume supplies the increase in storage required to achieve the higher surface gradient (figure 12-b). When the inflow decreases (figure 12-c), pool outflow will temporarily exceed pool inflow. This will cause a decrease in pool volume, as required to lower the water surface to the desired final steady-state flow profile (figure 12-d).



Figure 12.—Upstream flow change with the constant downstream depth method of operation.

Constant downstream depth method of operation has disadvantages, when combined with the downstream operational concept (demand-oriented operation), because pool storage must change oppositely to the natural tendency. As shown on figure 13, a flow change from the downstream end of a pool causes the depth to change in the wrong direction. When a decrease in pool outflow occurs (figure 13-a), the tendency is for pool storage to increase. To pivot the water surface about the downstream end, however, pool volume must decrease. The same problem will exist with an outflow increase (figure 13-b), as the tendency to reduce pool volume will be contrary to the requirement of increasing it.





To accomplish the required volume changes, inflow change at the pool's upstream end must over-compensate for the outflow change. Inflow must be changed by a greater amount than outflow until the new steady state profile is achieved. Alternatively, if changes in demand can be predicted, inflow can be changed in advance of the outflow change.

Therefore, in a canal that operates with the constant downstream depth method, changes in demand are much more difficult to manage than changes in supply. The canal responds more easily and quickly to supply-oriented operations than to demand-oriented operations. Flow changes that originate at the upstream end can be fairly large without creating problems. Flow changes originating from the downstream end must be relatively small and gradual to avoid excessive depth fluctuations. Often, anticipation is used to improve the system response to changes in demand by creating upstream flow changes in advance of demand changes.

Any method of control can be used to implement the constant downstream depth method of operation. Local manual control traditionally has been used, but automatic or supervisory control can successfully implement constant downstream depth method of operation. The target depth (setpoint), must be referenced at the water surface pivot point. The depth at this point can be controlled with either the upstream or downstream canal check gate as shown on figure 14. The upstream gate would be controlled to satisfy a downstream operational concept (figure 14-a), and the downstream gate would be controlled to satisfy an upstream operational concept (figure 14-b).



Figure 14.—Control alternatives for the constant downstream depth method of operation.

# **Constant Upstream Depth**

With this method of operation, a constant upstream depth is maintained by pivoting the water surface at the upstream end of the canal pool as shown on figure 15. The constant upstream depth method is sometimes called "level bank"



Figure 15.—Constant upstream depth method of operation.

operation, because canal banks must be horizontal to accommodate the zero-flow profile. The construction of a level bank canal is the main drawback to this method. A level canal bank increases the cost of construction considerably, especially for concrete-lined canals. Most existing canals could not use level bank operation unless canal bank and lining were added to the downstream portion of each pool. Exceptions to this would be canals with little elevation drop between checks, or those operating at flows well below maximum flow capacity. Turnouts can be located anywhere within a pool, as canal water depth should always be at least the full-flow normal depth. If constant head is required, however, turnouts should be at the upstream end of pools. Wasteways should be located similarly for best operation. If bypass weirs are to be included in check structures, the weir crest must be higher than the zero-flow depth at the downstream end of the pool.

The constant upstream depth method of operation is most effective when combined with the downstream operational concept (demand-oriented operation). Flow changes originating at the downstream end of the pool cause canal water depths to change in the direction needed to achieve new steady-state profiles.

Figure 16 illustrates the response of a level bank canal to changes in demand. A decrease in pool outflow will initially cause the downstream depth to rise (figure 16-a). This increase in pool storage will facilitate the change to a raised water surface profile, as required to pivot about the constant upstream depth. Conversely, an increase in outflow decreases the downstream depth towards the desired lower steady state level (figure 16-b).

This excellent response to demand is the major advantage to level bank operation. Essentially, regulatory storage is built into the canal. At low flows, the additional water stored in canal pools is readily available to supply increases in demand. At higher flows, storage volume is available above the water surface where excess canal flow can be stored in the event of a decrease in outflow. This allows the pool to react to demand, since the changes in storage within a pool can take place after downstream flow changes are made.



Figure 16.—Downstream flow change with the constant upstream depth method of operation.

Level bank operation is inappropriate for supply-oriented canals. The operation would be inefficient and the additional expense for level bank construction would be unjustified.

Level bank operation can be accomplished successfully with any method of control. Control can be based upon maintaining the target depth at the upstream pivot point; this allows the target to be located immediately downstream of the check gate structure being controlled. Automatic float-actuated gates use this principle to react to downstream demand [8, 9]. Better response to demand can be achieved by locating a depth sensor at the downstream end of the pool, to control the check gate at the upstream end. Control then must be based on the variable depth at the downstream end of the pool.

# **Constant Volume**

This method of operation is based on maintaining a relatively constant water volume in each canal pool at all times. The water surface will pivot about a point near midpool as the flow changes from one steady-state to another. The constant volume method of operation is sometimes called "simultaneous operation," because the simultaneous gate operating technique often is used to keep the pool volume constant.

Storage wedges will exist on either side of the midpool pivot point as shown on figure 17. For any given flow change, volume change in each of these wedges is equal and opposite. When flow decreases, volume of water in the upstream wedge decreases and volume increases in the downstream wedge. When flow increases, the converse occurs.

The main advantage of constant volume method of operation is the ability to quickly change flow conditions in the entire canal system. With the constant upstream depth and constant downstream depth methods, excessive time is required to either build up or deplete the storage in the entire canal system when



Figure 17.—Constant volume method of operation.

changing the steady-state rate of flow. Constant volume operation avoids lengthy delays, because total volume of water in the canal system does not change significantly.

One disadvantage of constant volume method of operation is the additional canal bank and lining required at the downstream end of each pool, as compared to a conventional canal bank. However, the additional height required to accommodate the zero-flow water surface is only about one-half that required for level bank operation.

Another disadvantage involves the adjustment of check structures. Using local manual control, it is quite difficult to accomplish constant volume operation. Local automatic control can be used, but the supervisory control method is best suited for constant volume operation. Using supervisory control, all control structures can be adjusted simultaneously from a central location.

# **Controlled Volume**

A canal system can be operated by managing the water volume contained in one or more canal pools. Volume can be changed to satisfy operational criteria by allowing the pivot point to move within each pool. Because operation is based on volume, either flow or depth may be used as the measured parameter. Unlike the previously discussed methods of operation, the water surface pivot point is of relatively little importance for controlled volume operation. In fact, the pool water surface may rise and fall without a pivot point, similar to a reservoir.

Controlled volume operation offers the most flexibility of any method of operation. Canal operation can adapt more easily to normal, abnormal, and emergency conditions because a constant depth limitation does not exist. Operational flexibility primarily is restricted by depth fluctuation limits. A canal system operating within the controlled volume method has the capability to respond to a wide range of flow conditions. Sudden large flow changes that otherwise might require the use of off-channel storage or wasteways often can be controlled successfully within the canal using the controlled volume method.

Controlled volume is a particularly suitable method to operate canal systems that include off-peak pumping considerations. (Electric power often is less expensive during off-peak periods, when power demand is low, than during on-peak periods, when power use is high.) Substantial savings in power costs can be achieved when pumping is maximized during the low-rate periods and minimized during high-rate periods. This can be accomplished by lowering water levels in canal pools during on-peak hours and raising water levels during off-peak hours.

An example of controlled volume operation is illustrated on figure 18. The example shows a rapid outflow reduction at the downstream end of the canal. The check gates upstream are all adjusted simultaneously to reduce the canal flow, but the amount of flow reduction is smaller at each successive check. Therefore, flow into each canal pool at the upstream gate is greater than outflow—increasing the volume of water in each pool. After the volume has increased by a desired amount, additional gate movements can match inflow and outflow to prevent excessive depths.

In creating the operations in this example, several aspects could be considered. Depth fluctuations can be managed to avoid rapid drawdown at the upstream ends of the pools without wasting water or exceeding the maximum depth allowed at the downstream ends. Limiting the drawdown can prevent damage to the canal lining. Another aspect might be to transform rapid flow change at the downstream end into a gradual flow change in the upstream canal pools, by using pool storage as a buffer. As a result, the disturbance to the upper pools is minimized. If the rapid outflow reduction in this example occurred during an offpeak power period, the storage increase would build up a low-cost reserve supply in the canal. The reserve could be depleted to meet deliveries at a later time when power is more expensive.

One of the disadvantages of controlled volume operation is that it requires using the supervisory control method. Without computer assistance, the complexities of controlled volume operations would require frequent intervention by operations personnel. Computer-directed control would use specially developed software to control the check gates automatically—maintaining the desired volumes—without frequent operator intervention. Another disadvantage of controlled volume operation is the possible need for greater freeboard or a larger canal prism cross section.



(a) Initial simultaneous flow reduction



(b) Flow imbalance, causing volume to increase





(d) Final steady-state, volume increase

Figure 18.—Controlled volume method of operation example.

# **Canal System Control Methods**

A canal system can be controlled by the following methods:

- Local manual—on site control by a human operator (ditchrider)
- Local automatic—on site control by control equipment without human intervention
- **Supervisory**—control from central headquarters with different levels of participation by the watermaster
- **Combined**—combination of the above methods

Each canal control method has its own characteristics and advantages. The selection of the method that will upgrade a canal operation does not require knowledge of the associated control equipment details. However, selection is facilitated when each basic method of control is clearly understood. Control fundamentals and selection of an appropriate control method are discussed more extensively in the *Canal Systems Automation Manual* [1]. The following briefly discusses each method.

# Local Manual Control

Local manual control is the conventional method of controlling a canal system. Labor saving devices and machines, such as a gate motor hoist, may be used on site to assist the ditchrider when adjusting canal check gate openings. The procedure basically involves:

- An order by the water user
- A change (increase or decrease) in the input of water at the head of the canal to meet that order
- Adjustment at the check gate and canalside turnout structures by the ditchrider when the front of the wave arrives

An experienced ditchrider can anticipate the water arrival time within acceptable limits. This type of operation is greatly personalized. On a large canal, many people are involved. The ditchrider (in the field) must report by mobile radio or telephone canal data such as water levels and gate positions to the watermaster. The watermaster (at the central headquarters) needs to know these data to implement the schedule on the rest of the system. Team effort is involved and all member musts use judgment in their respective area of responsibility. Successful operation depends in large measure on team skill.

# **Local Automatic Control**

Local automatic control allows unattended canal operation achieved through an arrangement of mechanical, electrical, and electronic components located on site. The equipment monitors water depths and gate positions. The sensed information is interpreted by specially developed equations referred to as control algorithms. The algorithms are designed to calculate adjustments required to position the canal check gates and to satisfy the actual operating needs.

For the development of this method, one must be capable of blending technical knowledge and practical experience into the design of the local automatic control system. Control algorithms and control parameters are developed by engineers having knowledge of control theory. Their procedures depend upon the experience of the canal watermaster and ditchriders. Therefore, using a combination of control engineering and operators' experience is essential for this method of operation.

Required on site human input is reduced to periodically monitoring the canal operation. Automatic control equipment does not require on site manual adjustments by the ditchrider to achieve proper canal operation. However, an alarm system is required to notify central headquarters of abnormal conditions such as control equipment failure, high or low water levels, local power outages, and communication channel failures. Therefore, a communication channel is necessary between each check gate controller and the headquarters to provide the information by alarm. The watermaster at the headquarters monitors the alarm conditions and promptly initiates corrective action based upon the alarm condition.

# **Supervisory Control**

Supervisory control is the operation of the canal system by the watermaster from a central location referred to as the headquarters or master station. The master-station equipment performs the function of collecting data from remote sites on the canal system, analyzing the data, and presenting the data in a suitable format for further action by the watermaster. Each remote site, such as the canal check gate structure, requires a remote terminal unit (RTU). The RTU monitors data such as water levels, gate positions, and alarm conditions, and transmits these data to the master station. The RTU also controls the remote site—it adjusts the gate position based on the watermaster's instructions received from the master station. Therefore, this type of operation requires a communication system between each RTU at the remote sites and the master station.

Direct control of the canal system is the watermaster's responsibility at the headquarters. Effectively, many of the ditchrider's duties are moved from the field location to a centralized location. Supervisory control enables all required

information from the entire canal system to be centralized at one location. Changes in one portion of the system can be recognized promptly and appropriate control action implemented. Flow can be adjusted simultaneously at many canal check gate structures resulting in a mass transfer of water in the shortest time possible, providing an improved or upgraded operation.

# **Combined Control Systems**

Local manual, local automatic, and supervisory control systems are not mutually exclusive. In many water projects, the operation involves the use of a combination of two or perhaps all three methods. The relative merits of the three types of control depend on the circumstances of use. For example, a gravity type turnout may require a local automatic controller to automatically maintain a constant delivery rate if the main canal water level changes frequently. The ditchrider is not always available to visit the site frequently enough to make the necessary gate opening adjustments to compensate for the water level variation and maintain a constant delivery rate.

Installing a turnout local automatic controller upgrades a turnout gate operation. However, the main canal system supplying water to the turnout may still operate in a conventional manner; i.e., by the local manual control method. Instead of changing the turnout gate for a new delivery rate, the ditchrider enters a new setpoint value for the discharge into the local automatic controller. Hence, the operation combines the local manual and local automatic control methods and the canal operation has been upgraded.

The operation can be upgraded further by installing local automatic controllers at the main canal check gate structures. However, the turnout local automatic controller still requires daily setpoint changes. This could be accomplished by supervisory manual control. The watermaster (at the master station) transmits the new setpoint to the appropriate local automatic turnout control at the proper time relieving the ditchrider from this task. This example combines local automatic and supervisory manual control. The master station equipment could be programmed to determine the proper time for the setpoint change based on the current demand schedule also programmed as input data. Then, the new setpoint is transmitted automatically to the proper local automatic turnout controller at the correct time. In this degree, local automatic control is combined with supervisory computer-directed control while freeing the watermaster from normal daily water scheduling tasks.

# **Check Gate Operation**

# **Check Structures**

Canal control structures regulate the flow and depths of water. The most common type of canal control structure is the *check structure*. The name is derived from the function of checking, or slowing, the flow velocity. A check structure causes the water surface to rise in the canal upstream of the structure. In some countries, check structures are called "cross regulators." A check structure can range in complexity from a simple fixed weir (in the channel) to a large structure containing many moveable gates [10, 11].

The canal check gate structure has become the dominant tool for implementing canal system operations. Because the check gate structure is the most common control structure, most of the examples in these notes use check gates as the boundaries between canal pools. Typically, radial gates are used in large checks; vertical slide gates are more common in smaller check structures. The primary purposes of canal check gate structures are to (1) control water surface elevations, and (2) regulate the flow passing through the structure.

A schematic of a typical canal check gate illustrating steady-state free and submerged flow conditions is shown on figure 19. Usually, the check gate upstream depth, Yu, is checked up to a desired level. Often, this level is prescribed to be the normal depth for the canal's maximum design discharge. A steady-state condition exists when depths and flow remain relatively constant with time. Gate flow is considered *submerged* when the toe of the downstream hydraulic jump submerges the vena contracta that develops immediately downstream from the gate lip [7, 12]. Conversely, gate flow is considered *free* when the vena contracta is not submerged and is exposed to the atmosphere.



Figure 19.—Check gate steady-state free and submerged flow conditions.

The typical canal check gate operates *submerged*. In some cases, free flow will develop at low flow rates. A canal system should not be designed to have both submerged and free flow conditions occurring within the range of normal canal operations. The rapid change in discharge, as flow transitions between submerged and free conditions, can cause operational problems.

Flow through a check gate is complex. The relation between discharge and gate opening is dependent upon upstream and downstream water depths, physical characteristics of the gate structure, and flow condition (free or submerged). Accurate discharge algorithms have been developed for radial gates [12]. The discharge algorithms apply to canal radial gates designed by the Bureau of Reclamation and are based on empirical calibration.

Operation of a canal system is accomplished primarily by controlling flow through the check structures. Several canal check gate operating techniques have been devised that can be used to change canal flow and to establish a new steady-state flow condition. The three most commonly used techniques are:

- 1. Sequential Each check gate is operated in a progressive order in either the downstream or upstream direction.
- 2. Simultaneous All check gates are operated at the same time.
- 3. Selected Individual check gates are operated independently of other checks in the canal.

These three techniques differ primarily in the timing of gate adjustments. Each facilitates flow changes within the entire canal system, but each achieves the desired depths and flows in a different manner.

# **Sequential Operating Technique**

Operating the canal check gates sequentially, progressing either downstream or upstream, is a technique commonly used to change canal system flow. The sequential check gate operating technique is especially compatible with local manual control. A ditchrider easily can adjust check gates sequentially while traveling a length of canal. Sequential check gate operation transfers water downstream and flow changes are made at canalside turnouts when the translatory wave arrives. The wave arrival time is dependent on the canal length between the headworks and the turnout location. Therefore, the number of flow changes that can be made at a canalside turnout is limited for the sequential gate operating technique.

On conventionally operated canals, the basic procedure is to initiate a flow change at the headworks and progress in the downstream direction. Canalside

turnouts and check gates are adjusted in sequential order as the flow change arrives. This procedure is shown on figure 20. Figure 20-a shows a flow increase (at check 1) that generates a positive translatory wave. The ditchrider can follow the translatory wave downstream and make adjustments at the canalside turnouts enroute as required by the water schedule. Then, as the wave arrives, gate(s) at check 2 can be adjusted (figure 20-b). The ditchrider continues downstream making flow changes at successive canalside turnouts and check gates (figure 20-c). An experienced ditchrider anticipates arrival of the flow change and ensures compliance to delivery schedules within acceptable limits.

Sequential gate adjustment, progressing in the downstream direction, can be performed to achieve a constant downstream depth in the canal pool. The new water surface profile is developed by pivoting the water surface at the downstream end of each canal pool (figure 20-d). During the time interval between the old and new steady-state flow conditions, pool inflow exceeds outflow. This excess flow fills in the translatory storage wedges between the old and new water surface profiles, as shown by the shaded areas on figure 20-d. The opposite translatory storage wedge development occurs when flow in the canal pool decreases.

Sequential check gate operation should progress upstream when abnormal flow changes occur. For instance, if an unexpected decrease in downstream flow requirements occurs, the necessary reduction in canal flow may take too long when progressing downstream beginning at check 1. A flow reduction can be initiated immediately at the downstream canal pool and progress upstream.

Sequential check gate operation for an emergency shutdown of the canal system is shown on figure 21. The decrease in canal flow begins at the most downstream gate (figure 21-a) and progresses to the next upstream check gate (figure 21-b) as the negative translatory wave arrives. The closing of successive check gates progresses upstream (figure 21-c) and establishes a new steady-state flow condition (figure 21-d).

This upstream progression pivots the water surface profile at the upstream end of each canal pool. The storage wedge that develops may encroach into the canal prism freeboard. Temporary freeboard encroachment is acceptable during short duration abnormal operation of the canal system, as long as the water level does not exceed the top of the canal lining. To prevent excessive water depths from developing at the downstream end of the canal pool, the successive upstream check gates may need to close before the translatory wave arrives. Less time is available for the storage volume to develop and the pivot point will shift downstream, as shown on figure 22.



(d) New steady-state flow condition





(a) Flow decrease at check 4 downstream











(d) New steady-state flow condition

Figure 21.—Sequential gate operating technique progressing upstream.



Figure 22.—Sequential gate operation progressing upstream before wave arrives.

A ditchrider (local manual control) will find it difficult to maintain a constant downstream depth in canal pools with sequential check gate operation progressing upstream. The natural tendencies of pool storage changes are contrary to the downstream pivot point (see section 8). Therefore, only gradual flow changes can be accommodated without changing the depth at the downstream end of canal pools.

However, sequential check gate operation progressing upstream can be implemented with a local automatic control system. The automatic control system can be designed to respond to the downstream demands soon after they occur and to adjust the next upstream check gate. The resulting disturbances will continue to progress upstream and cause automatic adjustment of the check gates sequentially toward the head of the canal without a ditchrider intervening. Therefore, changes in canalside turnout demands are coupled automatically to the canal headwork—similar to the behavior of a pressure pipe system. This type of automatic control system can successfully maintain constant downstream depths if flow disturbances are not too large.

The supervisory control method also can operate a canal system by sequential gate operation progressing either downstream or upstream. Supervisory control allows the ditchrider's tasks to be shifted from the canal check location to the watermaster's headquarters.

# Simultaneous Operating Technique

Adjusting all canal check gates simultaneously can establish a new steady-state flow in the canal system in the shortest time. The simultaneous check gate operating technique is illustrated on figure 23. Beginning with steady-state conditions (figure 23-a), a flow increase is created by opening all gates simultaneously (figure 23-b). The generated positive and negative translatory waves begin propagating downstream and upstream, respectively, simultaneously in every canal pool. The traveling translatory waves will meet near midpool and tend to cancel. Therefore, the new steady-state flow condition quickly develops (figure 23-c). The water surface pivots near midpool—an important characteristic of simultaneous check gate operation. Water depths, at each end of the canal pool, change for each new steady-state flow condition.



Figure 23.—Simultaneous gate operation with midpool pivot point.

When the water surface pivots near the middle of the pool, a flow change does not require a change in pool storage. For a flow increase (figure 23-c) the storage wedge increases upstream and decreases downstream from the pivot point. The opposite occurs for a decrease in flow. The water volume in the upstream and downstream storage wedges is about equal, so the total volume of water in each canal pool will remain relatively constant for all steady-state flow conditions.

The depth fluctuations associated with the simultaneous gate operating technique must be scrutinized. Water level decreases should not exceed allowable drawdown rates for normal operation. Excessive drawdown can result in canal lining failure. During normal operation, increases in water depth should not be allowed to encroach into the freeboard for a sustained time. The canal bank and lining need to be high enough to accommodate the depth increases that are caused by simultaneous gate operations. The canal may have to be operated at lower than normal depths so that sufficient freeboard is available for flow changes. Therefore, as steady-state flow approaches canal maximum design flow, the capability to make large flow changes decreases.

Simultaneous closure of all check gates is ideal for an emergency shutdown of the canal system. During an emergency, encroachment into the freeboard is permitted for a short time. Usually, a sudden simultaneous shutdown will minimize this encroachment compared with other check gate operating techniques that react more slowly to the emergency.

When using the simultaneous check gate operating technique, it is possible to shift the water surface pivot point either upstream or downstream before a new steady-state flow develops. A two-step adjustment of all check gates is required, with a time lapse between initial and final gate operations. The initial flow change creates an unbalanced flow condition in each canal pool to increase or decrease the storage wedge water volume. The secondary flow change then rebalances the inflow and outflow after the desired pool volume change has been achieved.

For example, figure 24 illustrates how the pivot point of the water surface can be shifted from the midpoint to the downstream end of a canal pool during an increase in flow. The initial simultaneous gate operation (figure 24-a) includes an additional increment of gate opening,  $\delta GO$ , at all the canal check gates. This additional gate opening increment is always larger at the upstream check gate—creating an unbalanced flow into the canal pool. Therefore, QIN is greater than QTO plus QOUT.

The intermediate water surface pivot point will occur near the midpoint of the canal pool as the generated translatory waves meet (figure 24-b). However, flow mismatch will increase the translatory storage until the pivot point has been shifted to the downstream end of the canal pool (figure 24-c). At this time, all check gates are simultaneously closed by the increment  $\delta$ GO so that inflow once again matches outflow (figure 24-d).

The additional increment included in the initial gate movement,  $\delta GO$ , can be selected to increase or decrease the storage. Thereby, the pivot point can be deliberately shifted upstream or downstream by the two-step simultaneous gate operating technique regardless of flow change (increase or decrease). Water



Figure 24.—Two-step simultaneous gate operation.

volume in each canal pool will vary, if desired, for each steady-state flow condition. Two-step simultaneous check gate operation is one technique to enact the controlled volume operational method.

Simultaneous gate operations cannot be accomplished by local manual control unless ditchriders are stationed at every check structure so they can communicate with each other when flow changes are to be initiated. Realistically, the simultaneous gate operating technique can be accomplished only by using the supervisory control method. New gate openings can be transmitted rapidly from a central location to remote terminal units at all check structures so that all gates are adjusted almost simultaneously.

# Selected Operating Technique

The selected gate operating technique is commonly used to make minor flow adjustments that do not necessarily affect the entire canal. Selected gate adjustments often are made to balance the operation of the canal system. Certain check gates may require an adjustment to maintain desired water depths in adjacent pools.

At times, water transfer may be necessary between surplus and deficient canal pools. The transfer can progress either downstream or upstream. If the water transfer involves more than one check gate structure in succession, either sequential or simultaneous gate operation could be used.

Selected gate operation permits adjusting water depths and flows within the canal system without having to adjust headwork inflow. This type of operation is especially advantageous when the headwork consists of a pumping plant with a minimum flow increment determined by pump unit capacity.

# The Application of Canal Automation

Advancement of automatic control equipment has greatly expanded the field of canal operation and control. *Automation* has become a common term when discussing modern canal systems. The improved operations afforded by an automated control system have many benefits, including increased crop production, reduced water use and waste, improved service to water users, and better response to emergencies. When automatic control was applied on the Corning Canal in California, benefits exceeded costs by a factor of two.

Manually controlled canal systems have an overall efficiency of about 40%, exclusive of the use of any return flows [13]. Automation can increase canal operating efficiency 10% or more [14]. Additionally, farmers can see an increase of 15% or more in crop yields [15]. The following discusses the application of canal automation to existing system.

# **Upgrading Existing Canal Systems**

Many opportunities exist for upgrading the operation of existing canals by adding automatic control systems. Control system planning begins with a description of project objectives. Specific expectations and goals should be identified so that the control system can be customized.

Physical characteristics of the existing canal system will limit operation and control possibilities. Constraints created by existing canal features need to be evaluated. For example, the size of the canal prism limits the maximum allowable flow, the amount of flow change, and depth fluctuations. The amount of in-channel or off-channel storage can greatly affect the operations of a canal. Other important features include check structures, turnouts, wasteways, and pumping plants.

Operating criteria should be established to create an efficient match between the canal system's capabilities and its requirements. One should begin by analyzing the present canal operations, and then pursue alternate methods that would improve operational efficiency. The method of operation should be selected before designing a control system. Then, local automatic control and supervisory control alternatives can be studied to define specific functions of the control system equipment.

An existing canal system may require structural modifications and additional equipment to accommodate a change in control method. Preparation details include site investigations, operation studies, and equipment considerations. At this stage, the upgrade feasibility can be studied. Feasibility is based on the estimated costs of the new control system and the benefits achieved.

When project feasibility has been confirmed, final design details are prepared. Specifications are written for procurement, installation, and acceptance testing of the control system equipment. On-site preparations update or modify the canal facilities as required to interface with the new control system. Then, control equipment is installed, calibrated, and tested. To ensure the equipment will operate as designed, testing is required before and after installation. After it becomes operational, equipment must be properly maintained to keep outages to a minimum.

# **Operation Studies**

Computer simulation studies are required to optimize the operation of complex canal systems. Studies are necessary to evaluate and verify the different methods of operation and control for various flow conditions. A canal system without wasteways or re-regulating reservoirs has little margin for error when flow is near maximum capacity. Control during abnormal and emergency conditions is critical. The evaluation, selection, and development of complex control techniques requires analysis with mathematical models.

Operation studies should include:

- Selection of control parameters for local automatic controllers.
- Development of supervisory control strategies and procedures for off-peak pumping, abnormal, and emergency operations.
- Evaluation of the canal system design—such as the type and location of check gate structures, wasteways, and storage facilities—to improve response and recovery characteristics.
- Evaluation of alternative delivery concepts; e.g., testing the effects of different turnout flow changes on the overall canal operations.
- Development of mathematical models that predict water supply and demand and optimize pump/generating schedules for complex canal systems.

Computer simulation of local canal controllers allows the operator to predetermine control constants, deadbands, and time delays before installation. Computer studies save trial and error in the field at the potential expense of the canal. A combination of technical expertise and practical experience is required to conduct operation studies properly and to develop the requirements and specifications for the control equipment.

# **Automation Requirements**

Preparing a canal system for control equipment installation may require modifications such as check gate motorization. Water level measurement equipment and enclosures for control equipment must also be provided.

Control equipment requirements vary with the method of control. Local automatic control involves monitoring and control of a remote site by on-site equipment without human intervention. Modern canal-side controllers are microprocessor based, similar to a personal computer. Typically, each remote site has an RTU (Remote Terminal Unit) that performs the functions of data collection, communication, and control. Local automatic control systems often include a one-way communication channel to transmit alarm signals to a central site, alerting operators of potential problems.

The RTU must interface with analog sensors. Depth, flow, and gate position, collected as analog data, is converted to digital data. RTU operations are defined by a set of logic and mathematical statements known as a control algorithm.

Algorithms receive and interpret data and compute appropriate control responses. A microprocessor RTU can function as a local automatic controller or as part of a supervisory control system.

A communication system is required between the master station and the RTUs located at the remote sites. The communication system allows two-way transmission of digital data. Possible types of communication systems are metallic cable, single channel VHF or UHF radio, or fiber optics.

Control equipment must be tested before it is installed on the canal system to ensure that it performs as specified. After control equipment is installed, it needs to be performance tested to assure calibration, interfacing, and communication are correct and will perform adequately.

Eventually, control system equipment will require maintenance, re-calibration, and repair. A preventative maintenance program must be initiated upon installation. A good preventative maintenance program will keep equipment failures and outage times to a minimum. An inventory of spare parts and components will aid timely repair. Periodic testing and examination of equipment should be scheduled.

### Water Operation and Maintenance Bulletin

Qualified technical expertise and training are important basic requirements. Local automatic and supervisory control methods require technical expertise to implement and maintain a successful control system. Operator training should be provided to familiarize operations personnel with control hardware and software. A critical requirement is the formulation of standard operating procedures for canal, such as startup and shutdown procedures and maximum allowable water level fluctuations in the canal.

# Part 2 DATA COLLECTION SENSORS

A Note About Costs: The material presented here was originally assembled in the mid-1990s, and sensor cost information is dated to that era.

# Water Level Sensors

# **Float Systems**

# **Mercury Switches**

*Description*: Mercury-filled reed relays can be used with floats, where a lever or arm on the float opens and closes the switch as water levels change. These switches can indicate when the water either rises or falls to a specific level, to turn pumps on or off or to actuate alarm annunciators. Often, these inexpensive limit switches indicate high or low water levels as a backup system for other water level sensors.

# Advantages:

- 1. Inexpensive
- 2. Easy to install, understand, and maintain

# Disadvantages:

- 1. Requires a stilling well
- 2. Only indicates when water level reaches discrete points
- 3. Friction can develop in moving parts

Cost: \$50 - \$200

# Magnetostrictive Probes

*Description*: This device uses a float containing a magnet, which slides vertically on the outside of a resonated-wire probe. The magnet creates a reflection point that is measured to indicate the float's position. Magnetostrictive probes are generally reliable and effective to measure water level in tanks, but less common in canal applications.

# Advantages:

- 1. Simple
- 2. Indicates constantly varying level, not just discrete points

### Disadvantages:

- 1. Requires stilling well
- 2. Friction can interfere with sliding action
- 3. More expensive than mercury switches
- 4. Limited measurement range

Cost: \$300 - \$500

# Potentiometers

*Description*: A potentiometer is an electrical device that has a rotating shaft and produces a variable output voltage that is proportional to shaft rotation. To measure water level, a float and counterweight are attached to a beading wire or a perforated metal tape. This wire or tape runs over a pulley or wheel on the potentiometer shaft. Shaft rotation indicates the level of the float, and potentiometer voltage is calibrated to water level. Typically, this arrangement will be mounted in a stilling well so the float indicates the level of the water surface in the well. Various designs have been used to prevent the cable or tape from slipping on the wheel.

Experience has shown that large floats and counterweights help reduce the relative effect of friction. Most of the problems with these systems are caused by installation or maintenance shortcomings that prevent the float system from moving freely with the water surface, or from the float cable or tape slipping on the wheel.

# Advantages:

- 1. Inexpensive
- 2. Relatively simple mechanical components
- 3. Accuracy within approximately +/- 0.01 foot

# Disadvantages:

- 1. Requires a stilling well
- 2. Friction or other problems can develop with moving parts

Cost: \$300 - \$500

# String Transducers

*Description*: A string transducer has a retractable cable that rewinds under spring tension. As the cable extends or retracts, linear displacement is measured using the rotation of an internal spool that winds up the cable. As with potentiometers,

voltage or current loop output varies in proportion to shaft rotation. By attaching a float to the end of the cable, water level can be measured much the same as with a potentiometer. The main difference is that a spring is used instead of a counterweight.

As with all float systems, satisfactory performance requires that friction be minimized. Spring tension must be sufficiently large and should not change appreciably over the measurement range, or accuracy will be reduced.

# Advantages:

- 1. Simple installation
- 2. Moving parts are internal; no counterweight or external wheel required

# Disadvantages:

- 1. Requires a stilling well
- 2. Friction and debris problems may develop
- 3. Inaccuracy may result if spring tension changes over the range of measurement

Cost: \$400 - \$800

# Shaft Encoders

*Description*: Shaft encoders measure shaft rotation with a magnetic or optical device. They provide a similar function as potentiometers, except the output is in digital format. Output is proportional to shaft rotation, so a float and counterweight can be used to measure water level. Shaft encoders may be either absolute or incremental. Absolute encoders, like potentiometers, have a fixed range of rotational motion and indicate the absolute rotational position of the shaft from one end of its range to the other end. Incremental encoders indicate the change in shaft rotation relative to some starting point and have no limit on the range of rotation.

# Advantages:

- 1. Accurate and reliable
- 2. Digital output signal
- 3. Wide range of measurement is possible, without affecting accuracy

# Disadvantages:

- 1. Requires a stilling well
  - 3. Friction or other problems may develop with moving parts
  - 4. More expensive than potentiometers

Cost: \$500 - \$1,500

# Submersible Pressure Transducers

*Description*: Pressure transducers or transmitters measure differential pressure across a diaphragm. Deflection of the diaphragm is measured with a strain gage, which produces an output signal that is proportional to pressure. Submersible pressure transducers measure water depth above the transducer by venting one side of the diaphragm to atmosphere. The sealed, self-contained transducer probe has a vent tube (breather) in the cable with the electrical wires. By placing the transducer at a fixed, known position below the water surface, transducer output can be calibrated to water depth.

Submersible pressure transducers are accurate and cost effective, and have widespread application. Because they sense pressure below the water surface, they are relatively unaffected by waves, foam, or debris on the water surface. However, submerged transducers can have problems with corrosion, clogging, freezing, and physical damage from debris, animals, or people. To minimize problems and damage potential, submersible transducers are usually installed in a stilling well or a pipe that extends into the water being measured. In cold climates, transducers must be brought inside for the winter to prevent damage from freezing. Also, transducers will fail if over-pressurized by being submerged too deep.

Measurement accuracy is proportional to the pressure range to be measured, and varies with instrument quality and cost. Accuracy within +/- 0.01 foot is possible. All pressure transducers will gradually "drift" out of calibration due to creep in the diaphragm over time. This drift may be negligible in good quality transducers but large enough to require frequent recalibration in lower quality instruments. Changes in water temperature can also affect accuracy. Many transducers have temperature compensation, but this too will vary with quality and cost.

### Advantages:

- 1. Widely used
- 2. No moving parts
- 3. Relatively accurate (depends on cost)
- 4. Small and easy to install; stilling well is not required

### Disadvantages:

- 1. Susceptible to freezing, corrosion, and clogging
- 2. Will fail if over pressured
- 3. Output may drift, requiring recalibration

Cost: \$400 - \$1,500

### **Bubbler Systems**

*Description*: A bubbler system is a type of pressure transmitter that measures water level by detecting the pressure required to force air through a submerged tube. The tube is mounted with the end of the tube below the water surface being measured, and the air emerges from the bottom of the tube as a stream of bubbles. The air flow rate is relatively small—just enough to prevent water from backing up into the tube—so the pressure required to push air through the tube is equal to the pressure at the tube's outlet. This pressure is proportional to the water depth above the bottom of the tube.

Although older bubblers were cumbersome and sometimes involved convoluted plumbing, newer bubblers are more compact. Some bubblers have a small compressor to develop the required air pressure, while others used a compressed gas such as nitrogen. Nitrogen is supplied from a high-pressure bottle with a regulator to maintain a constant output pressure. The only submerged part of a bubbler system is the air tube, which is inexpensive to replace if it becomes damaged. All of the electrical and mechanical components can be housed in a protective enclosure at a convenient location. The air tubing can run a long distance–sometimes several hundred feet–and still provide an accurate water level measurement.

A big advantage to bubblers is the location of the pressure sensor. The transducer is located at the air source instead of being under water. Because of this, the pressure sensor can be small and inexpensive yet highly accurate. Accuracy within +/- 0.001 foot is possible. Some bubblers have a temperature sensor and temperature compensating software to minimize error from temperature change. Self-calibrating "double bubblers" have two submerged tubes, installed so that the two orifices are separated by a fixed vertical distance. A single transducer measures pressure in each of the tubes as well as the atmospheric pressure. This technique compensates for temperature effects and drift in the transducer.

### Advantages:

- 1. Highly accurate
- 2. Easy to install; stilling well not required
- 3. Instrumentation is above water
- 4. Minimal influence from surface disturbances

# Disadvantages:

- 1. Higher than average cost
- 2. Compressor increases power requirement compared to electronic instruments
- 3. Use of compressed nitrogen is cumbersome and requires maintenance

Cost: \$1,200 - \$3,000

# **Ultrasonic Sensors**

*Description*: These devices transmit an ultrasonic signal in a cone-shaped pattern, which is reflected off the surface to be measured and received by the sensor. The time interval from transmit to receive is measured, and distance is computed from this travel time and the speed of sound. To measure water level, the sensor is mounted above the water surface pointing downward. As such, the sensor and mounting structure do not contact the water and are unaffected by water quality, sediment, or debris. Usually, a stilling well is not required. However, disturbance on the water surface or obstructions in the signal path will interfere with the measurement. Surface wave, foam, floating debris, and ice can cause problems, as will spider webs and vegetation between the sensor and water surface. A temperature gradient between the sensor and water will also introduce error. Ultrasonic sensors are not as accurate as some other types of sensors, so are most applicable where precise measurement is less important.

# Advantages:

- 1. Ease of installation and calibration
- 2. No contact with water
- 3. Stilling well not required

# Disadvantages:

- 1. Surface disturbance effects
- 2. Mediocre accuracy
- 3. Temperature-induced error

Cost: \$400 - \$2,000

# **Resistance Tapes**

*Description*: A resistance tape is sometimes called an "electric tape measure" because it measures distance to the point of water contact. The sensor consists of a stainless steel tape with a gold contact stripe on one side. The steel tape is insulated and wrapped with a gold-plated, nichrome wire, then enveloped in a jacket. Hydrostatic pressure causes the helix wire to short against the gold contact stripe, which changes the electrical resistance in proportion to the distance to the contact point. Resistance is measured to yield water level.

# Advantages:

- 1. Simple installation
- 2. No moving parts
- 3. Inexpensive

Disadvantages:

- 1. Not very durable
- 2. Minimal accuracy
- 3. Hysteresis

Cost: \$200 - \$300

# **Gate Position Sensors**

# String Transducers

*Description*: String transducers can be used for gate position measurement in much the same way as for measuring water level, except the retractable cable is attached to the gate or gate stem instead of a float. The cable extends or retracts as the gate goes up and down, and transducer output is calibrated to gate position. Friction in the retractable cable and non-linearity of the spring tension are usually not a problem, because they will not affect gate movement or gate position measurement.

# Advantages:

- 1. Simple installation
- 2. Moving parts are internal

# Disadvantages:

- 1. Debris can hang up on the cable or break the cable
- 2. Calibration must account for non-linearity for overshot gates and radial gates

Cost: \$400 - \$800

# **Potentiometers and Encoders**

*Description*: Potentiometers and shaft encoders can be used to measure gate position when rotation some component of the gate can be equated to gate position. Usually, rotation in the gate hoist or motor actuator can be linked to the potentiometer or encoder.

# Advantages:

- 1. Inexpensive
- 2. Relatively simple mechanical components
- 3. Accuracy within approximately +/- 0.01 foot is possible

# Disadvantages:

- 1. Gear lash (slop in gate hoist gearing) may introduce error
- 2. Converting sensor output to gate position can be complex

Cost: \$200 - \$1,000

# Inclinometers

*Description*: An inclinometer is an instrument that measures slope or tilt angle. Many different type of inclinometers are available, based on several different principles of operation. By attaching an inclinometers to the structural arm of a radial gate, gate position can be computed from the measured angle of inclination. Similarly, the position of an overshot leaf gate can be computed by measuring the leaf angle. The inclinometer needs to be submersible for some of these installations, and the electrical connection wire must be routed from the attachment point to data collection equipment on the bank.

# Advantages:

1. Can measure gate position when other methods won't work

# Disadvantages:

- 1. Mounting and wiring details can be difficult
- 2. Instrument will sometimes be under water
- 3. Converting sensor output to gate position can be complex

Cost: \$300 - \$1,000

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# Mission

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