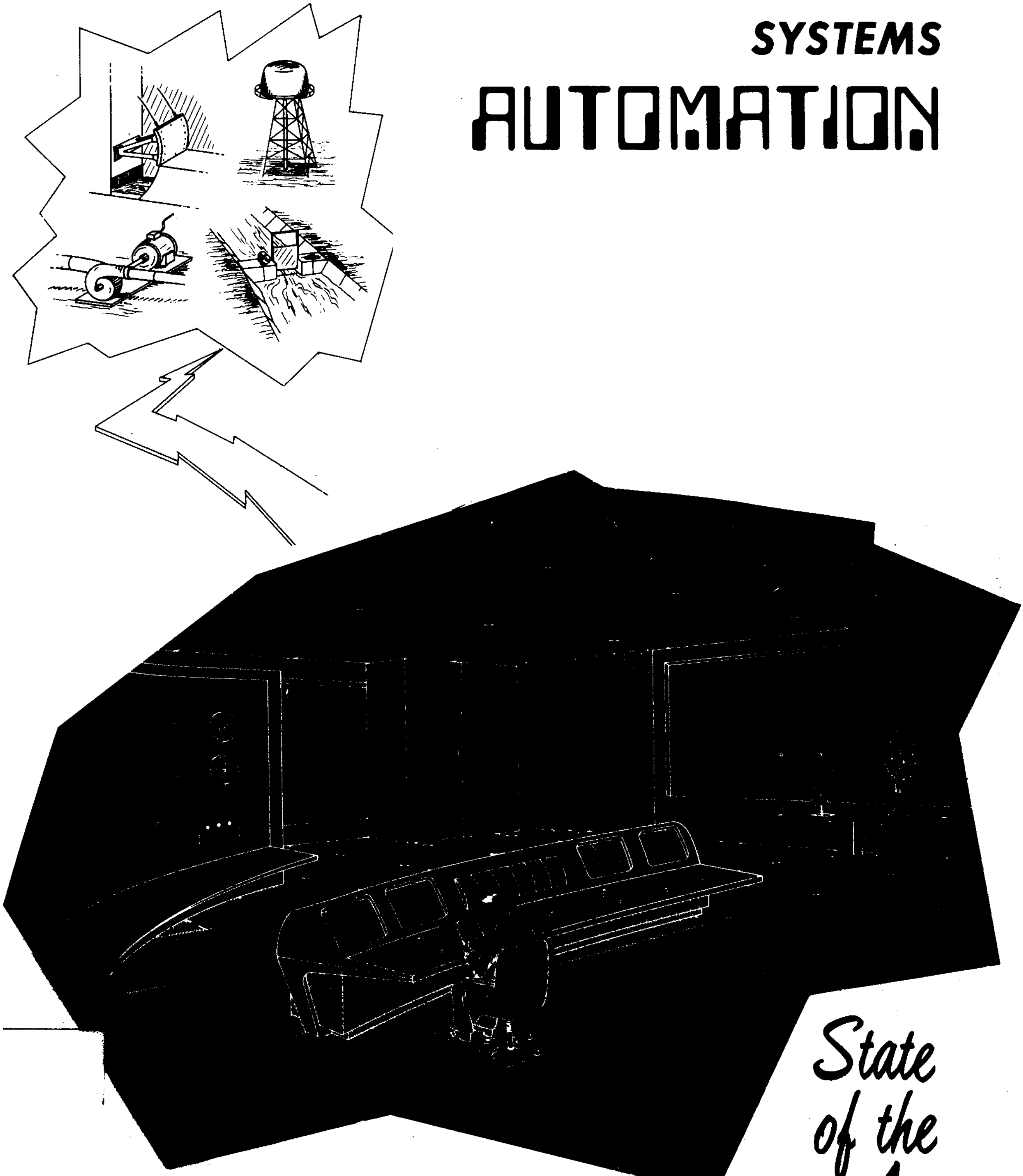
WATER
SYSTEMS
AUTOMATION



State
of the
Art

WATER
SYSTEMS
AUTOMATION

Current information on automation of Reclamation water systems,

A State of the Art report by the Water Systems Automation Team.

JULY 1973

UNITED STATES DEPARTMENT OF THE INTERIOR
Rogers C. B. Morton, Secretary

BUREAU OF RECLAMATION
Gilbert G. Stamm, Commissioner

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The Water Systems Automation Team composed of Lloyd F. Weide, Hydraulic Structures Branch; Rudy S. Hogg, Electrical Branch; Joseph L. Johnson, Mechanical Branch;–all Division of Design; Jack C. Schuster, Hydraulics Branch, Division of General Research; and Charles A. Calhoun, Team Leader, Operations Branch, Division of Water O&M appreciates the help of other Reclamation employees in preparing this report. Particular acknowledgment is given to Benjamin A. Prichard of the Operations Branch, Division of Water O&M; Clark P. Buyalski, Hydraulics Branch, Division of General Research; Edward A. Serfozo, Electrical Branch, Division of Design; Joseph M. Lord, Jr., Hydrology Branch, Division of Planning Coordination; and to Robert E. Haefele and Genevieve S. Thomas of Technical Services Branch, Division of Engineering Support.

Regional Automation Coordinators who have furnished input to this report are: R. W. Slater, Region MP; J. A. Rawlings, Region UM; and W. L. Jamison, Region LM. John G. Hoffman of Rio Grande Project wrote the bulk of the mathematical model description.

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PREFACE

In June 1971 the Water Systems Automation Team was formed at the Bureau of Reclamation's Engineering and Research Center. That Team has the dual responsibility of managing research and development of water systems automation equipment and concepts and coordinating water systems automation activities at the E&R Center. Regional Automation Coordinators were selected to provide liaison with the Team on automation activities within each region.

By letter dated April 17, 1972, Commissioner of Reclamation Ellis L. Armstrong assigned the Team the task of writing a "state-of-the-art" report on water systems automation.

This report describes the current state of development of automatic equipment and concepts used on or planned for Reclamation projects. Emphasis is placed on open-channel conveyance systems. The need for automating, remotely controlling, and/or monitoring storage dam outlet works and spillway gates; diversion dams; pumping plants; canal checks, wasteways, and turnouts; and pipe systems is discussed. Types of automation having potential application to water systems are described.

A Research and Development Program is currently under way to explore the application of various types of automation to water systems. The interface between the water systems automation effort and the irrigation management effort is also discussed. A description of planned applications of automation to individual canals and major projects follows. Cost considerations related to automation conclude the report. The appendices include definitions, a tabulation of existing automation installations on Reclamation projects, and a description of the parameters of downstream control.

Advances in technology now make automatic control feasible for almost any water system. Equipment is now becoming available which can be used to monitor and control even the most complex installation. However, the application of these new tools of technology to water projects is limited by their cost.

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SUMMARY

The purpose of this report is to provide operators, planners, and designers with current information on automation of water systems. In the report the term "automation" is used in a broad sense to include all remote control and automatic control equipment which aids or replaces man in the operation of water systems. The Bureau of Reclamation has incorporated varying degrees of automation in the design of water systems for many years.

The scope of this report is limited to the application of automation to Reclamation water systems. Emphasis is placed on open-channel installations because in most cases today open-channel conveyance systems are operated under less than optimal conditions. Subjects covered include automation needs, types of automation, research and development, planned installations, and cost considerations.

Water deliveries from Federal Reclamation projects totaled nearly 27.0 ***million acre-feet*** *during 1971. Water service was provided to nearly 16* ***million people****. Deliveries were made to over 147,000* ***farms*** *comprising over 10* ***million acres of irrigable lands*** *and to 249* ***municipalities or other entities*** *for municipal, industrial, and miscellaneous uses. Some 47,000* ***miles of canals and laterals,*** *305* ***storage reservoirs,*** *and 316* ***diversion dams*** *were in operation on Bureau of Reclamation projects to provide this service.* Considering these varied and extensive facilities and current and projected water needs, the best practical methods of water management should be developed and instituted to assure efficient use and conservation of existing developed water supplies. These methods, including use of automation, should be adopted for planning new water projects.

Water systems are automated to improve service to water users, to increase efficiency of operation, and to reduce cost of operation. Automation of water systems is a product of an interdisciplinary effort to develop devices to improve operation of these systems. Tools such as analog electronic circuitry, computers, mathematical models, and self-contained mechanical controllers are required. The type of automation installed on a particular project depends on the type of operation desired and the complexity of that system. Factors such as cost of labor, value of water, and reliability of equipment, require consideration. With increasing water system complexity, automation is more often justified now that it was in the past. Most new water systems should be designed with some degree of automation.

Less than optimal operation of an open-channel conveyance system is frequently due to the difficulty of matching the inflow and outflow of the system. Mismatches between diversions and deliveries can occur as a result of inaccurate regulation, unexpected changes in inflow or outflow, lack of adequate storage, and the long time lag inherent in conventional canal operation. For instance, many conventionally operated canal systems require a full day or more of travel time for a change in flow to get through the conveyance system. The ability to accommodate increases or decreases in demand at the turnouts due to unexpected rainfall, critical temperature changes, or other reasons is dependent upon the time lag of the system. Automation can greatly decrease the effect of this time lag, compensate for inaccurate regulation, and generally provide better service to the water users at less cost and with less waste of water.

Pressure pipe systems are the best means of providing automatic control of discharge to a turnout where delivery is based on demand. However, pipe systems are usually more expensive to construct than open-channel systems and some water conveyance systems are not intended to be operated to meet a demand. Proper automation of a water system requires an analysis of what the system is intended to do and an economic comparison of the alternatives to maximize the benefits.

Advances in technology now make some types of automation possible for almost any water system. Equipment is now becoming available which can be used to monitor and control even the most complex installation. However, the application of these new tools of technology to water projects is often limited by economic considerations.

A partial inventory of types of automation in use on Reclamation projects is included as an appendix to this report. The inventory includes installations on carriage facilities-canals, carriage facilities-pipelines, diversion dams, major pumping plants, and storage reservoirs-outlet works. Information on the type of equipment and mode of control is included where known. Also included in the appendix is a list of definitions of commonly used automation terms and a description of the basic parameters of downstream control.

AUTOMATION NEEDS

Automatic and remote controls are needed for water storage and conveyance systems to improve service to water users, increase efficiency of operation, and reduce cost of operation.

Recent Bureau of Reclamation water-use studies have shown that an average of only 44 percent of the water delivered to irrigators' fields on Reclamation projects is stored in the root zone for beneficial comsumptive use by crops. Seepage from canals and laterals accounts for 20 percent of the total water diverted for irrigation in the United States. These percentages do not represent real losses because much of this water returns to streams or replenishes ground-water aquifers that provide the water source for wells or springs. ***However, there is a real need for improvement of management and utilization of water in irrigation operations.*** Factors responsible for inefficient management and utilization of irrigation water are many and often interrelated. Application of modern technology in programs of research and development for automation of water systems will improve the efficiency of project and farm irrigation systems and management of conveyance and distribution systems. ***More efficient use and better management of irrigation can make more water available for municipal, industrial, and recreational use to help meet today's and future needs.***

No absolute rule can be made to include or omit automatic or remote controlling and monitoring devices on specific features of Bureau projects. Planners, designers, and operators together face the tasks of analysis and synthesis to arrive at solutions for each feature and/or project. Comprehensive studies of costs, safety, and reliability along with the service to be provided by each feature and the overall type of operation desired should be assembled prior to final decisions. Listed below are some of the items which should be considered in these studies:

1. Water conservation measures.
2. Water rights—downstream requirements.
3. Operator attendance.
4. Accessibility of water system features.
5. Communication channels.
6. Degree of control desired.
7. Maintenance of automation system.
8. Reliability of forecasting.
9. Rapidity of inflow and time available for operation.
10. Consequences of overtopping storage or conveyance features.
11. Reliability of power source.
12. Reliability of automatic control equipment.
13. Shutdown time for power generating stations or pumping plants.
14. Economic comparisons.

The water users' need for water is not always predetermined sufficiently in advance to assure expeditious delivery or permit rapid shutoffs. Such uncontrolled situations as unexpected rainfall or the need for protective spray to prevent frost are often not readily accommodated. Control systems which make water more quickly available greatly enhance the margin of profit for water users, and those which accommodate quick shutoffs can improve system efficiency.

Automation of water systems is needed to reduce labor cost to the water user. Simple automatic devices have been used for many years to operate single water control structures. Although these devices are limited in the degree of control they can provide, they are proven labor-saving devices. In the past most such devices have been for control of individual structures. A real need now exists for equipment and concepts which will provide efficient operation of complete conveyance and/or distribution systems. This requires a systems approach to fit the concepts and equipment to the operational needs. The end product will go beyond automation per se and will include operations research techniques to optimize the controls and operations. Further sophistication of automation devices will not only reduce labor costs but help conserve water through better operation of water control structures.

The facilities of a typical water system can be classified generally as storage works, diversion works, conveyance system, and distribution system. The storage works consist usually of one or more storage reservoirs, generally having outlet works for regulation of water releases therefrom, and a spillway for protection of the dam. The diversion works may consist of a typical diversion dam with headworks for controlling releases into the conveyance system, and with a sluice gate and spillway for stream regulation and protection of the structure. It may also consist only of a headworks or a pumping plant discharging into the conveyance channel. The conveyance system generally is an open-channel system with structures for control of flow in the system and for delivery into the distribution system. It may also be a pipe or aqueduct with control and delivery structures. The distribution system is a series of open ditches or pipe laterals with a control structure and a delivery structure to the water user. Often the same control concepts can be applied to the conveyance and distribution systems.

Automation has been applied in varying degrees to all types of water control structures from the storage works through the distribution systems. Each water control structure serves a specific function in a water system. Generally speaking, all of the control structures control either a water surface elevation by regulation of a control gate or pumping plant, or control the quantity of water being discharged through or into a particular structure. The type of automation selected to accomplish a particular control structure function or to operate a total water system depends upon the requirement for and economics of the particular situation. The discussion of the need for automation in the following sections includes descriptions of the functions of various water control structures as they apply to the segments of the total system. The concepts of operation of the control devices and the applications of these devices are discussed in the next chapter—Operation and Automation.

STORAGE WORKS

Outlet Works

Perhaps more than any other water control structure, outlet works of dams are operated on a scheduled basis. At present, changes for system demands are seldom made automatically at the storage reservoir. Consequently, most outlet works are either manually or remotely operated. *Operation of water systems in a manner which automatically meets the demands of the water users will require automatic operation of outlet works.* In many systems, remote control of a distant storage dam outlet works can result in a cost savings due to the elimination of the need for a full-time dam tender.

Spillways

In contrast to the routine operating purposes served by other automatic applications discussed in this report, spillway gate automation serves primarily as an emergency protective device. Spillways pass flood inflows in excess of outlet works discharge and available reservoir storage capacities. *The use of gated spillways introduces* *the possibility of overtopping and failure of the dam if the gates are not properly operated during critical flood periods.* Concrete dams provide greater safety against failure due to overtopping; therefore, automatic operation of those spillway gates is not usually required. Automatic spillway gate operation is provided on some Reclamation earth dams to insure proper gate operation.

DIVERSION WORKS

Diversion Dams and Structures

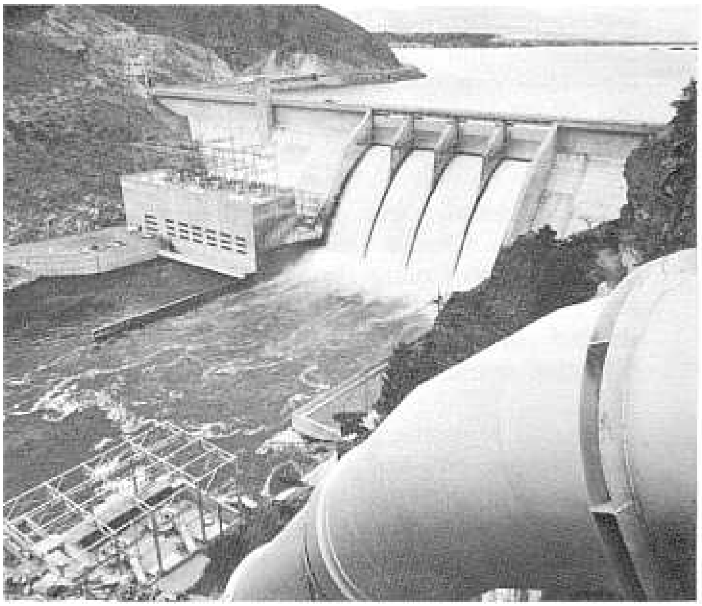
While diversion dams and canal headworks are often self-contained and isolated, they can be the focal point for demands of the distribution system. ***The control operation must not only meet downstream demands in the river and diversion demands, but also must dampen hydraulic transients to provide smooth operation of the entire system.*** Operation can be very complicated and often requires a hierarchy of control features. For example, a minimum downstream release to the river may be required to meet water rights and/or fish and wildlife commitments. Additional available supply may be diverted. Diversion discharge is, of course, limited to diverison demand and system capacity. Excess supply is usually wasted or bypassed downstream. The discharges involved are often defined legally and very stringent measurements, monitoring, and controlling are required. Automatic controls can be designed to not only provide the control functions required at these installations, but also to perform the logic required for hierarchical decisions.

Pumping Plants

Pumping plants are required to raise water from a water supply to an elevation where gravity flow can deliver the water to the user. Pumping plants are usually designed with several pumping units of various sizes so that the discharge from several combinations of units can closely approximate the water demand at any particular time. *Water conveyance systems that operate with manually controlled gate structures can satisfactorily be supplied by a pumping*

Red Bluff Diversion Dam, a feature of the Central Valley Project in California. This structure illustrates the complicated operations often encountered at irrigation headworks. The facility includes fish diverters and ladders, a sedimentation basin and spawning bed, and the diversion works for the Tehama-Colusa Canal, all of which require well coordinated operation. Photo P-602-200-5667 NA

Helena Valley Pumping Plant and Canyon Ferry Dam, Montana. The two pumps in the foreground lift water to be discharged into the Helena Valley Canal for delivery to irrigators and municipal users. Photo P296-600-971A



plant that has pumping units with manual ON-OFF control. However, when the water conveyance system is operated automatically on a demand basis, the supply pumping plant must also include automatic downstream control. Thus, the degree of pumping plant automation and the number and sizing of pumping units are defined by the degree of automation provided for the downstream water system.

CONVEYANCE AND DISTRIBUTION SYSTEMS

Canal Checks

Canal check gates should be automated to improve the operation of a canal, to isolate reaches of a canal in the event of a break, and to eliminate repetitive operator attendance.

To provide full turnout discharge or delivery from a canal, a specific minimum depth of water is required. Automatic controls will sense deviations of water surfaces on the canal and operate adjacent checks upstream or downstream to provide a nearly constant water level. Interference or interplay between canal checks in series may cause hydraulic transients to build up and create undesirable conditions. Optimum operation will result only from proper control of the entire canal system. A control scheme which takes this interplay into account can result in operation as efficient as that of a closed pipe system.

Canal breaks can flood the surrounding countryside. Checks can be operated in such an emergency to isolate reaches of a canal so that the entire canal is not drained. To provide the desired checking action, the check gates may be operated manually, remotely, or automatically.

Manual operation requires manual opening and closing of the gate at the canal check. Remote monitoring and control has the advantage of bringing water level and gate position information to a central point. From this control center man or computer can make decisions to operate the control gates for the entire system.

Prototype installation of automatic controls above a canal check. Photo P801-D-73319

Pipe Systems

Full pressure pipe systems provide the best system of automatic control of discharge. *For demand systems, water delivery to turnouts, as with household faucets, can vary from no flow to full flow or vice versa automatically with no prior scheduling by the user. Full pressure pipe systems meet this demand.* ***Because of this inherent capability, a higher state of automation has been achieved for full pressure pipe systems than for open systems.*** However, these pipe systems are sometimes prohibitively expensive; thus low head pipe systems or open channel systems are used. Also, demand systems do not have universal application.

Low head pipe systems present special control problems due to their tendency to amplify harmonic surges. The cost of such a system is usually between that of a comparable open-channel and a full pressure pipe system. Many miles of low head pipe have been installed on Reclamation projects. Generally, such systems do not have the rapid response of full pressure systems and prior scheduling for operation is required. Special needs do exist for the automatic operation of both full pressure and low head pipe systems. On Reclamation projects, common control problems include limiting head to economic ranges, limiting discharge, and limiting water-hammer transients.

Turnouts

Automation of gravity flow turnouts is needed to provide uniform deliveries from distribution systems. A changed water surface in a canal or a changed pressure in a pipeline change the rates of flow through turnouts from the canal or pipeline. Turnout flows that increase or decrease unexpectedly are difficult to accommodate and often create costly and time-consuming problems for irrigators using surface irrigation. ***Automation can eliminate these problems with equipment that adjusts a turnout to maintain uniform delivery in spite of fluctuating water surfaces or pressures.***

Operators of manually controlled canals and laterals often find it difficult to maintain uniform water surfaces while making the changes necessary for operation. This difficulty is increased by the occurrence of unexpected storms. The automation of control structures will increase the stability of water surfaces on canals and laterals where such automation is installed. However, different concepts of automation provide different degrees of stability, some of which are not compatible with gravity-flow turnouts. Automation of the turnout structures can eliminate this incompatibility, thereby increasing the overall flexibility of operating concepts. Improved operation resulting from automated turnout structures will not only benefit irrigators by minimizing problems associated with

Aerial view of the intake channel to the Pleasant Valley Pumping Plant, a major turnout on the San Luis Canal a few miles from Coalinga, California. Photo P805-200-587 NA nonuniform delivery, but will also permit the operators of distribution systems to be more accurate in scheduling operations. Accurate scheduling promotes the conservation of water resources by eliminating the need for operation waste.

Wasteways

Wasteways are the traditional safety valves of canal operation. They remove excess water and prevent overtopping the canal. Scheduled excess or operation waste is caused by inability to adjust turnout flows to exactly equal flow into the canal. Unscheduled excess occurs as the result of unscheduled reduction in delivery flows or inflow resulting from storm runoff. Wasteways require automation to assure that either scheduled or unscheduled excess water is removed from the canal without attendance by an operator.

Wasteways have been automated in the past whenever canals are designed to accept storm inflow or where large amounts of unscheduled excess water can be expected from other sources. Future installations should include such provisions. Operational waste should be eliminated or greatly reduced where a high degree of automation is provided for other structures within a system.

OPERATION AND AUTOMATION

CONCEPTS OF OPERATION

General

If a sufficient supply of water exists and the conveyance system is capable of transporting the appropriate flows, then a water system can be operated to meet the needs of the users. Such a demand-type system is not feasible, however, if the supply or the conveyance of water is limited to lesser amounts than required. Where the use of water must be limited because of less than adequate storage or conveyance capacities, a supply-type system is necessary. For instance, a domestic water supply usually operates to meet the demands of the users whenever a faucet is turned on. However, in times of water shortages, water use is limited and water is available only on a rationed or prorated basis. Conversely, in any water system, if water is available in plentiful supply and the conveyances are adequate, the system can be operated to meet the demands. Otherwise, water may be only available to users with the highest priorities or all users may have available only a fraction of their full demand.

The two most common methods of operating a water system utilize either upstream or downstream control. With upstream control the sensor is located upstream from the structure being controlled and with downstream control the sensor is located downstream from the structure being controlled. Upstream control is associated with a supply-type operation and downstream control is associated with a demand-type operation. Also, open-channel systems have predominantly been operated with unstream control while pressure conduit systems have for the most part been operated with downstream control.

Each of the structures described previously can be operated with either of these methods but upstream control has been the traditional method of operation on open-channel systems. Whether upstream or downstream the method of operation can be independent of the automation incorporated therein. However, downstream control of open-channel systems has been achieved largely through the use of automatic devices.

The operation of storage dam outlet works is usually based on meeting the needs of the water users consistent with providing storage reserves. Thus, releases from storage during periods of adequate supply serve to meet the full demands of the users. During periods of limited supply, however, the releases are restricted and a system of priorities or across-the-board reductions is imposed. The flow of water can be traced through the system from source to user and the control structures described previously can be operated to meet the demand on the system or to deliver a restricted supply to the users.

Upstream Control

Equipment that is operated to regulate a water surface immediately upstream from the controlling element provides upstream control, Figure 1. When more water is supplied than is required to satisfy deliveries, the excess is passed downstream to the end of the conveyance where it must be wasted or stored. When the supply is less than the demand, deficiencies will first affect deliveries at the lower end of the system. Satisfactory operation depends upon the amount of water supplied to the system. This type of operation is called a supply system. To assure that all deliveries are satisfied, operators of supply systems usually introduce a little

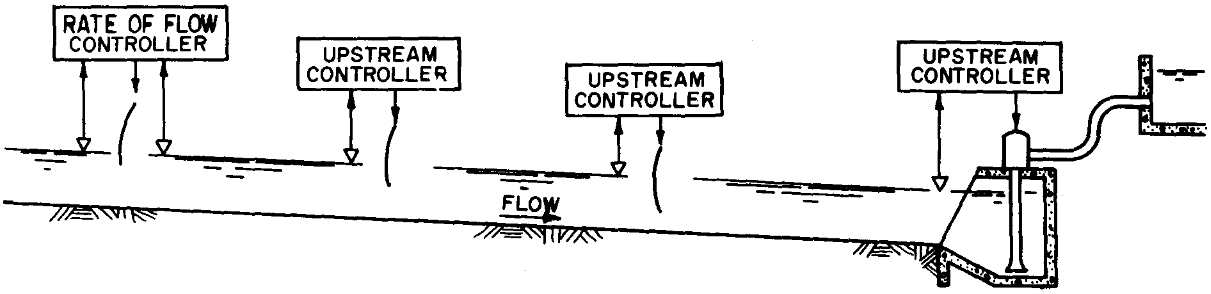


Figure 1.–Upstream control–Supply operation.

excess water into the system, which results in operational waste.

Traditional operation of a water system is complex, requiring numerous visits to control structures for adjustment when changes are made. Water is introduced into the system according to schedules developed from orders placed by users. As the water reaches each control structure in the system, that structure must be adjusted to pass the desired flow. When changes are large, adjustment at individual structures may require several hours. Satisfactory operation requires scheduling sufficiently in advance to allow water to travel from the source to arrive at the point of delivery at the desired time.

Automation of upstream control is most appropriate for structures where inflow cannot be scheduled, such as spillway control gates on dams, and wasteway gates that remove storm inflow from a canal. Automation of upstream control is also generally appropriate for structures in conveyances that are operated in the traditional manner. Traditional operation becomes more appropriate as the distance between control structures becomes greater. Other situations which are compatible with traditional operation are long lengths of conveyances with insignificant turnout requirements and conveyances where travel time is not critical such as a channel which transports water from a large storage source to a large storage sump.

On traditionally operated canals, water surfaces upstream from control structures are normally maintained at a constant elevation for all flow conditions, Figure 2. The achievement of uniform flow through each check reach is delayed by the need to either build up or draw down storage within the reach. Extensive systems that require considerable time between the introduction of water into the system and delivery often use regulating reservoirs to speed up response.

Automation can minimize the need for developing schedules for the operation of upstream controlled structures. In all other respects, the requirements for operating an automated upstream controlled conveyance are the same as for local manual operation in that:

1. Deliveries may be controlled manually or by some other automatic equipment.

2. Operators must develop schedules for introducing water into the conveyance based on desired delivery rates, desired delivery times, and the time required for water travel to the delivery locations.

These similarities permit the installation of upstream controls on individual structures

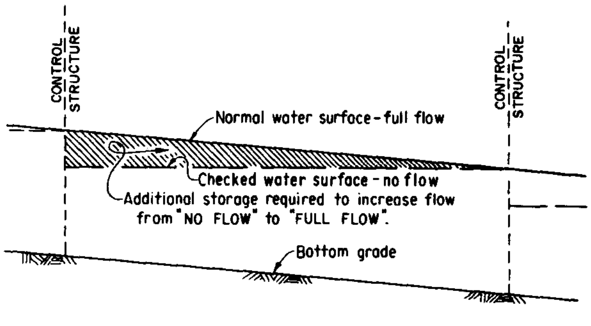


Figure 2.–Traditional concept of canal operation.

without requiring automation of the entire conveyance. Rate-of-flow controllers are often utilized at headworks or inlet structures to assure that inflow into the conveyance remains uniform.

Downstream Control

Equipment that is operated to regulate a water surface downstream from the controlling element provides downstream control. The sensor location is selected at a point that provides the best intelligence to relate downstream demands to upstream inflow, to provide stability of control, and to maximize the channel capacity. Generally, this means that the sensor should be at the downstream end of the reach, Figure 3. Such location reduces the need for considering variations of friction factors, but usually increases the effect of time lag.

Where downstream controls are used to maintain uniform flow through a Parshall flume or over a weir they become rate-of-flow controllers. The control water surface should be located appropriately for measuring depth of flow through the structure. The measuring structure should be installed as near as practical to the controlling element to reduce lag. Commercial rate-of-flow controllers are also available to suit nearly all types of commercial measuring devices.

Downstream control provides a demand-type operation in which overall operation is controlled by the amount of water being withdrawn from the conveyance. As water is withdrawn, controlling elements are adjusted to introduce water into the system. Operational waste is minimized because the amount of water being supplied to the system at any time is determined by the amount of water being withdrawn.

Downstream control eliminates the need for developing schedules for either the operation of individual structures or for introducing water into the system. Except for control of deliveries, no manual input is required as long as sufficient water is available at the inlet or headworks structure. When the supply of water is not sufficient to meet the demand, deficiencies first affect deliveries at the upper end of the system.

Pressure pipe conveyances inherently provide a demand-type operation. However, several factors make demand-type operation more difficult to achieve on open-channel systems. Gravity flow with a free water surface is more sluggish and more sensitive to relative variations in head than is flow through pipe under pressure. The dead time or time required for a change of flow to move through the system is much greater for an open system than for a pipe system. Water surfaces must be controlled more closely because the physical facilities required to contain wide fluctuations are much more extensive and costly.

Because pressure pipe conveyances inherently provide a demand type of operation, the operators of pipe systems readily recognize the concept of downstream control. Conversely, the concept is difficult for many operators of open-channel systems to understand because it is contrary to their traditional method of operation. Upstream controls are not normally intermingled with downstream controls on a conveyance except downstream controlled rate-of-flow controllers are sometimes used at

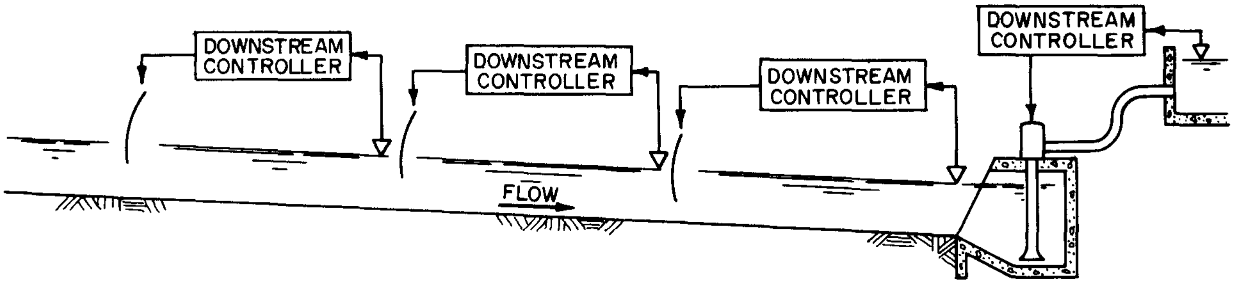


Figure 3.–Downstream control–Demand operation.

the headworks of upstream controlled canals. However, different conveyances within a system may be appropriate to either method of control depending upon operational requirements.

Downstream control is most appropriate for automating structures where deliveries cannot be scheduled, such as in a municipal or industrial water supply system. The appropriateness of downstream control increases with increasing difficulty in preparing accurate schedules for both introducing water into the conveyance and detailed operation of control structures. An increasing trend towards demand-type operation by irrigators also increases the appropriateness of downstream control for all conveyances that have appreciable delivery requirements.

Controlled Volume Operation. During the formulation of plans for operating the California Aqueduct, the California Department of Water Resources developed a new concept of canal operation. ***Operation by this method, called controlled volume operation, virtually eliminates the need for regulating reservoirs while increasing operational flexibility. Response time is reduced to the time required to achieve stable flow within a check reach. However, adjustments at control structures must be scheduled and well coordinated.*** This method of operation is included in operational studies that are underway for the Granite Reef Aqueduct on the Central Arizona Project.

This new concept was originally called constant volume operation because it appeared that the volume of water within each check reach would be maintained at a nearly uniform value for all flow conditions, Figure 4. However, hydraulic analysis shows that this is not always the case. Controlled volume operation does reduce the need to build up or draw down storage required for traditional operation.

By controlling water surfaces upstream from control structures at elevations that are higher than required for flow at design capacity, controlled volume operation provides capability to pass design flow through each structure at any time. Simultaneous adjustment at all structures makes it possible to adjust canal operation at any time to any desired condition. Remote adjustment of these control structures is needed to provide the coordination required. Detailed schedules of flow requirements at each structure are also needed. Computer-assisted operation is desirable where numerous adjustments must be made simultaneously.

TYPES OF WATER SYSTEMS AUTOMATION

General

The trend in recent years has been toward increased automation of water systems, as described previously in this report. Not only are automatic controls desired for existing installations but automatic operation is also being included for features that are either under construction, in the design stage, or being planned for future construction. *This trend increases the importance of understanding both the concepts that are available for operating water systems and the present capabilities of automation to conform to these concepts.*

The application of automation to water systems has been in the form of local automatic (feedback) control or remote control. These categories are somewhat overlapping, however, in that remote automatic operation can use feedback control. Nevertheless, the following discussion of feedback control, remote control, and applications serves to describe the current state-of-the-art for automation of water systems.

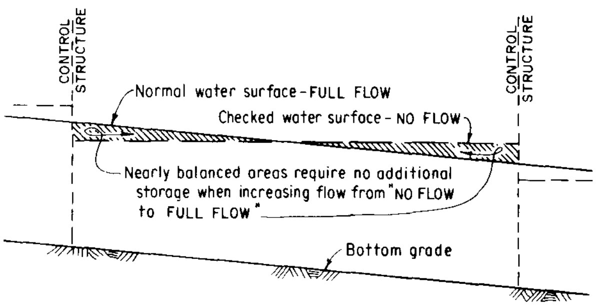


Figure 4.–Constant volume concept of canal operation.

A completely automatic system requires no input from operators for normal operation. Arrangements of equipment sense physical conditions and make the decisions and adjustments necessary for operation. Municipal water systems often provide highly automated operation in which overall operation of the system is controlled by individual users as they withdraw water from the system. Operators do not enter the decisionmaking process until the conveyance becomes relatively large. Irrigators also desire this type of demand operation.

Because of difficulties in estimating realistic friction factors for conveyances and discharge coefficients for gates, operators of water conveyance systems normally utilize water surfaces at selected locations within the system as indicators of desirable conditions. It thus becomes appropriate for automatic control equipment to utilize water levels to control operation. Flow is normally measured where required for accounting purposes or to assure proper operation of the system. The alternative method of controlling operation by estimating flows at all control structures presents additional complications.

The automation of industrial processes is highly developed. Knowledge of the characteristic results of different control functions and appropriate application of these functions has developed into a specialty. Where similarities exist this knowledge and much of the equipment developed for industrial automation has application to Bureau requirements for automatic operation of water conveyance systems. *Much of the equipment needed for automatic operation of Reclamation pipe conveyances is available commercially. However, while present technology now makes it possible, there is very little commercial equipment that has been developed specifically for, or can be appropriately applied to, automatic operation of open-channel conveyances.*

Feedback Control

General. *Basic feedback control systems are designed to return a portion of the output signal to the input of a controller to maintain a prescribed relationship between input and output signals.* This feature provides a means to damp out oscillations and produce minimum overshoot for a more stable and responsive control system.

Feedback controls for the automatic operation of water conveyance systems can control either rate-of-flow or water surfaces. The following discussion is directed primarily towards controllers that control water surfaces although the principles involved also apply to rate-of-flow controllers. Feedback controls that operate equipment to control water surfaces do not require the difficult field calibrations of gates and valves that are associated with rate-of-flow controllers.

The characteristic manner in which feedback controls perform control functions, or react to deviations of the controlled variable, is called the mode of control. The five common modes of control are ***two-position control, floating control, proportional control, reset action,*** and ***rate action.***

Two-position, floating, and proportional controls provide three different control functions, and all three of these modes of control are in common use on Reclamation projects. Equipment installed for each of these types of control varies widely because some of the automation on Reclamation projects has been developed independently by operating personnel. Limitations imposed by mechanical equipment and differing local conditions have also required modification of the control function in many instances.

Reset action is generally used with proportional control to eliminate the offset that is inherent in this mode of control. Rate action never exists alone, but is always combined with proportional or proportional plus reset actions to increase the speed of response and reduce overshoot of the controlling element. Equipment for accomplishing proportional plus reset control of water systems is under development. Future studies are planned to include proportional plus rate control and proportional plus reset plus rate control.

Mathematical representation of these control functions becomes desirable when feedback control is to be programed into a computer for real-time control or study. Feedback control can be represented mathematically by the generalized process control algorithm

$$\text{Output} = \underbrace{K_1\,(e)}_{\text{Proportion}} + \underbrace{K_2 \int_0^N e\,(dt)}_{\text{Reset}} + \underbrace{K_3\,(de/dt)}_{\text{Rate}}$$

where output = position of the controlling element

K_1, K_2, and K_3 = real numbers representing gain factors of proportion, reset, and rate, respectively

e = deviation of the controlled variable (error)

de and dt = increments of deviation and time, respectively

N = period of time for reset action

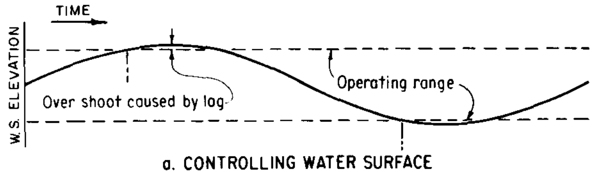
Two-position control is a special case of the proportional portion of this algorithm in which Output = ON or OFF and e = 0 or 1. Floating control is a special case of the reset portion of this algorithm where e = 1, 0, or −1.

Two-position Control. *Two-position control is the simplest mode of automatic control.* The control function moves the controlling element to one of two extreme positions as determined by the controlled water surface. When these two extreme positions become fully opened or fully closed, the controller becomes an ON-OFF controller, and can be an electrical switch for the operation of pumps, Figure 5.

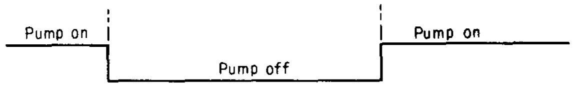
Water surfaces controlled by two-position controls will cycle continuously from one side of the operating range to the other. Excessive cycling can be reduced by increasing storage in the operating range. Corrective action should be slightly larger than the maximum requirement. ***Two-position controls are most appropriate for installations where storage is large as compared to the rate of corrective action.*** If storage is large and corrective action occurs at a suitable rate, lag becomes immaterial.

Floating Control. Floating control is more properly called single speed floating control. *In contrast to two-position control, which changes the position of the controlling element from one extreme position to the other (ON-OFF), floating control changes the position of the controlling element at a constant speed whenever the controlled water surface deviates from its target depth by a predetermined amount.* The direction of gate movement is determined by the direction of the deviation. The controlling gate makes no movement as long as the controlled water surface is within the dead band (the desired range of operation). When the controlled water surface is outside the dead band, the controlling gate will continue to move until either the water surface returns to the dead band or the gate reaches a fully opened or fully closed position. The control function and its common modifications are shown in Figure 6.

The speed at which the controlling element moves is critical for floating controls. Movement is at a much slower rate than for two-position control because intermediate positioning is desired. Controlled water surfaces have an inherent tendency to cycle, which can be minimized and often limited to the width of the dead band by a proper speed of corrective action. Significant lag in the system, or rapid load changes even though small, will aggravate these cycling tendencies. ***Floating control is most appropriate for installations with no***

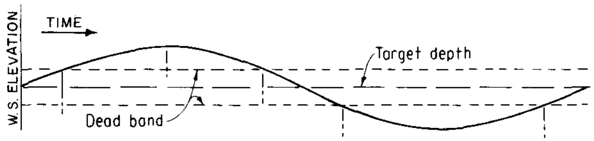


a. CONTROLLING WATER SURFACE
(CONTROLLED WATER SURFACE SIMILAR)

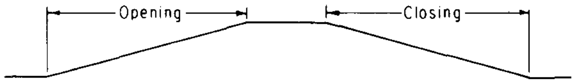


b. CONTROL FUNCTION IN PUMP OPERATION
(ORIENTED FOR DOWNSTREAM CONTROL)

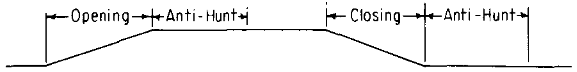
Figure 5.—Two-position control.



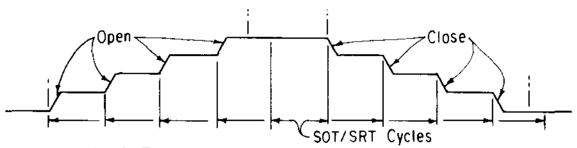
a. CONTROLLING WATER SURFACE (RESULTS OF CONTROL NOT SHOWN)



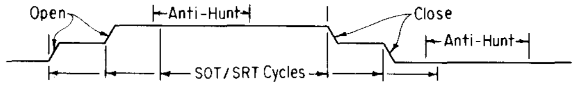
b. CONTROL FUNCTION IN GATE OPERATION (ORIENTED FOR UPSTREAM CONTROL)



c. CONTROL FUNCTION MODIFIED BY ANTI-HUNT



d. CONTROL FUNCTION MODIFIED BY SOT/SRT



e. CONTROL FUNCTION MODIFIED BY SOT/SRT AND ANTI-HUNT

Figure 6.–Floating control.

appreciable lag and where load changes can be counteracted by gradual changes in gate position. Corrective action should be slightly faster than needed to accommodate the most rapid load changes that can occur.

When the controlling gate moves too rapidly it behaves like two-position control with characteristic cycling of the controlled water surface and frequent reversal in direction of gate movement (hunting). Because the mechanization provided on most Reclamation gates is intended to permit manual adjustment as rapidly as practicable, the resulting speed of movement is usually much faster than desired for single speed floating control. *In order to achieve the slower movements required for their installations, most operators have incorporated timers into the control equipment to provide* ***set-operate-time/set-rest-time (SOT/SRT)*** *cycles of operation for gate motors.* Adjustability in the timer settings provides flexibility to select the appropriate average speed of gate movement for each structure. A completely stable gate position for uniform flow is seldom achieved by this modification, because, as the gate moves a predetermined amount in each cycle, it seldom arrives at the exact position required. However, controls that make two small adjustments or less in an hour are ususally considered satisfactory.

A controller that reacts too slowly cannot keep pace with changes and lags behind deviations of the controlled water surface. By the time a lagging controller has made sufficient adjustment of the controlling element to reverse the direction of water surface movement, the adjustment is often larger than needed to maintain uniform flow. Unless the control function is modified, the gate will continue to move while the water surface is returning to the dead band, increasing overshoot in corrective action. Similar lag then creates overshoot in the opposite direction so that long period cycles develop. Flow conditions can amplify these cycles.

In order to reduce these long period cycles, some operators have incorporated a friction clutch and additional switches into float-operated equipment to provide an antihunt device. The antihunt device prevents additional gate movement when the controlled water surface is returning to the dead band, even though the water surface is outside the dead band. Use of the antihunt device increases the range of changes that can be accommodated by single speed floating control. The device is not completely effective because it can stabilize uniform flow outside the dead band for some flow conditions. In addition, when installed for downstream control it frequently prevents desired gate movement.

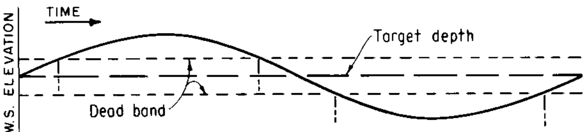
The major portion of operating time on open channel conveyance systems usually involves uniform flow. When changed flow conditions are required, the changes are made as rapidly as possible. In order for a controller to be satisfactory, it must not only provide a stable gate position for uniform flow, but also it must be able to change the gate opening rapidly to suit flow changes. Single speed floating control usually does not have the range of operation needed to suit the extremes of both of these requirements. As a result, most controllers are adjusted to provide gate movements slightly larger than needed for uniform flow and antihunt devices are added to reduce the cycling that occurs with flow changes.

Proportional speed floating controllers, available commercially, provide the flexibility that is lacking in single speed floating control. Proportional speed floating control provides a type of action in which the controlling element moves faster in its corrective action as the controlled variable deviates farther from its desired value, Figure 7. This changing speed of movement requires that the controlling element be operated by a variable speed motor in lieu of the constant speed motors usually installed to operate gates on Reclamation canals.

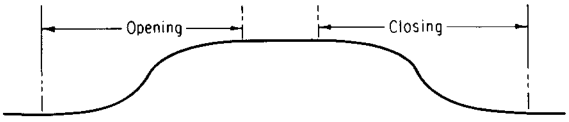
Flexibility of some SOT/SRT floating controllers has been increased by superimposing additional control stages, with wider dead bands and faster gate movement, upon a single speed floating controller. This modification also provides a type of action that is similar to but more restricted than that provided by proportional speed floating control. Figure 8 shows some of the control functions attainable by combining two stages of floating control. *The results of mathematical model studies show that one additional stage greatly increases the capability of a controller.* Two- or three-stage floating controls can probably be designed to eliminate the need for an antihunt device on installations appropriate for floating control.

Flexibility has also been provided for some floating controllers to accommodate rapidly changing water surfaces by the addition of a function that increases the width of the dead band each time the gate moves, Figure 9. This modification results in a gate movement that strongly resembles proportional control. ***Increasing the dead band width provides a variable rest time and cycle time so that these controllers become set-operate-time/variable-rest-time (SOT/VRT) controllers.*** The variable rest time inherently provides antihunt action with all its associated advantages and disadvantages.

Proportional control. *With proportional control (more properly called*

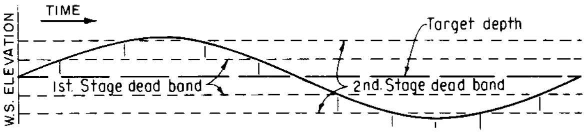


a. CONTROLLING WATER SURFACE
(RESULTS OF CONTROL NOT SHOWN)

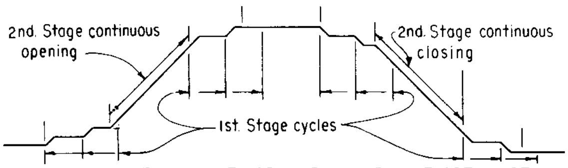


b. CONTROL FUNCTION IN GATE OPERATION
(ORIENTED FOR UPSTREAM CONTROL)

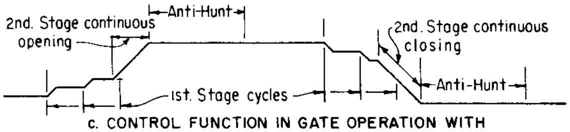
Figure 7.–Proportional speed floating control.



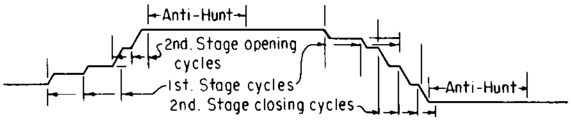
a. CONTROLLING WATER SURFACE
(RESULTS OF CONTROL NOT SHOWN)



b. CONTROL FUNCTION IN GATE OPERATION WITH SOT/SRT 1st. STAGE
(ORIENTED FOR UPSTREAM CONTROL)

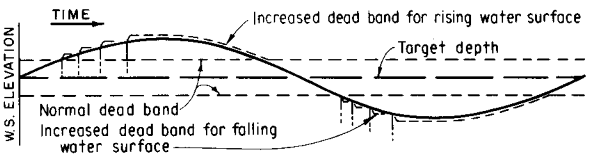


c. CONTROL FUNCTION IN GATE OPERATION WITH ANTI-HUNT AND SOT/SRT 1st. STAGE

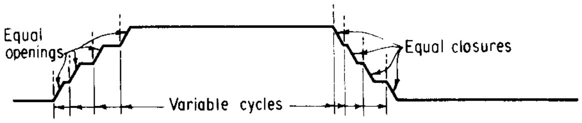


d. CONTROL FUNCTION IN GATE OPERATION WITH ANTI-HUNT AND SOT/SRT BOTH STAGES

Figure 8.–Two-stage floating control.



a. CONTROLLING WATER SURFACE
(RESULTS OF CONTROL NOT SHOWN)



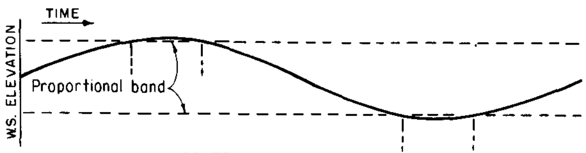
b. CONTROL FUNCTION IN GATE OPERATION
(ORIENTED FOR UPSTREAM CONTROL)

Figure 9.–SOT/VRT floating control.

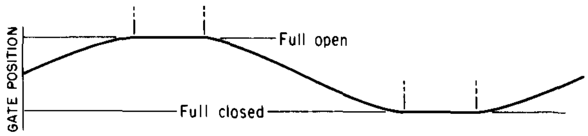
proportional-positioned control), the position of the controlling element has a fixed relationship to the controlled variable. A controlling gate has a position for each water surface elevation that is defined by multiplying deviation of the water surface by a gain factor. The elevation of the controlled water surface varies from one edge of the proportional band for no flow to the other edge of the band for full flow, Figure 10.

Because the controlled water surface must be expected to vary throughout the proportional band, proportional control is not appropriate for installations where it is necessary to maintain a constant water surface elevation. ***Where designs provide a range within which the water surface can fluctuate, or where fluctuation throughout the proportional band can be tolerated, proportional control becomes appropriate.*** For example, upstream proportionally controlled gates are most appropriate for flood control structures, because designs usually include an operating range compatible with the proportional band. At such installations the proportional action of the gate combines with storage that increases rapidly as the controlling water surface rises to provide the usually desired function of retarding flow from storm runoff. Flow through the gate is related to the amount of water impounded rather than inflow at any specific time.

Very little information is available on past usage of proportional controls for automating canal control structures. Except for the limitations imposed by the need for a proportional band, proportional control is appropriate for either upstream- (supply-) or downstream- (demand-) type operation. Adaptability to combination with dead time (lag), and the reset and rate modes of control make it most appropriate for downstream control. Resulting operation should inherently be very responsive to changes of any size at any point in a system, and have a high degree of safety against overtopping the canal in emergency conditions.



a. CONTROLLING WATER SURFACE
(RESULTS OF CONTROL NOT SHOWN)



b. CONTROL FUNCTION IN GATE OPERATION
(ORIENTED FOR UPSTREAM CONTROL)

Figure 10.–Proportional control.

The width of the proportional band and its associated range of controlled water surface variation is a function of gain factor. In canal operation, an inverse relationship exists between gain factor and stability of flow. Stability increases as gain factor decreases. These relationships work against each other to create stability problems when a narrow proportional band is desired. The width of proportional band required to achieve stable flow in canals often becomes unacceptable for gravity deliveries. However, the range of water surface variation is usually not large enough to have a serious effect upon pump discharges. Therefore, proportional control is generally appropriate for use on open systems where deliveries are made by pumping.

Proportional Plus Reset Control. *Proportional control can be made more acceptable for open systems with gravity deliveries by the addition of a reset function to eliminate the proportional deviation.* Addition of the reset function does not eliminate variations of the controlled water surface elevation that occur when flows change, but it does return this water surface to the elevation that existed before the change. Minor differences in position of the controlled gate account for the characteristic differences shown in Figure 11 between water surfaces controlled by proportional control and those controlled by proportional plus reset control.

By recovering the controlled water surface to the original target depth, proportional plus reset control makes overall operation of the canal similar to traditional operation in that flow changes also require appreciable changes in the storage of each check reach. Gates at the upstream end of the canal will make larger adjustments to accommodate these storage

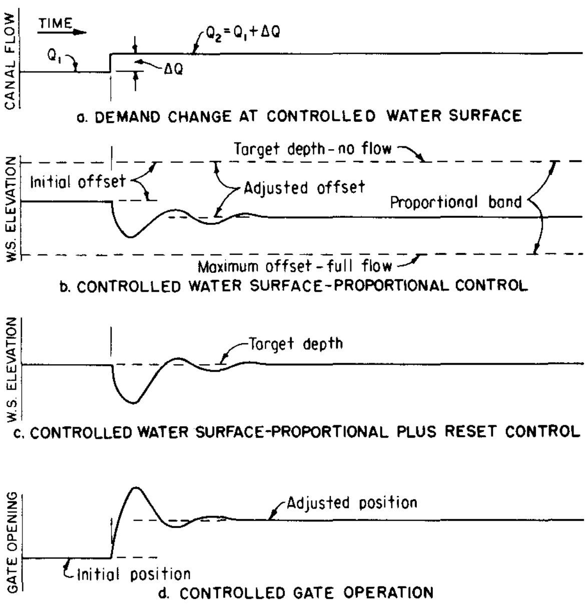


Figure 11.–Characteristic results of control by proportional and proportional plus reset modes oriented for downstream control.

changes. Water surface fluctuations will be temporary, disappearing as the reset function takes effect. As long as incremental flow changes do not exceed 20 percent of design capacity, controlled water surface fluctuations are expected to be no larger than those that occur from manual operation, and automatic operation is expected to be highly responsive to changes anywhere in the system. However, canals operated by proportional plus reset are not as safe against overtopping as canals operated by proportional control because decreased demand causes upsurges similar to the downsurges caused by increased demand. The possibility of power outages on systems with large pump deliveries may require additional canal freeboard.

Remote Control

Manual Operation. The capability for remotely operating control structures often results in improved operation of water conveyance systems. Any installation that provides the capability for remote control should also include telemetering of sufficient data so that the operator can determine the results of adjustments and also be alerted to the development of undesirable or dangerous conditions in the system.

Operation by remote manual control can be quite similar to operation by local manual control. Schedules for operation of the various control structures should be developed based on experience. However, the additional flexibility of controlling all structures from a master station permits a high degree of coordination in adjusting structures. Properly utilized, this coordination can greatly reduce the time required to accomplish flow changes in many conveyance systems.

Automatic Operation. Automatic operation of remote control systems becomes desirable on installations where numerous adjustments must be made within a short period of time, or where close attendance by an operator is required over a long period of time. Additional equipment to accomplish automatic operation is usually located at the master station. This equipment is energized to perform control functions either at predetermined times or in response to conditions interpreted from telemetered data.

While special equipment can be assembled to perform some individual operations automatically, an interface with a computer greatly increases the flexibility of automatic controls for accommodating numerous and varied control functions. In addition to programing that accomplishes selected control functions at predetermined times, a computer can also be programed to interpret telemetered data and perform complicated control functions. Because of this extreme flexibility, ***the adaptability of a computer in providing a programmable master supervisory control (PMSC) appears to be limited only by the ingenuity and imagination of the designer.***

Equipment. Commercial equipment is generally available for manually performing remote control functions from a master station. Commercial equipment is also available for telemetering data concerning most of the conditions encountered, and for automatically performing many of the control functions required. Special arrangements of equipment can usually be assembled from commercially available components to accommodate those situations where equipment is not readily available. Some situations will require development of new equipment and specialized computer programing.

The major portion of cost for a remote control system is represented by the communication channels that are required between the master station and all remote stations. The type and number of circuits required are determined by the manner in which the controls are to be operated and by the amount of data that is to be telemetered. Direct-current (dc) channels are suitable for sending impulse-type signals and usually require a separate channel for each set of data. Voice grade channels with tone transmitting equipment can accommodate large quantities of data.

Alternatives for providing communication channels include direct wire, radio, and microwave. For most reliable operation, direct wire systems, whether buried or overhead, should be dedicated exclusively to the control system. Radio or microwave systems may require repeater stations where distances are great or where adverse topographic conditions exist. Selection of the type of communication system is usually based on economic factors. A completely separate backup communications system is always desirable and strongly recommended for extensive conveyance systems.

GENERAL APPLICATIONS

Open Channel Systems

Successful applications of feedback controls for the automatic operation of open channel conveyance systems are in use on Reclamation projects in the following categories:

1. Two-position control of pumps, oriented for both upstream and downstream control.
2. Upstream control of the sluice gates in diversion dams and the inlet gates or valves of headworks structures by both floating and proportional modes to maintain uniform diversions.
3. Upstream control of wasteway gates in canals and spillway control gates in dams by both floating and proportional modes to pass excess water.
4. Upstream floating control of gates in individual canal control structures and in a series of canal control structures to pass canal flows through the structures while maintaining desired upstream water surfaces at the other structures in the system.
5. Downstream floating control of gates in individual canal control turnouts and headworks structures to maintain uniform flow through measuring structures.

Because of simplicity, two-position controls are probably the most widely used mode of feedback control. The ON-OFF characteristics of these controls make them most appropriate for the operation of pumps. Oriented for downstream control, they operate pumps to maintain the water surfaces in reservoirs at the elevations desired for operating distribution and conveyance systems. Oriented for upstream control, they are commonly used to operate sump pumps to remove unwanted accumulations of water from structures and drains. The operating ranges of pumps in a multiple pump installation are often overlapped and staggered to increase flexibility in total pump discharge. These controllers are usually activated by either electrical probe or float-operated switches.

There are very few successful applications of unmodified single speed floating controls on Reclamation projects. Their use appears to be limited to installations where slower than normal speed motors have been added to gates originally installed for manual operation. Floating controls are usually activated by either probe or float-operated switches. The antihunt function is much easier to perform when float-operated switches are used.

Reclamation projects do not include any open-channel distribution or conveyance *systems that are completely automatic in operation.* The Friant-Kern Canal on the Central Valley Project in California and the West Canal on the Columbia Basin Project in Washington represent the most extensive applications of automatic canal operation among the various Reclamation projects. Both of these canals utilize a large number of little man controllers that have been developed by the operators. The term *"little man"* has been applied at different times to such a wide variety of installations that its definition is somewhat obscure. *In general, the term applies to single-stage floating controllers modified by SOT/SRT, and often includes an antihunt device.* Little man controllers have also been assembled that include (1) two or three stages of floating controls, (2) a 1-revolution-per-day motor that raises or lowers the target depth a fixed amount each day for filling or unwatering a canal, and (3) a 24-hour clock that can be set to open a turnout at some predetermined time.

Operators on the Friant-Kern Canal pioneered the development of little man controls. The development of similar controls on the Columbia Basin Project was completely independent of the earlier effort. Both developments perform almost identical functions but with considerably different equipment. Schematic diagrams of this equipment are shown in Figures 12 and 13. Both of these developments, operated by floats, disclosed a need for an antihunt device.

Because floating controls are appropriate for situations where there is no appreciable lag, they are best suited for the control of water surfaces that are adjacent to the controlling gates. Where floating controls do not achieve satisfactory control, the failure is often due to excessive lag. Lag increases as the distance between the controlled water surface and the controlling gate increases. Lag is created by a controlling gate that moves too slowly, or by a sensed water surface that is damped excessively in a stilling well. The corrective actions of an antihunt device and the use of multiple stage controllers can make some allowance for lag. But there are many situations in which the use of floating controls is not appropriate.

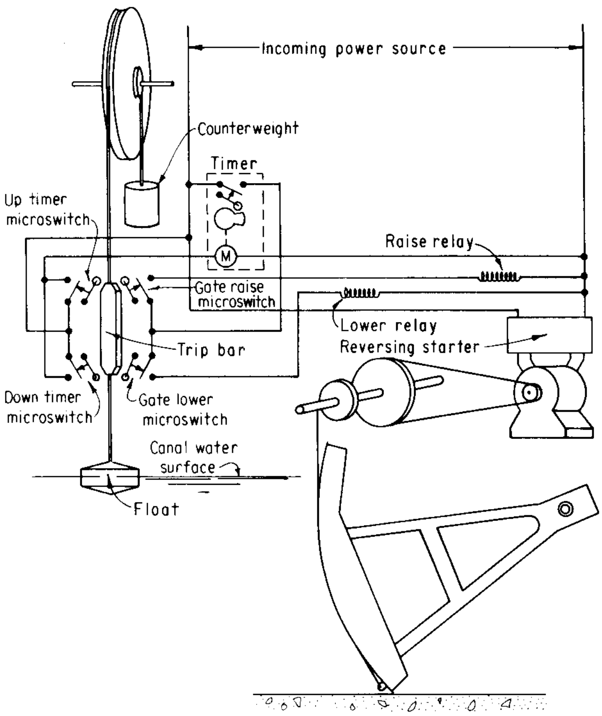


Figure 12.–Schemati diagram for a Columbia Basin type little man controller.

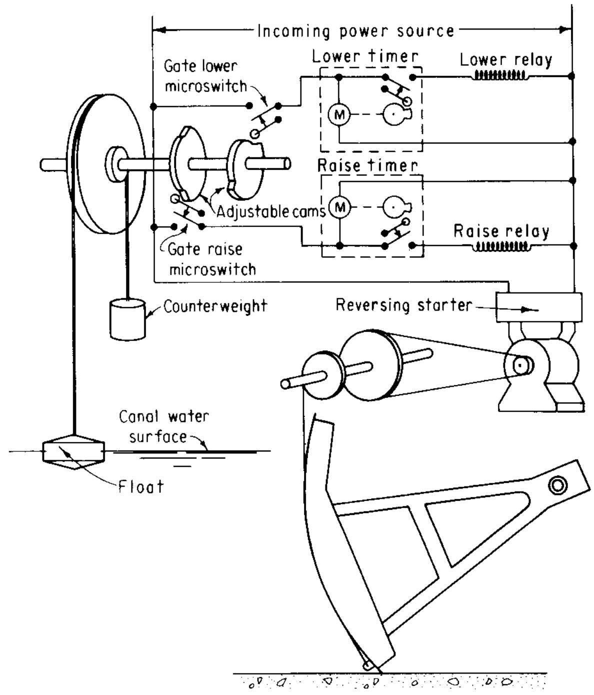


Figure 13.–Schematic diagram for a Friant-Kern type little man controller.

As a general rule, floating control can be considered appropriate for upstream control but not for downstream control. An exception is made to this rule for downstream control when the controlled water surface is located sufficiently close to the controlling gate so that the effects of lag are not objectionable.

Some attempts have been made to operate a series of canal control structures by downstream floating controls of the little man type. While most of these attempts have been unsuccessful, both the Friant-Kern and Corning Canals have achieved a degree of control that operators have tolerated. Downstream control equipment is installed on the last three check structures of the Friant-Kern Canal to control water surfaces immediately downstream from the structures. Adjustment of target depth is required for any significant flow change.

Controlled water surfaces on the Corning Canal fluctuate continuously through a range of about 1 foot in about 2-hour cycles. Additional limit switches are required on the gates to prevent excessive gate movement to maintain fluctuations within this range. Operators tolerate these fluctuations because (1) canal demand is not fully developed, (2) all deliveries from the canal are pumped, and (3) the automatic demand-type operation of the canal is better than they have been able to otherwise achieve.

Reclamation has for many years installed upstream proportional control equipment on spillway control gates of large dams and on sluice gates of diversion dams where automatic operation is desired. Gate operation can be either electrically or hydraulically powered. Hydraulically powered systems are presently considered to be the most reliable. Electrically powered systems are activated by float-operated switching equipment that is very similar to the equipment required for floating control. Proportional action is provided by a traveling crosshead interconnected with the gate to raise the switches as the gate opens, see Figure 14. Hydraulic systems use large floats and counterweights to unbalance forces that open or close the gates in response to water surface movements in the floatwells. Control equipment includes weirs and orifices that are designed to control rates of flow into and out of the floatwells at the rates required to provide proportional action in the gate, see Figure 15. Counterweights may be attached either to the operating shaft of the gate or behind the pin bearing.

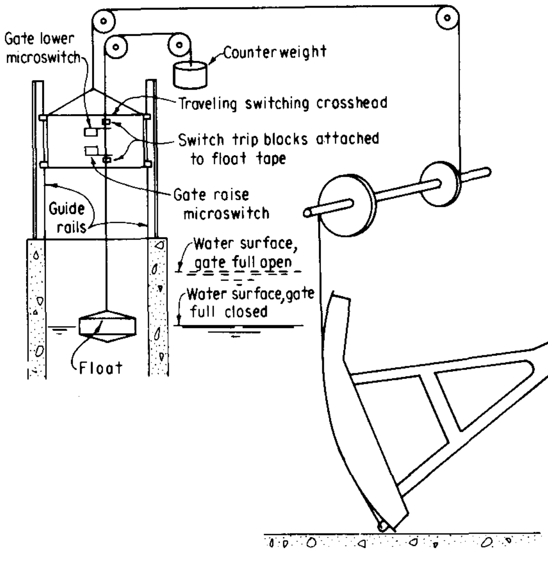


Figure 14.–Schematic diagram of equipment for proportional upstream control of electrically powered gate.

Pipe Systems

Several factors make complete automation more readily attainable for pipe systems than for open channels. The *inherent downstream control* of a pipe system in which sufficient pressure is maintained to deliver full capacity is a very influential factor. Another very important factor is the *relative simplicity of accommodating surges* by increasing the strength of the pipe. Physical enlargement of the facilities by surge tanks or other devices is required only at isolated locations. To all of these factors must be added the fact that *commercial equipment is readily available* for automatic control of pipe systems. Much of this commercial equipment has been developed to meet specific needs.

Recently constructed Reclamation pipe systems for both conveyance and distribution provide a high degree of automatic control

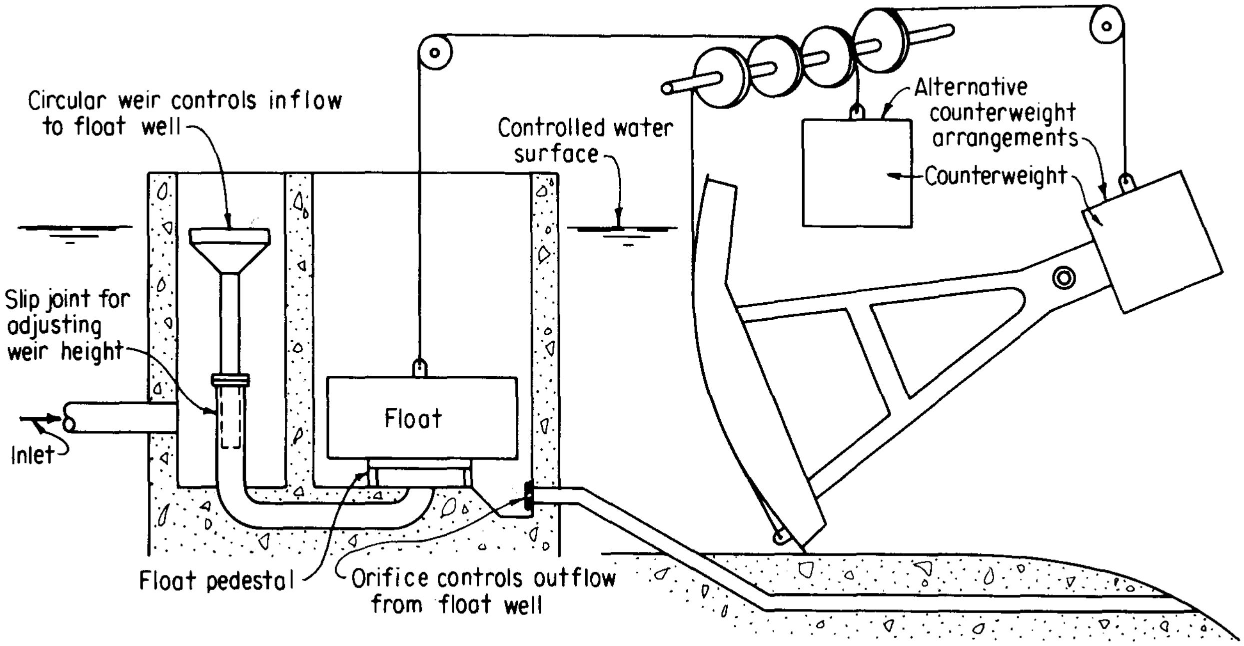


Figure 15.–Schematic diagram of equipment for upstream control of hydraulically powered gate.

utilizing feedback controls widely. Older systems are also being automated. Full pressure systems utilize feedback controls widely to achieve virtually complete automatic operation. Low-pressure systems, and systems wherein flow is controlled to a great extent by gravity rather than pressure, combine feedback controls with remote operation to improve operation. While no Reclamation pipe systems are computer controlled at this time, information is becoming available on computer controlled pipe systems from several segments of the water control industry.

Design of these control systems requires a thorough knowledge of both the conveyance and the control functions performed by automatic equipment. Investigations often reveal the need for special requirements or limitations. However, designers confidently approach automation for pipe systems with the attitude that any automatic operation desired by operators can be provided.

RESEARCH AND DEVELOPMENT

GENERAL

Research and development are necessary to provide methods and equipment for automation of water systems. Theories, methods, and equipment have been developed to automatically control a wide variety of industrial processes. The control theories and principles developed for industry are useful in the research and development necessary for water systems automation. Normally, the automation satisfying the needs of industry is not directly convertible to the needs of water distribution. For example, stabilizing the discharge in a long canal requires a long period of time compared to that necessary for maintaining a uniform voltage level in an electric power network. Also, mechanisms used in industry for process control are not directly adaptable to control of water systems.

The research and development program under way in Reclamation is concentrating initially on the problems of open channel automation. Valuable tools such as mathematical models and laboratory models are used in this effort. Immediate application of improved control techniques is needed for the operation of existing and new projects.

Papers and reports on completed phases of this program are written and published as progress is made. *The results of the research and development will be the basis for a water systems automation manual to be published in the future.*

MATHEMATICAL MODELING

The mathematical model is becoming a valuable tool for the researcher, the designer, and the operator. The results of applying a particular scheme of operation to a water system can be determined by constructing a mathematical model of the system and imposing operational and control concepts on the model. Designing the mathematical model with sufficient flexibility can result in a versatile tool. The ultimate mathematical model would simulate any water system under any scheme of operation. This ultimate model does not appear to be practical at the present time. However, mathematical models of open-channel systems can be versatile enough to accommodate a wide range of canal systems being studied under a variety of operating schemes. Likewise, mathematical models of pressure pipe systems are usually designed not as unique models limited to one system but as models which can be used to study a wide range of systems and assumptions of operation. Thus, the response of a water system can be determined for any number of schemes.

The use of mathematical modeling readily permits application of various principles of control theory to automation of water systems. Equations of flow are combined to describe the performance of the conveyance and structures. Although a precise prediction of hydraulic transients in open channel systems is difficult to attain, mathematical simulation of the canal or pipeline provides an adequate model for analyzing the results of applying various schemes of automatic control. The more complete and accurate the equations and data used in the model, the better will be the representation of the system and its operation.

A detailed theoretical and applied analysis of the hydraulics of a water system is necessary in developing the mathematical model and automatic control equations. Accurate knowledge of the surface and pressure wave travel periods in various parts of the system is needed to establish time constants for the controls. Resistance to flow through canals, pipes, and structures guiding the flow throughout the system must be known in assembling a mathematical model that will accurately describe the system.

The mathematical modeling techniques presently in use or under study by Reclamation are analog, characteristics, and implicit methods. Each method may have a place in the research and development of water systems automation. One may be beneficially used for study of the entire system, another for a detail of that system. In Reclamation work, the characteristics method has received the greatest attention in development because of the promise of more immediate results. The implicit and analog methods of developing the mathematical models appear to be more general than the characteristics method. For example, the implicit method is not limited to subcritical flows and can give a detailed description of supercritical flow. However, flow processes encountered in the water systems automation program have yielded to analysis by the method of characteristics. For this reason, an intensive study of the analog and implicit methods has not been required, but study of these methods will be part of the future development of mathematical models.

Currently, the most widely used mathematical model is the computer program "Unsteady Open Channel Flow, Method of Characteristics." This program simulates gradually varied unsteady flow in open trapezoidal channels. It is particularly adapted to irrigation canals which are characterized by a series of open-channel reaches. The program is primarily intended for the purpose of simulating the response of canal flow to any one of several concepts of automatic control.

Gradually varied unsteady flow in open channels is characterized by two basic partial differential equations, a continuity equation and a momentum equation. Because of the mathematical complexities involved in obtaining exact integration of these two equations, numerical finite-difference methods of integration are normally employed to solve them. In this program, a numerical finite-difference method known as the method of specified time intervals is used. This method belongs to the more general category of solutions known as the method of characteristics.

By the method of specified time intervals, each channel reach is subdivided into a number of subreaches of equal length and the depth and velocity of flow are computed at each of the delineating boundaries between the subreaches. The depth and velocity thus computed are not determined as continuous functions of times, but rather, computed values are obtained at discrete points in time only. The time interval between discrete points in time is specified by the user and is the same for all delineating boundaries such that solutions are attained at all boundaries for the same coincident points in time. Details of this method are described in Chapter 15 of the text by V. L. Streeter and E. B. Wylie entitled "Hydraulic Transients," McGraw-Hill, Inc., 1967.

Each channel reach is bounded on either end by a control structure. These control structures serve as connecting links between the series of open-channel reaches. Unsteady flow through control structures is simulated by a succession of short, steady-state conditions, using appropriate combinations of steady-state equations to simulate the physical facilities. Appropriate steady-state equations representing any particular control structure are solved simultaneously with the unsteady-flow equations representing the adjacent open-channel reaches to form an effective link between the control structure and the adjoining open-channel reaches.

At each control structure, any combination of the following physical facilities may be simulated: in-line flow through orifice gates, in-line flow through stoplog bays, in-line flow over check gates, in-line flow through an inverted siphon, in-line flow through a minor transition in invert grade and/or channel section, diverted flow through a constant discharge turnout, and diverted flow through an overflow wasteway.

Positioning of the orifice gates may be accomplished either by preselected schedules of gate position versus time or by any one of several schemes of automatic feedback control. The several schemes of automatic control which are provided include both the upstream concept and the downstream concept of operation.

The major items of input consist of:

1. *The physical and hydraulic properties of each open-channel reach (bottom width, side slope, bottom grade, length of reach, Manning's friction factor, etc.).*

2. *The physical and hydraulic properties of each control structure (number and size of orifice gates, number and size of stoplog bays, discharge coefficients, siphon head-loss coefficients, etc.).*

3. *Initial depths and velocities of flow on both sides of each control structure and at all delineating boundaries between subreaches.*

4. *Initial gate positions.*

5. *The specified time interval and the total real time to be simulated.*

6. *The parameters required to represent the scheme of automatic control to be used, or preselected schedules of gate position versus time for gates which are not to be controlled automatically.*

7. *Preselected schedules of turnout discharge.*

8. *Identification and editing data required to identify and control the output.*

The output consists of:

1. *A tabulated listing of major items of input data.*

2. *Cathode-ray-tube plots (Fig. 16) of selected physical and hydraulic data plotted against time (depth, velocity, discharge, gate openings, etc.).*

The major limitations of the program are:

1. *The program is valid for gradually varied unsteady flow only. No provision has been made for rapidly varied unsteady flow (bore waves).*

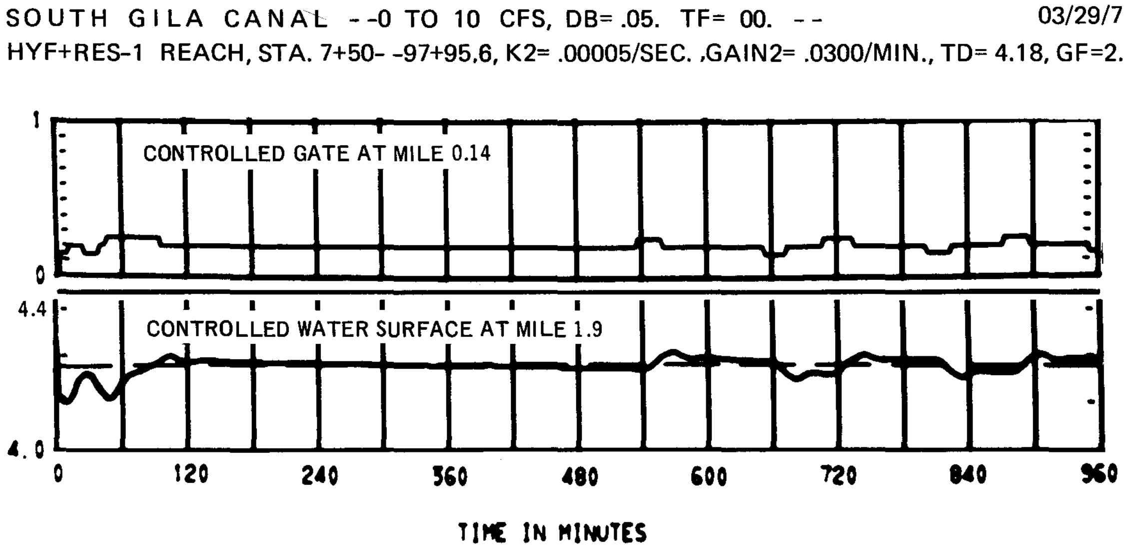


Figure 16.–Typical cathode-ray-tube plot of output data from mathematical model studies.

2. The program is restricted to trapezoidal channels only.

3. The program is valid for subcritical flow only. No provision has been made for supercritical flow.

4. Relatively short-time intervals must be used to achieve accurate results. For this reason, considerable amounts of computer time are required for long channels which must be simulated over long periods of time (time periods of several days duration). Programs which use any of the methods of solution generally known as the implicit method are probably better suited for problems of this category, since relatively longer time intervals may apparently be used successfully with this method.

This program was originally developed by Michael J. Shand at the College of Engineering, University of California, Berkeley. Numerous modifications have been made to the original program since it was received at the Engineering and Research Center.

Mathematical models have also been developed for pressure pipe systems. While the analysis of operation under various schemes of automatic control has been a part of the pressure pipe modeling, the main purpose of the pressure pipe models has been to facilitate water hammer and hydraulic transient analysis.

LABORATORY MODELS

Physically modeling a control is a necessary step in the research and development of a complex system. A control has a sensor to measure the change in the controlled variable, such as water level, velocity of flow, gate position, or soil moisture. A comparator within the control determines from the sensor whether changes are required from a previously made adjustment. Local or remote interactions between the control and the controlled structure are transmitted over a communications channel. The mathematical model cannot define physically the effect of a part of the control on other parts; therefore, components are assembled to study the control function.

A complete canal model or simple tank of water with inlet and outlet may be satisfactory for the development of a control. The facility provides, through the sensor, an electrical or mechanical input to the control that follows the change of controlled variable indicated by the mathematical model. Deviations in the control output significantly different than those predicted by the mathematical model may be cause for further development of the facility, mathematical model, or control.

The use of laboratory models allows the researcher to develop optimal controllers. For example, modular construction of the control components requires research and development to find compatible units. Size, reliability, stability of operation, and range are factors to be judged in relation to initial cost and maintenance in developing the control. The development includes the selection of commercially available electrical and mechanical parts that will lower the cost of the control. The control should be designed so that maintenance can be performed with standard test instruments. Specifications and procedures for installation, adjustment, operation, and maintenance become a part of the research and development study.

CONTROL DEVELOPMENT

Laboratory Simulations

Studies are in progress on local proportional controllers developed on operating canals and through contractual programs. Configurations of the controls differ depending on the location of the controlled structure relative to the sensed water surface. *Generalized controller designs incorporating the best features from individual devices are planned objectives of the research and development.*

Studies of the methods, devices, and control parameters* are in progress both in the Engineering and Research Center Laboratory and at operating canals. Relatively simple equipment is being used in the laboratory to investigate the characteristics of a control, Figure 17.

The mathematical model provides information regarding water-level fluctuations and the response of the control structure. Parameters used in the mathematical model are being studied by installing a control in the laboratory and then sensing water-level changes that follow the model prediction. Correspondence between the mathematical and physical models of gate opening and time of opening indicates the validity of the design assumptions.

Delay time and control circuits are assembled in a control configuration. Circuit responses to changes in heat and humidity are evaluated in an environmental test box. Deviations from predicted operating limits may be measured and corrections made before using the control on a canal.

Equipment Operating Environment

The operating environment of an automatic control in an irrigation water system is severe and does not have the uniformity provided for comparable equipment in industrial processing. Extremes of heat, cold, moisture, dust, remote location, and vandalism will occur in water distribution systems. Thus, control systems must be designed to meet the operating characteristics and the reliability needed for essentially unattended operation on a water control structure.

Phases of the environmental research can be performed in the laboratory. Equipment can be studied in chambers having variable temperature and humidity. Causes for deviations from a computed level of operation can be promptly studied and corrected in a minimum time. Modifications to equipment to overcome effects of the simulated environment are more quickly handled, leading to rapid progress in development.

Figure 17. Laboratory evaluation of control components. (a) environmental chamber, (b) data acquisition equipment, (c) automatic control components. Photo P801-D-73320

Upon completion of the laboratory assembly and testing, control equipment can be further developed at a field site. The field installation becomes a research and development laboratory. Water control structures are operated by the automatic controls to find weaknesses not disclosed by the mathematical and laboratory simulations. A period of intensive observation by operators or designers is necessary while the equipment undergoes the variety of environmental changes occurring at a field site. Comprehensive evaluation may show the need for further study in the laboratory or design office.

Floating Control

Both analysis and development are in progress on floating controls. Water surface elevations near a control structure are used by operators in adjusting gate openings in open channels. The development of floating controls to maintain a nearly constant level at selected locations was a natural outcome of such operation. The controls

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*See Appendix III

were developed independently and thus the assembled apparatus performed similar functions but differed in the types of components. In time, commercial devices also became available.

Because of a continuing need for the single speed or variable speed floating control, studies are in progress to partially standardize the design. A basic unit will be designed for general application. Options will be provided for modifying the control function to expand the capability of the device.

Proportional speed floating controllers are not being developed because of their commercial availability. If the commercial devices prove unsatisfactory, research and development of these controllers will be included in the program.

Proportional Control

EL-FLO Controller. An analog proportional controller called Hydraulic Filter Level Offset (HyFLO) was designed and placed in operation on the Corning Canal for testing. Studies of principles and equipment were performed on the project and at the E&R Center.[11] [12]** An "offset" (proportional band) was allowed in the operation of Corning Canal, Red Bluff Unit, California, Figure 18.

Operation disclosed that the hydraulic filter (fluid time delay) became inoperative because of airborne and waterborne debris. An electronic time delay was then developed and installed and the controller was renamed the Electronic Filter Level Offset (EL-FLO) Controller. Electronic circuits and components were also improved before the controllers were returned to the field for trial. Subsequent operation has shown the electronic time delay to be a reliable piece of equipment.

Smith Controller. An open-channel response of water delivery similar to that for a closed conduit system would greatly improve operations. Response of this kind requires eliminating or minimizing the nonoperating time (dead time) of the water control device. The Smith Control Method incorporates a possible means of eliminating the dead time.[11]

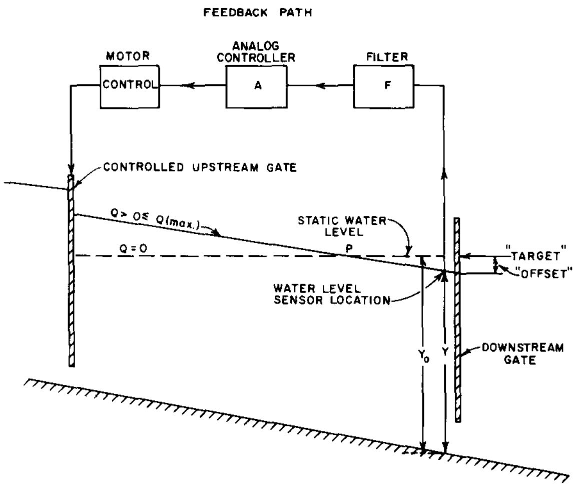

Figure 18.–Schematic of downstream control by the HyFLO method.

The controller has two elements considered to act independently. These elements are a linear predictor and a control to eliminate surges. The time lag is minimized by the use of an analog model of the canal in the controller. The model in effect predicts the change in water surface that will occur at the sensing point. By anticipation in the analog model the gate can be moved to the necessary control opening to adjust the flow to the required steady state.

Principles of this controller are now being studied on the mathematical model. Promising results from the study could possibly lead to the development of an analog or digital controller. *Such a controller would be capable of making rapid and precise changes of flow for efficient water delivery.*

Proportional Plus Reset Control

An "offset" in the canal water surface was allowable at Corning. For satisfactory delivery, an "offset" was not allowable in the South Gila Canal, Yuma-Mesa Project, Arizona. Therefore, a reset control was added to the proportional

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**Numbers refer to reports in Reference List.

control circuitry. A long-term analog-type integrator for resetting was not available. As a substitute, a circuit was designed to vary the speed of a direct-current motor according to the rate of change of the water level. The output of a potentiometer connected to the motor provides a voltage necessary to move a gate and return the water level to a target elevation.

Satisfactory completion of the proportional plus reset controller will allow the use of another mode of control on Reclamation water systems. This mode of control has been used widely in industrial applications for some time. ***Completion is planned as a result of the field trials in 1973 on the South Gila Canal.***

Proportional Plus Reset Plus Rate Control

Applications of proportional or proportional plus reset control are sometimes less than ideal because of the large initial overshoot of the controlling element. This large overshoot can often be drastically reduced by the addition of rate action to the controller. In applications to electric power control, the addition of rate action has reduced the initial overshoot by 50 percent from the best conditions obtainable with proportional or proportional plus reset control. The large overshoot in certain applications is often due to a large dead-time or large transfer lag. Also, the proportional band must be set exceptionally wide and the reset rate unusually slow to avoid excessive cycling. Load changes then create a large error in the controlled variable and a long time is required to reach the set point. Rate action provides a large initial correction to bring the variable up to the set point rapidly, reducing the overshoot. Also, the time and magnitude of cycling are reduced. ***Development of rate action is planned in the near future.***

Computer-operated Supervisory Controls

Large water conveyance and distribution systems may adapt to control from a centralized computer system. Alternatives include the use of a combination of local automatic and centralized computer control systems. Each of these possibilities requires research and development because of the wide variety of choices.

Computers appear attractive for control of water because they can be programed to control specific parts of the system. These parts can be controlled in entirely different ways to meet specific conditions without the use of specialized components. Also, as water system control theory develops, computers offer the flexibility of applying new methods of control at a future time without major alterations to the controlled structures.

Initial studies indicate virtually any control method using on-site control components can be programed into a computer. The computer then provides an equivalent control of the structure but performs the control from a central location. Progress in this area can occur only through intensive research into the literature and commercial applications and the development of computer programs applicable to water systems.

Study of local control and supervisory control is planned for the laboratory. A canal simulation model will be designed for investigating the capabilities of the control modes analyzed in the mathematical model. This model will include a set of response times and structures with controls to receive commands. As an intermediate step to field application, the laboratory canal model will help resolve discrepancies between the abstract mathematical model and the field application of the control.

IRRIGATION SCHEDULING - MANAGEMENT INTERFACE

An important development parallel to water systems automation in the Bureau of Reclamation is the Irrigation Management Services (IMS). IMS provided information relative to the scheduling of irrigations on 96,000 acres of irrigated land in six states during the 1972 irrigation season. *Irrigation scheduling provides benefits to the irrigator, the irrigation* *district, to the Nation, and the Bureau of Reclamation. These benefits by their categories are as follows:*

1. Benefits to the irrigator are:

Increased crop yields in quantity and quality
Better utilization and savings of labor
Better utilization and savings of water
Reduced leaching of soil fertility and soil additives
Reduced restrictions during periods of peak demand
Reduced drainage requirements

2. Benefits to the irrigation district are:

Better control of deliveries
Reduced demand on the delivery system during periods of peak demand
Savings in cost and use of water
The capability to forecast delivery requirements
Reduced drainage problems
Reduced maintenance requirements
Computerized water records
An increased economical base associated with the irrigation enterprise

3. Benefits to the Nation and the Bureau of Reclamation are:

Improved economics of irrigation
Reduced environmental impact of irrigated agriculture
Improved utilization of the natural resources
New and detailed planning and operational criteria for irrigation

Some of these benefits may be relevant to one irrigated area and irrelevant to another. This program is most important in that it treats the causes and not the symptoms of many of the ills associated with irrigation.

Many of the benefits are identical or similar to those for automation. To a certain extent irrigation scheduling is a form of automation and a joint development is required. A recent feasibility-grade design and cost estimate study for automating the Garrison Diversion Unit in North Dakota concluded that computer requirements for programmable master supervisory control are compatible with those required for irrigation scheduling.

PLANNED INSTALLATIONS

Personnel at the Bureau of Reclamation's E&R Center are currently developing local automation equipment for three existing canal systems. These are the Coalinga Canal and Corning Canal, California, and the South Gila Canal, Arizona. Also under consideration are computer-assisted automation systems for use on major projects such as the Garrison Diversion Unit, North Dakota, and the Central Arizona Project, Arizona. A brief description of these installations is included below. Additional development of automation is also being performed through various regional offices. Some of these developments relate to control of the Potholes and East Low Canals, Washington, and the Enders, Medicine Creek, Norton, Red Willow, and Trenton Dams, Nebraska and Kansas.

COALINGA CANAL

The Coalinga Canal includes 12 miles of concrete-lined canal and is supplied from the San Luis Division of the California Aqueduct, Figure 19. Water is introduced into the canal by the 1,185-cfs Pleasant Valley Pumping Plant. Flow downstream from the pumping plant is controlled by three check structures.

The pumping plant is designed for essentially unattended operation. Six large pumping units will be operated manually to accommodate major changes in demand and three small units will cycle on and off automatically to suit minor fluctuations in demand. The plant is also designed for possible future supervisory control (if this becomes a desirable feature).

The canal controls were originally designed to operate using a three-stage upstream SOT/SRT floating control and a regulating reservoir to provide operation without waste. A delay in the

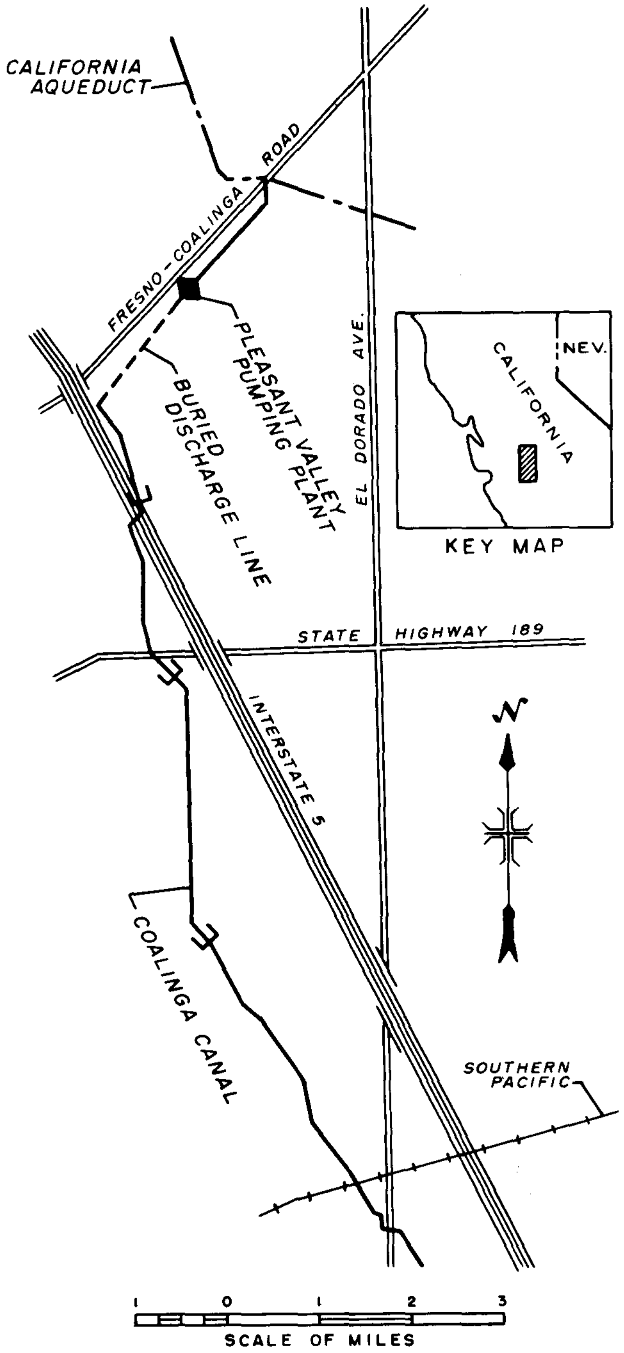


Figure 19.–Coalinga Canal.

completion of the project prevented utilization of these controls. During the delay ongoing research into downstream control techniques demonstrated that proportional plus reset control could better serve the water users by reducing scheduling and storage requirements of the system. Mathematical model studies have also shown that use of downstream control will eliminate the need for the regulating reservoir.

It is anticipated that communications channels will be provided by project-owned buried cable between structures and an alarm circuit will be extended to a master station by a leased circuit.

Design of the controls for this project is now proceeding based on use of proportional plus reset downstream control. The project is expected to be completed in 1973.

CORNING CANAL

The Corning Canal includes 21 miles of earth-lined canal and is supplied from the Sacramento River at the Red Bluff Diversion Dam, Figure 20. Water is introduced into the canal by the 500-cfs Corning Pumping Plant and flow downstream from the pumping plant is controlled by 14 check structures.

The pumping plant is designed for unattended operation. Three 125-cfs pumping units and one 53-cfs pumping unit are started or stopped manually to approximately satisfy the demand. The two remaining 53-cfs units cycle on and off automatically to adjust for minor fluctuations in demand. The plant is also designed for future automatic control of the four remaining pumping units for on-off control by float switches operated from the canal water level. The use of automatic canal-side pumping plants causes severe control problems on this canal due to the fluctuating flow demands for the plants. Power failures at the canal-side plants also cause severe problems because the canal freeboard must accommodate the rejected water.

The Corning Canal controls were initially designed to operate with one of the first versions of single-stage downstream SOT/SRT floating control (without antihunt). However, before the controls were installed it was recognized that a similar downstream control system installation on the South Gila Canal in Arizona produced unstable control. To avoid a similar problem on the Corning Canal the equipment was installed for upstream control, but upstream control

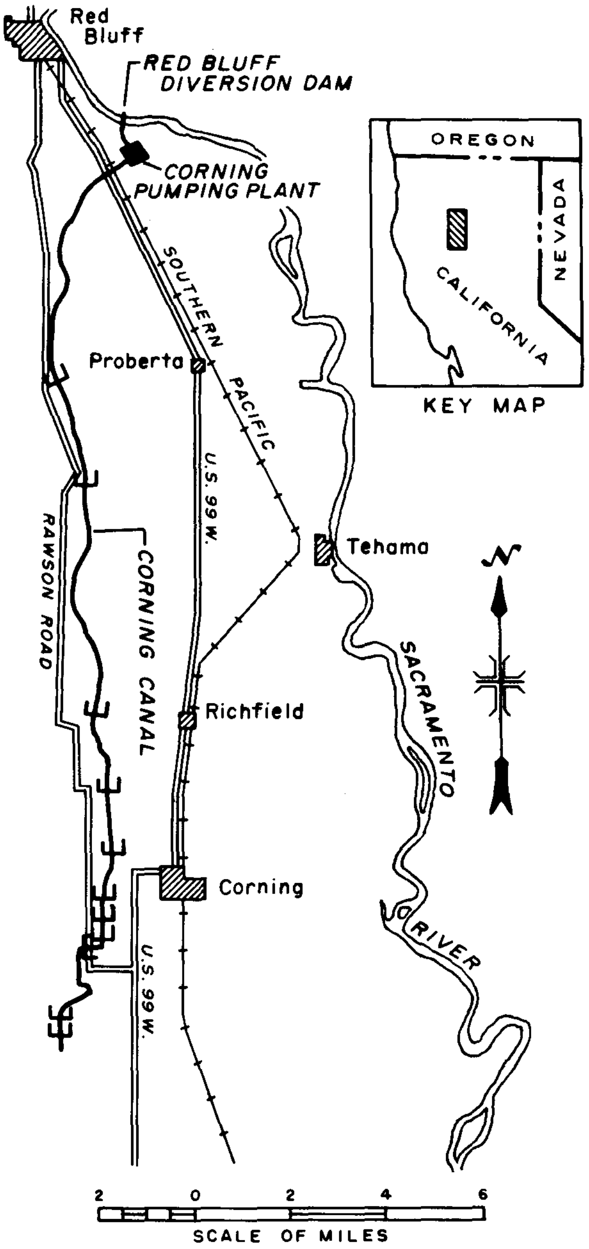


Figure 20.–Corning Canal.

proved to be inadequate to maintain canal-side demands on the Corning Canal. Subsequently, the control equipment was modified to downstream control with antihunt and gate movement limit switches, which allowed the canal to operate with marginally satisfactory stability.

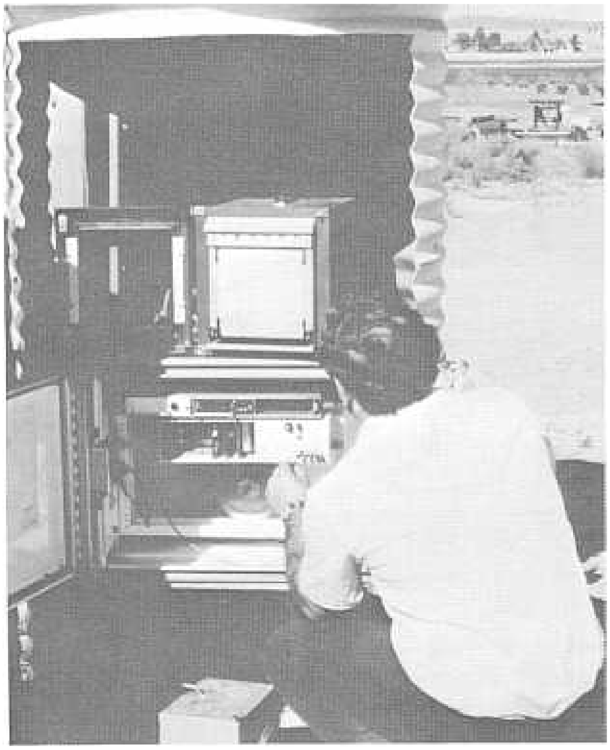
Recognizing the need to have a better understanding of transient behavior of an open channel and to have a stable and responsive downstream control system, the Regional Office, Sacramento, sponsored an investigation of the downstream control concept through a research contract with the University of California. The resulting research produced the Hydraulic Filter Level Offset (HyFLO) method of control for which equipment was subsequently designed and installed to operate the first check structure. The hydraulic filter portion of the equipment proved unsatisfactory in actual operation and an electronic filter was developed and installed in place of the hydraulic filter. The Electronic Filter Level Offset (EL-FLO) equipment has been operating satisfactorily (with minor equipment problems) on three check structures since April 1972. The gate movements and water levels have been recorded and will be used to evaluate the method of control and help verify the mathematical model.

The communications channels are provided by leased, buried cable between each structure. No alarm circuit is provided at the present time.

Additional EL-FLO equipment will be purchased and installed so that all 14 check structures will have automatic downstream control. Completion of this portion of the project is expected by 1974.

SOUTH GILA CANAL

The South Gila Canal includes 7.7 miles of concrete-lined canal and is supplied from the Gravity Main Canal, Figure 21. The canal includes nine check structures and is designed for a gravity flow of 110 cfs.



Closeup view of the EL-FLO Plus Reset Controller inside the stilling well just above the South Gila Canal Check No. 2. The electronic recorder above the controller and the Type F recorder below were used to collect data on equipment and canal performance. Photo P801-D-73318

The canal controls were originally designed to operate with the initial version of automatic single-stage downstream SOT/SRT floating control. Initial operation of the system was plagued with unstable water levels and various equipment problems. The downstream controls that were installed initially were finally abandoned and rewired as a combination of upstream and manual controls.

Extensive mathematical model studies have failed to reveal any modification that can be made to the floating controls to achieve the degree of control that is considered necessary. These studies have also shown that downstream proportional control provides the desired stability but the water-level offsets that would be required on this canal would be intolerable to the gravity deliveries. However, the model studies show that proportional plus reset control

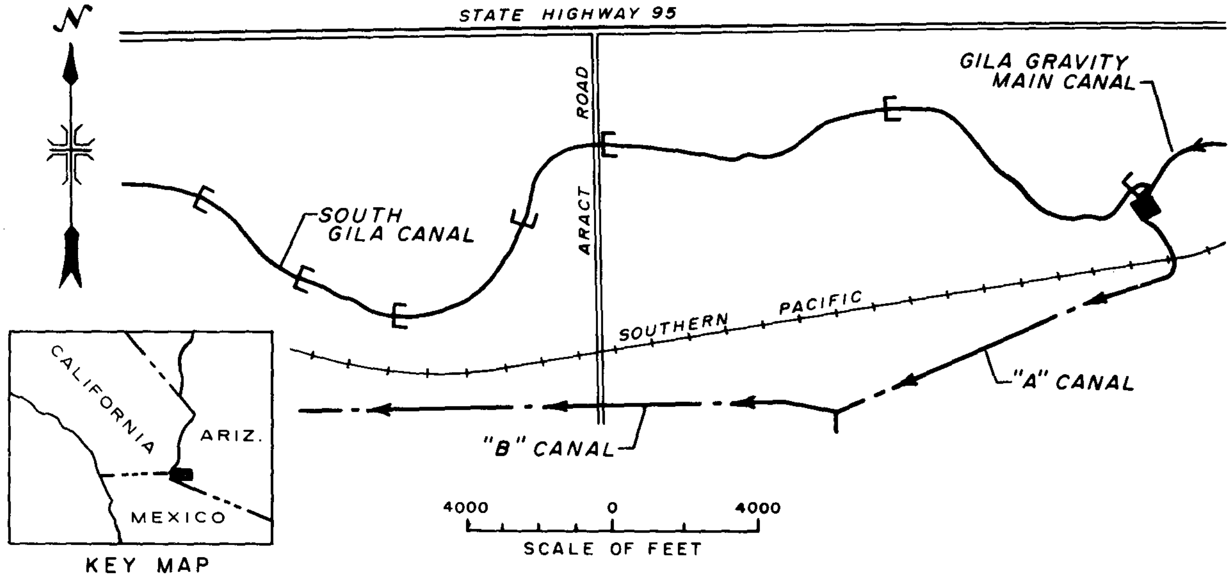


Figure 21.–South Gila Canal.

should provide control that meets the desired criteria. Therefore, the South Gila Canal has been selected as the prototype canal for development of this mode of control.

Also as a separate research feature on the South Gila Canal, the Bureau of Reclamation will develop and install an upstream floating controller with a set-operate-time/variable-rest-time (SOT/VRT) feature on the first section of the canal for operation of the canal headgate. The controller will operate essentially as a downstream controller by operating the gate in response to the water level a short distance downstream from the headgate.

Communications channels are provided by project-owned buried cable between structures. No alarm circuits are provided at the present time.

The controls for South Gila Canal are expected to be operational by 1974.

GARRISON DIVERSION UNIT

Automation of the Garrison Diversion Unit is in the initial stages of development and portions of the conveyances are already under construction. The initial structures are being designed for manual operation with provisions for future automation. The conveyances will include several hundred miles of canal, 4 reservoirs, 4 major pumping plants, and 53 canal control structures, Figure 22. The project will include the McClusky, Velva, New Rockford, Warwick, James River Feeder, and Oakes Canals and will utilize a portion of the James River for water conveyance. The widespread and complex nature of the project makes automation a very desirable feature as a means of minimizing the number of operating personnel required. Initial feasibility studies have shown that automation of the project can be best accomplished with a Programmable Master Supervisory Control (PMSC) system. Computers would be used to analyze programed water schedules and perform the computations required for total automatic control of all structures based on scheduled and actual water demand. The system may include one central master station with possible satellite master stations at two or three other locations. Each master station would include displays of system conditions using two or more cathode-ray tubes. Also under consideration is the use of inexpensive versions of local automatic feedback controllers to back up the PMSC system.

The types of communication channels to be used have not been determined but initial

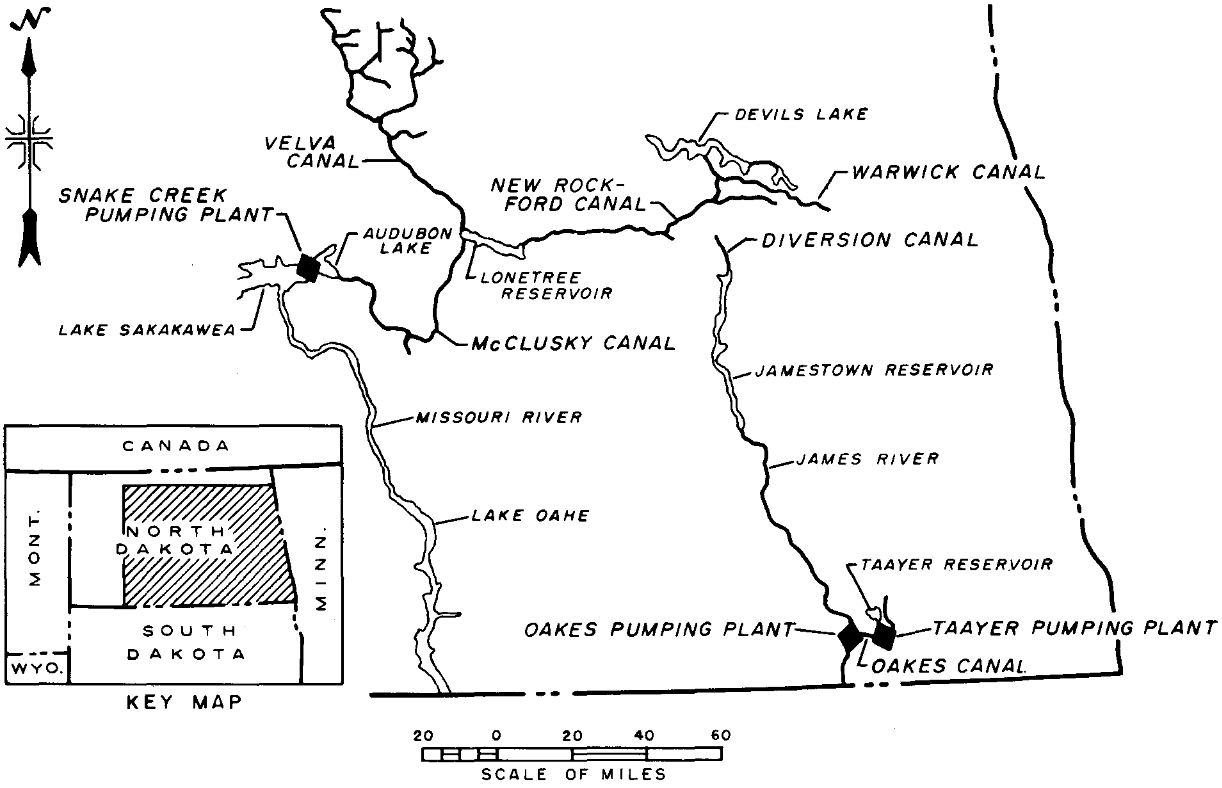


Figure 22.—Garrison Diversion Unit.

studies suggest a combination of leased or project-owned buried cable, radio, and microwave.

The distribution portion of the project is expected to be included in the automatic system for the conveyances. This will make justification of a PMSC-type automatic system more attractive than any other type of system based on existing technology.

The Garrison Diversion Unit is one of the few projects where major consideration has been given to automation during design of the conveyances. It is anticipated that this planning will result in optimum efficiency of water conveyance.

CENTRAL ARIZONA PROJECT

The Central Arizona Project will include approximately 275 miles of concrete-lined canal, 10 pumping plants, and 3 storage reservoirs, Figure 23. The water conveyance features will include the Granite Reef, Salt-Gila, Tucson, and San Pedro Aqueducts. Extensive studies of automation have not been made for this project to date, but mathematical modeling is being used to attempt to define the methods of automatic control that will be appropriate. Preliminary investigations indicate a PMSC-type system will be advantageous due to the size and complexity of the project.

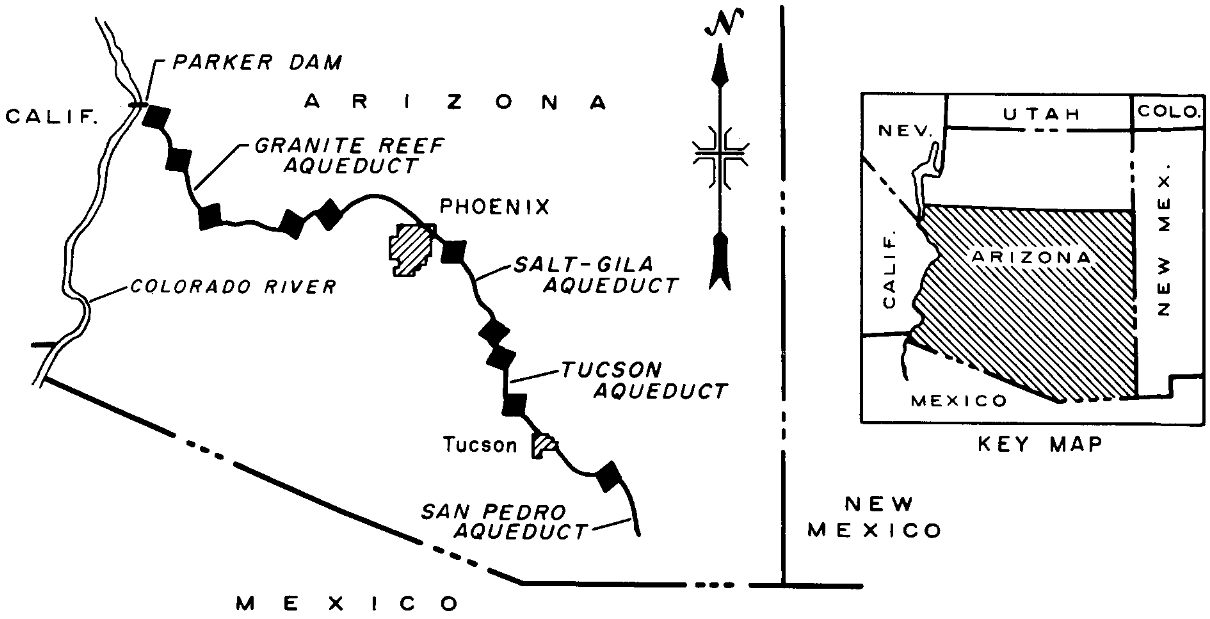


Figure 23.–Central Arizona Project.

The type of control to be provided for the pumping plants has not yet been defined, but it is anticipated that the plants will include local-automatic computer control with supervisory control interfaces to the master station. When this project reaches the design stage, the technology may allow local-automatic computer control of each canal control structure with supervisory control interfaces to the master station.

The communication channels for the Central Arizona Project have not been defined but it is anticipated that either leased or project-owned buried cable or radio will be used.

COST CONSIDERATIONS

GENERAL

Information on the costs of implementing water system automation is incomplete and the application of the limited data to differing situations is difficult. ***The following information is intended to serve as a general guide in investigations leading to the implementation of automation.*** For most studies, this general knowledge will not be sufficient and additional information will be needed for a specific analysis. Economic analyses of this type cover a definite period during which there are investment costs and annual costs. While this report does not include the economic analysis of a project, it provides general information on costs of automation.

On Reclamation projects, the investment cost of automation has generally ranged from less than 1 percent to 3 percent of the total project cost. *This investment can usually be broken into three components, namely, (1) communications system, (2) automatic equipment, and (3) other items including installation, programing, and debugging.* On most widespread projects, Item 1, the communications system, is the most expensive component.

COMMUNICATIONS SYSTEMS

Data and control signals can be transmitted by either direct wire or radio/microwave. Direct wire may be either buried or overhead cable. Communication facilities can be either project-owned or leased from the telephone company. Each of these methods has advantages and disadvantages. Project-owned buried cable has proven to be quite reliable, except as it is affected by cuts from excavating equipment, burrowing animals, or vandalism. For long distances, however, buried cable can be very expensive compared to radio or microwave. Also, rough terrain or rock trenching may increase the installation cost of buried cable. *An average installed cost for buried cable of $1 per foot is often used in estimates.* While the cable itself may be purchased for $0.25 to $0.50 per foot, the installation often pushes the total to the $1 per foot figure.

Voice grade telephone circuit leases typically range from $0.50 to $4 per mile per month. The distance is usually figured point to point from the remote station through a telephone switching center to the master station. Thus, the mileage is charged from the shortest point-to-point distance from the sensor through the telephone system to the control center. Also, telephone companies often add an additional one-time construction charge on installations where special routing of dedicated circuits are involved. Less than desirable service has been experienced with some leased communication channels because of administrative and technical problems.

Investment costs for microwave or radio systems are not directly proportional to distance. This cost is usually constant for distances up to 50 or 60 miles. This distance is sometimes restricted by topography. Repeater stations are required for greater distances. Data transmission by microwave or radio can be adversely affected by atmospheric activity. *As a minimum, a simple radio transmitter and receiver have a purchase price of about $1,500. Installation and auxiliary equipment will increase this figure considerably.*

Annual operation, maintenance, and replacement (OM&R) costs are important in communication system cost considerations. OM&R costs are included in the lease charge for telephone circuits. However, some additional

O&M costs are usually required for administration by the operating entity. When facilities are owned rather than leased, OM&R costs should include replacement costs based on the expected life of the installation. A buried cable life of 35 years is used in Reclamation studies. Microwave and radio can have considerably higher OM&R costs than buried cable. Replacement costs are based on a typical life of 15 years for microwave and radio equipment in Reclamation usage. Also, this equipment requires periodic preventive maintenance to insure dependable operation. An important consideration in determining OM&R costs is the availability of qualified electronic technicians at remote locations.

Communication costs are often small for local-automatic control installations because of the close proximity of the controlled water surface and the controlling element. However, reliable system operation for many local-automatic controllers often requires alarm circuits for notification of abnormal operating conditions. The cost of providing communication channels for these alarm circuits often approximates the cost of communication channels for more elaborate control systems.

AUTOMATIC EQUIPMENT

Investment costs for automatic equipment vary with the type of equipment considered. Local-automatic equipment can often be self-contained as is the usual equipment for automatic operation of a motorized gate at a canal check, turnout, wasteway, or diversion dam. Such automation has been accomplished for as little as $1,000 per gate. Most of the automatic control installations on Reclamation projects are of this type. The basic equipment for these simple installations usually consists of a float or probe to sense water surface elevations and additional components to energize the gate motor. In contrast to these simple installations, the purchase price of computers for a computer-controlled system can range from a few thousand dollars to several million dollars. Recent technological developments and competition have resulted in drastic reduction of computer costs. This is particularly true for minicomputers which have many automatic control applications.

OTHER ITEMS

Installation, programing, and debugging are lumped together for purposes of discussion of costs. For computer-controlled systems, programing and debugging can cost as much as the equipment. However, once developed, the programing is often usable at more than one installation. This can result in a considerable savings in cost for later installations after the initial development has been accomplished.

A dependable source of electrical power is a prerequisite for satisfactory operation on most Reclamation water systems. With greater usage of automation, this will be even more essential because a power failure can result in abnormal operating conditions. Reliability of the power source should be investigated in determining the need for backup power. Backup power can be obtained by using batteries or engine generators. The more elaborate backup systems can cost several thousand dollars.

APPENDIX I

DEFINITIONS

Many of the definitions used in the automation industry have been developed for a specific segment of the industry and are too restricted for application to water-conveyance systems. Others have been expanded to become so broad that they offer no real definition. The following definitions, although similar to those encountered in studying automation terms, are suggested as being better directed towards basic principles:

Algorithm. A rule of procedure for solving a mathematical problem.

Analog. Anything that is analogous or similar to something else.

Automatic Control. Adjustment of the controlling element accomplished by an arrangement of equipment without attendance by an operator.

Automation. (1) The implementation of processes by automatic means; (2) the theory, art, or technique of making a process more automatic; (3) the investigation, design, development, and application of rendering processes automatic, self-moving, or self-controlling. (From IEEE STD 100-72.)

Controlled Variable. A physical quantity controlled to a desired value.

Controlling Element. The principal item of equipment adjusted to regulate the controlled variable.

Downstream Control. Feedback control utilizing a controlled variable downstream from the controlling element as the controlled variable.

Feedback Control. Automatic control that senses deviation of the controlled variable from a desired value and performs a control function to take corrective action. The controlled variable becomes the controlling variable.

Local Control. Adjustment of the controlling element accomplished at the site.

Manual Control. Adjustment of the controlling element accomplished by an attendant.

Master Station. A station from which remotely located equipment is controlled and which receives telemetered data.

Programed Control. Automatic control by equipment that accomplishes predetermined adjustments of the controlling element at predetermined times.

Rate-of-flow Control. Feedback control utilizing rate of flow (Q) through the controlling element as the controlled variable.

Remote Control. Adjustment of the controlling element accomplished from a distant point.

Remote Station. A station wherein equipment is controlled from the master station and from which data are telemetered to the master station.

Supervisory Control. An attendant and/or automatic equipment maintaining surveillance of physical conditions and/or telemetered data; performing control functions to maintain controlled variables at desired values; and providing notification of abnormal conditions.

Telemetering. Sensing, encoding, and transmitting data to a distant point for interpretation.

Upstream Control. Feedback control utilizing a controlled variable upstream from the controlling element as the controlled variable.

APPENDIX II

PARTIAL INVENTORY OF TYPES OF AUTOMATION ON RECLAMATION PROJECTS

This partial inventory is intended to present information on types of water-system automation in use on Reclamation projects. Automatic and remote control equipment is included. The inventory is not all-inclusive but is based on information readily available at this time. One source of information was the "Survey of Automatic or Remote Control Equipment for Water Conveyance Systems" conducted with each region in 1970.

Automatic equipment has been installed on spillway gates at storage reservoirs. However, recent information is not readily available on these applications. Also, application of this type of equipment is usually intended to function only in emergency flood control situations and as such is different from most of the control equipment included in this report.

1. Carriage facilities–Canals.
2. Carriage facilities–Pipelines.
3. Diversion dams.
4. Major pumping plants.
5. Storage reservoirs–Outlet works.

1. Carriage Facilities - Canals

Project - Name of canal	Length Miles (kilometers)	Initial capacity Cubic feet per second (cubic meters per second)	Section (initial reach) Bottom width Feet (meters)	Section (initial reach) Water depth Feet (meters)	Section (initial reach) Side slopes	Automation
All-American Canal System						
Coachella Canal	124 (200)	2,500 (71)	60 (18)	10.3 (3)	2:1	Remote manual control of check gates
Boise Project						
Black Canyon Canal.	29 (47)	1,300 (37)	--	--	--	Upstream control of wasteway gate - Floating mode (SOT/SRT)
Central Valley Project						
Corning Canal	21 (34)	500 (14)	22 (7)	7.2 (2)	2:1	Downstream control of check gates - Proportional mode (EL-FLO)
Delta-Mendota Canal	115.7 (186)	4,600 (130)	48 (15)	16.6 (5)	1-1/2:1	Remote manual control of check gates
Friant-Kern Canal	151.2 (243)	4,000 (113)	36 (11)	15.5 (5)	1-1/4:1	Upstream control of check gates, Checks 1-9 - Floating mode Downstream control of check gates, Checks 10-13 - Floating mode
Madera Canal.	35.9 (58)	1,000 (28)	20 (6)	9.2 (3)	1-1/2:1	Downstream control of turnout M.P.32.2 - Floating mode (SOT/SRT)
Pleasant Valley Canal	6.3 (10)	1,100 (31)	12 (4)	11.3 (3)	1-1/2:1	Present operation upstream control of canal checks - Floating mode Planned operation downstream control of canal checks - Proportional plus reset mode

1. Carriage Facilities - Canals - Continued

Project - Name of canal	Length	Initial capacity	Section (initial reach) Bottom width	Water depth	Side slopes	Automation
	Miles (kilometers)	Cubic feet per second (cubic meters per second)	Feet (meters)	Feet (meters)		
San Luis Canal.	101.3 (163)	13,100 (371)	110 (34)	32.8 (10)	2:1	Remote control (manual and computer assisted) operated by the California Department of Water Resources
Colorado-Big Thompson Project						
Boulder Creek Supply Canal.	15.7 (25)	200 (6)	12 (4)	4.6 (1)	1-1/2:1	Upstream control of check gates - Floating mode (SOT/SRT)
Charles Hansen Feeder Canal Flatiron Section.	3.8 (6)	930 (26)	13 (4)	8.8 (3)	1-1/4:1	Upstream control of check gate - Proportional mode
Columbia Basin Project						
East Low Canal.	82.6 (133)	4,500 (127)	68 (21)	15.5 (5)	1-1/2:1	Upstream control of check gates - Floating mode (SOT/SRT)
Eltopia Branch Canal.	25.3 (41)	555 (16)	20 (6)	6.6 (2)	1-1/2:1	Upstream control of check gates - Floating mode (SOT/SRT)
Royal Branch Canal.	8.5 (14)	900 (25)	37 (11)	7.2 (2)	1-1/2:1	Upstream control of check gates - Floating mode (SOT/SRT)
Wahluke Branch Canal.	40.5 (65)	1,520 (43)	12 (4)	10.4 (3)	1-1/2:1	Upstream control of check gates - Floating mode (SOT/SRT)
West Canal.	82.2 (132)	5,100 (144)	38 (12)	16.4 (5)	1-1/2:1	Upstream control of 29 check gates - Floating mode (SOT/SRT)

1. Carriage Facilities - Canals - Continued

	Length	Initial capacity	Section (initial reach) Bottom width	Section (initial reach) Water depth	Section (initial reach) Side slopes	
Project - Name of canal	Miles (kilometers)	Cubic feet per second (cubic meters per second)	Feet (meters)	Feet (meters)		Automation
Deschutes Project						
North Unit Main Canal	65 (105)	1,000 (28)	60 (18)	5.6 (2)	1-1/2:1	Upstream control of check gates and upstream and downstream control of headworks gates - Floating mode (SOT/SRT)
Gila Project						
South Gila Valley Canal	7.7 (12)	110 (3)	5 (2)	4.2 (1)	1-1/2:1	Present operation upstream control check gates - Floating mode (SOT/SRT) Planned operation downstream control check gates - Proportional plus reset mode
Klamath Project						
"J" Canal	23.4 (38)	800 (23)	26 (8)	9.5 (3)	1-1/2:1	Remote manual control of headworks gates Upstream control of check gates - Floating mode (SOT/SRT)
Minidoka Project						
Cross Cut Canal	6.6 (11)	591 (17)	26 (8)	5.7 (2)	1-1/2:1	Upstream control of check gates - Floating mode (SOT/SRT)
Diversion Canal	0.7 (1)	220 (6)	10 (3)	5 (2)	1-1/2:1	Upstream control of check gates - Floating mode (SOT/SRT)
Milner-Gooding Canal.	70 (113)	2,700 (76)	50 (15)	12.6 (4)	1-1/4:1	Upstream control of check gates - Floating mode (SOT/SRT)

1. Carriage Facilities - Canals - Continued

Project - Name of canal	Length	Initial capacity	Section (initial reach)			Automation
			Bottom width	Water depth	Side slopes	
	Miles (kilometers)	Cubic feet per second (cubic meters per second)	Feet (meters)	Feet (meters)		
North Side Canal.	8 (13)	1,700 (48)	--	--	--	Upstream control of check gates - Floating mode (SOT/SRT)
South Side Canal.	13 (21)	1,325 (38)	57 (17)	7.5 (2)	1-1/4:1	Upstream control of check gates - Floating mode (SOT/SRT)
Unit "A" Main Canal	4.4 (7)	240 (7)	14 (4)	4.5 (1)	2:1	Upstream control of check gates - Floating mode (SOT/SRT)
Pick-Sloan Missouri Basin Program						
Three Forks Division						
East Bench Unit						
East Bench Canal.	44.2 (71)	440 (12)	20 (6)	6.6 (2)	2:1	Upstream control of check gate - Floating mode (SOT/SRT)
Solano Project						
Putah South Canal	32.3 (52)	956 (27)	12 (4)	10.3 (3)	1-1/2:1	"Q" controller at canal headworks - Proportional mode

2. Carriage Facilities - Pipelines

Project and feature	Length Miles (kilometers)	Initial capacity Cubic feet per second (cubic meters per second)	Type	Diameter Inches (centimeters)	Automation
		A. CONSTRUCTED			
Arbuckle Project					
Wynnewood Aqueduct (Includes Davis Branch and Refinery Branch). . .	17.9 (29)	9.6 (--)	Precast concrete	24--12 (61--30)	Downstream control of pump units - ON-OFF mode
Canadian River Project					
Main Aqueduct	322.7 (519)	183 (5)	Pretensioned, non-cylinder prestressed, reinforced concrete	96--15 (244--38)	Downstream control - ON-OFF mode for PP #1 - Remote control (manual) PP #2 "Q" controller - Proportional mode regulates flow into reservoirs Central system remote control (manual) of upstream valves
Norman Project					
Norman Pipeline	8.4 (14)	21.8 (1)	Precast concrete	33 (84)	Downstream control of pump units - ON-OFF mode
Ventura River Project					
Main Pipeline System.	33.9 (55)	--	--	54--12 (137--30)	Downstream control of pump units - ON-OFF mode - Proportional control for chlorinator
Washita Basin Project					
Fort Cobb Aqueduct.	20.9 (34)	16 (--)	Precast concrete	33--15 (84--38)	Upstream control limits head in pipeline - Proportional mode
Foss Aqueduct	50.8 (82)	19.7 (1)	Precast concrete	42--6 (107--15)	Downstream control of pump units - ON-OFF mode

2. Carriage Facilities - Pipelines - Continued

Project and feature	Length Miles (kilometers)	Initial capacity Cubic feet per second (cubic meters per second)	Type	Diameter Inches (centimeters)	Automation
Weber Basin Project Davis Aqueduct.	21.6 (35)	355 (10)	Precast concrete	84--21 (213--53)	Upstream control - Floating mode for stream water intake to aqueduct

3. Diversion Dams

Project Name of Division (Pick-Sloan Missouri Basin Program) Name of Unit (Pick-Sloan Missouri Basin Program) Name of Diversion Dam, State, Stream Type of Structure	Diversion capacity Cubic feet per second (cubic meters per second)	Height Feet (meters)	Crest length Feet (meters)	Volume Thousand cubic yards (thousand cubic meters)	Automation
Colorado-Big Thompson Project					
North Poudre Diversion Dam, Colorado, Cache la Poudre River					
Concrete ogee weir	250 (7)	6 (2)	200 (61)	1 (1)	Remote manual control of diversion gate
Hammond Project					
Hammond Diversion Dam, New Mexico, San Juan River					
Rockfill overflow, embankment wings.	90 (3)	12 (4)	1,370 (418)	25 (19)	Upstream control of sluiceway gate - Floating mode (SOT/SRT)
Klamath Project					
Lost River Diversion Dam, Oregon, Lost River					
Concrete multiple-arch weir, embankment wings.	3,000 (85)	26 (8)	675 (206)	20 (15)	Remote manual control of diversion gates - See O&M Release #32
Pick-Sloan Missouri Basin Program					
Frenchman-Cambridge Division					
Red Willow Unit					
Red Willow Creek Diversion Dam, Nebraska, Red Willow Creek					
Baffled apron weir, embankment wings	90 (3)	11 (3)	1,095 (334)	35 (27)	Upstream control of sluice gate - Floating mode (SOT/SRT)
Middle Loup Division					
Farwell Unit					
Arcadia Diversion Dam, Nebraska, Middle Loup River					
Concrete gate structure, embankment wings.	850 (24)	8 (2)	7,960 (2,426)	14 (11)	Upstream control of sluice gate - Floating mode (SOT/SRT)

3. Diversion Dams - Continued

Project Name of Division (Pick-Sloan Missouri Basin Program) Name of Unit (Pick-Sloan Missouri Basin Program) Name of Diversion Dam, State, Stream Type of Structure	Diversion capacity Cubic feet per second (cubic meters per second)	Height Feet (meters)	Crest length Feet (meters)	Volume Thousand cubic yards (thousand cubic meters)	Automation
Three Forks Division					
East Bench Unit					
Barretts Diversion Dam, Montana, Beaverhead River					
Concrete gate structure, embankment wings.	640 (18)	10 (3)	1,720 (524)	13 (10)	Remote manual control of canal headworks gates
Rogue River Basin Project					
Ashland Lateral Diversion Dam, Oregon, Emigrant Creek					
Concrete ogee weir, earth dike	48 (1)	5 (2)	74 (23)	3 (2)	Upstream control of sluice gate - Floating mode (SOT/SRT)
Oak Street Diversion Dam, Oregon, Bear Creek					
Concrete weir, stoplogged crest.	75 (2)	5 (2)	138 (41)	3 (2)	Downstream control of sluice gate - Floating mode (SOT/SRT)
Salt River Project					
Granite Reef Diversion Dam, Arizona, Salt River					
Concrete ogee weir, embankment wings	3,650 (103)	18 (5)	1,128 (344)	35 (27)	Remote computer assisted control of gates
San Juan-Chama Project					
Blanco Diversion Dam, Colorado, Blanco River					
Concrete ogee weir, embankment wings	520 (15)	20 (6)	200 (61)	4 (3)	Downstream control of sluice gate Upstream control of diversion gates with overriding control to limit tunnel diversion - Floating mode (SOT/VRT)

3. Diversion Dams - Continued

Project Name of Division (Pick-Sloan Missouri Basin Program) Name of Unit (Pick-Sloan Missouri Basin Program) Name of Diversion Dam, State, Stream Type of Structure	Diversion capacity Cubic feet per second (cubic meters per second)	Height Feet (meters)	Crest length Feet (meters)	Volume Thousand cubic yards (thousand cubic meters)	Automation
Little Oso Diversion Dam, Colorado, Little Navajo River Concrete ogee wier	150 (4)	15 (5)	295 (90)	3 (2)	Downstream control of sluice gate Upstream control of diversion gates with overriding control to limit tunnel diversion - Floating mode (SOT/VRT)
Oso Diversion Dam, Colorado, Navajo River Concrete ogee wier, embankment wing.	650 (18)	23 (7)	790 (241)	18 (14)	Downstream control of sluice gate Upstream control of diversion gates with overriding control to limit tunnel diversion - Floating mode (SOT/VRT)

4. Major Pumping Plants - 1,000 Total Horsepower or Greater

Project - Name of plant	Number units	Total capacity Cubic feet per second (cubic meters per second)	Dynamic head Feet (meters)	Total horsepower (metric horsepower)	Automation
Central Valley Project					
Trinity River Division					
Cow Creek Unit					
Wintu Pumping Plant	4	100 (3)	295 (90)	4,000 (4,056)	Downstream control of pump units - ON-OFF mode
Friant-Kern Canal Distribution System					
Delano-Earlimart Irrigation District					
Plant No. D-3	11	94 (3)	31--49 (9--15)	1,090 (1,105)	Downstream control of pump units - ON-OFF mode
Sacramento River Division					
Colusa County Water District					
Pumping Plant 2A.	7	84 (2)	111 (34)	1,500 (1,521)	Downstream control of pump units - ON-OFF mode
Pumping Plant 2A1	6	83 (2)	111 (34)	1,450 (1,470)	Downstream control of pump units - ON-OFF mode
Pumping Plant 2B.	6	83 (2)	101 (31)	1,300 (1,318)	Downstream control of pump units - ON-OFF mode
Pumping Plant 2C.	6	85 (2)	103 (31)	1,025 (1,039)	Downstream control of pump units - ON-OFF mode

4. Major Pumping Plants - 1,000 Total Horsepower or Greater - Continued

Project - Name of plant	Number units	Total capacity Cubic feet per second (cubic meters per second)	Dynamic head Feet (meters)	Total horsepower (metric horsepower)	Automation
Corning Canal Pumping Plant	6	477 (14)	59--71 (18--22)	4,050 (4,107)	Downstream control of pump units - ON-OFF mode
West San Joaquin Division					
San Luis Unit					
Dos Amigos Pumping Plant.	6	13,200 (374)	107--125 (33-- 38)	240,000 (243,360)	Remote computer assisted control - Operated by the California Department of Water Resources
Chief Joseph Dam Project					
Greater Wenatchee Division					
Brays Landing Unit Lateral System					
"A" Pumping Plant	5	31 (1)	317 (97)	1,500 (1,521)	Downstream control of pump units - ON-OFF mode
Pumping Plant No. 1	5	31 (1)	241 (73)	1,100 (1,115)	Downstream control of pump units - ON-OFF mode
East Unit					
Booster Pumping Plant.	4	76 (2)	652 (199)	7,500 (7,605)	Downstream control of pump units - ON-OFF mode
Howard Flat Unit					
River Booster Pumping Plant.	3	17 (--)	490 (149)	1,200 (1,217)	Downstream control of pump units - ON-OFF mode

4. Major Pumping Plants - 1,000 Total Horsepower or Greater - Continued

Project - Name of plant	Number units	Total capacity Cubic feet per second (cubic meters per second)	Dynamic head Feet (meters)	Total horsepower (metric horsepower)	Automation
The Dalles Project					
Mill Creek Pumping Plant.	5	54 (2)	228 (69)	1,800 (1,825)	Downstream control of pump units - ON-OFF mode
Lateral Distribution System					
"A" Pumping Plant	5	51 (1)	419 (128)	2,500 (2,535)	Downstream control of pump units - ON-OFF mode
"F" Pumping Plant	5	43 (1)	307 (94)	2,150 (2,180)	Downstream control of pump units - ON-OFF mode
Ventura River Project					
Rincon Pumping Plant.	2	6 (--)	900 (274)	1,040 (1,055)	Downstream control of pump units - ON-OFF mode
Ventura Avenue Pumping Plant No. 1.	4	50 (1)	429 (131)	3,200 (3,245)	Downstream control of pump units - ON-OFF mode
Ventura Avenue Pumping Plant No. 2.	3	48 (1)	220 (67)	1,800 (1,825)	Downstream control of pump units - ON-OFF mode

5. Storage Reservoirs - Outlet Works

Project Name of Division (Pick-Sloan Missouri Basin Program) Name of Unit (Pick-Sloan Missouri Basin Program) Name of Reservoir, State, Stream	Purpose	Capacity		Surface area	Automation
		Active	Total		
		Thousand acre-feet (million cubic meters)	Thousand acre-feet (million cubic meters)	Hundred acres (hundred hectares)	
Pick-Sloan Missouri Basin Program					
Lower Bighorn Division					
Yellowtail Unit					
Yellowtail Afterbay Reservoir, Montana, Bighorn River	P	3 (4)	3 (4)	2 (1)	Downstream control of canal headworks gates - Floating mode (SOT/SRT)
Three Forks Division					
East Bench Unit					
Clark Canyon Reservoir, Montana, Beaverhead River	I-FC-F&W	256 (316)	257 (317)	59 (24)	Remote manual control of outlet works gates
Rio Grande Project					
Caballo Reservoir, New Mexico, Rio Grande. . .	I-P-FC	344 (424)	344 (424)	116 (47)	Remote manual control of outlet works gates

APPENDIX III

PARAMETERS OF DOWNSTREAM CONTROL

A basic parameter for a controlled water distribution system by the downstream method is steady flow, $\Delta Q_{out} = \Delta Q_{in}$, Figure 24. In simplified terms, the flow out of a controlled section is expressed as:

$\Delta Q_{out} = \Delta G * B * C_d \sqrt{2g*\Delta H}$, where

ΔG = change in gate opening

B = gate width

C_d = gate discharge coefficient

ΔH = differential head across gate

The flow into a controlled section may be expressed in terms of an elementary wave traveling downstream in a trapezoidal channel.

$\Delta Q_{in} = \Delta Y * T(V+C)$ where

ΔY = change in upstream depth

T = top width of water surface

V = channel velocity

C = wave celerity ($\sqrt{gA/T}$) where A equals the cross-sectional area of the total flow

The ratio of $\Delta Q_{out}/\Delta Q_{in}$ must be unity for steady flow expressed as:

$$\frac{\Delta Q_{out}}{\Delta Q_{in}} = \frac{\Delta G}{\Delta Y} \left(\frac{B * C_d \sqrt{2g\Delta H}}{T(V+C)} \right) = 1$$

The ratio of $\Delta G/\Delta Y$, by definition, is the GAIN for the controller and is the first main control parameter:

$$\text{GAIN} = \frac{\Delta G}{\Delta Y} = \frac{T(V+C)}{B * C_d \sqrt{2g\Delta H}}$$

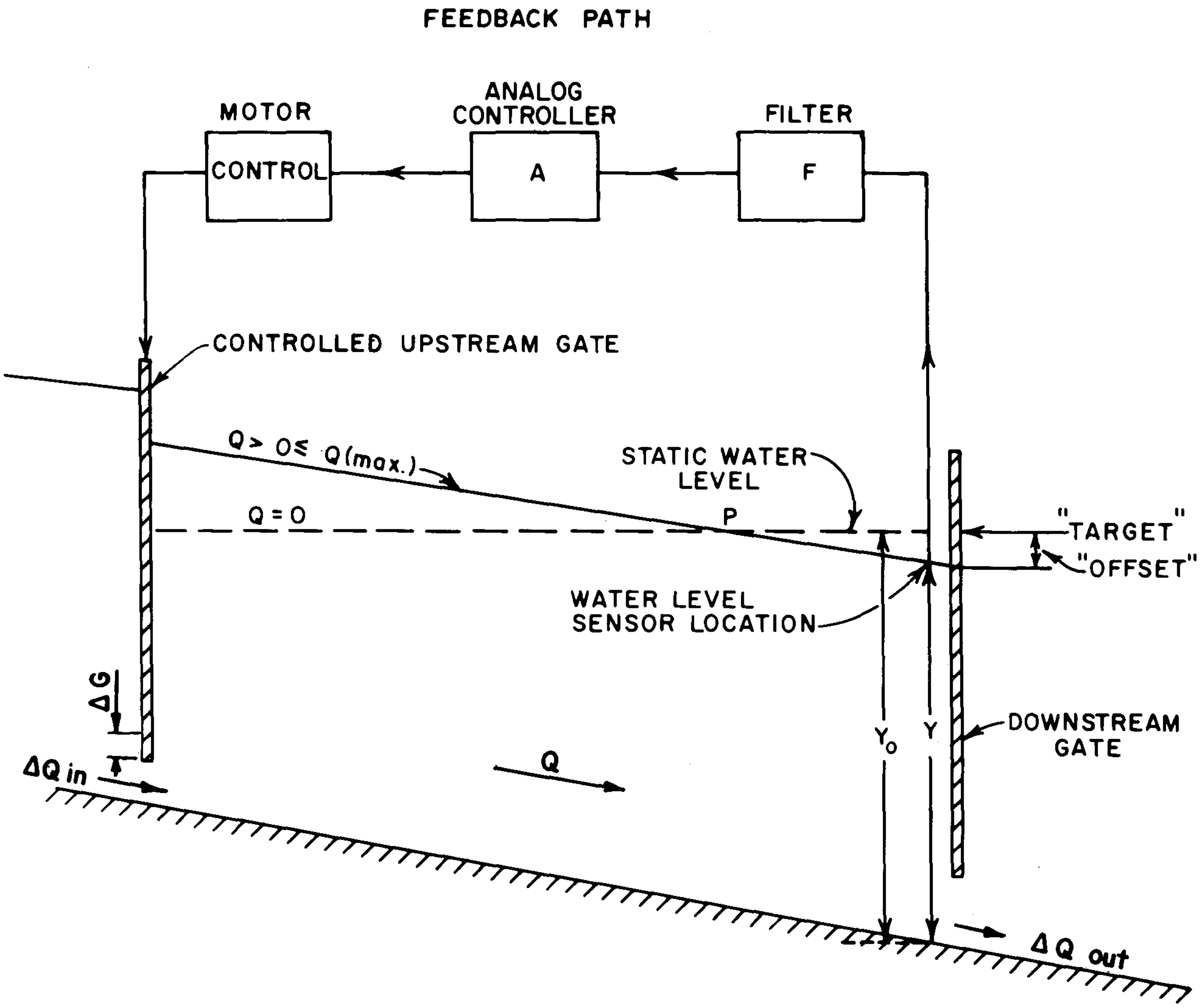


Figure 24.–Schematic of Downstream Control by the HyFLO Method.

The GAIN equation shows that the controller is dependent upon the characteristics of the upstream channel and the flow (submerged or free-flow) through the controlling check gate. After the GAIN is computed, the value of ΔY can be found by arbitrarily selecting a value for ΔG (usually 0.10 foot).

ΔG can be expressed in terms of the operate time, Δt_o, of the gate motor hoist. The change in gate opening has a displacement of $\Delta G = x * \Delta t_o$, where x is the rate of gate movement in feet per second. Solving for Δt_o gives:

$$\Delta t_o = \Delta G / x$$

The "offset" of the water level required for the increase or decrease of flow is the second control parameter, Figure 24. The maximum "offset" is defined as:

$$\text{Offset}_{(max)} = G_{(max)}/\text{GAIN}$$

where $G_{(max)}$ is the maximum gate opening required to discharge the maximum desired flow.

The "offset$_{(max)}$" would have to be a value less than the difference in elevation between the maximum safe operating level or spill crest and the normal water surface operating level. An attempt to use an offset less than determined above would require the GAIN of the controller to be larger. In turn the ratio of $\Delta Q_{out}/\Delta Q_{in}$ would be larger than unity and could cause excessive opening or closing of the gate (overshoot) and instability of control would result in unsteady flow.

The above analysis can be used to determine approximate values of the control parameters, GAIN and "offset$_{(max)}$." The approximate method provides a first approximation of the control parameters for a particular installation. Greater accuracy can be achieved through mathematical modeling before selecting final values.

The "time lag" of the system is the third control parameter. The need to minimize the possibility of unsteady flow requires that the gate changes be made out of synchronization with the waves caused by the gate movement. Mechanical, fluid, or electrical delay units between a level sensor and the control may be necessary to prevent an amplification of the wave.

Wave travel time between the sensor and controlled structure is computed from the relationship $C = \sqrt{gA/T}$. Selection of the response time of the system may be made from methods proposed by the University of California, Berkeley[11]. For steady flow and stable operation of the canal, gate movements must not coincide with the wave travel period.

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