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INTRODUCTION

Modern irrigation practices are straining the capabilities of manually operated canal systems. New principles of water application and scheduling are currently being developed and implemented. The thrust is towards higher irrigation efficiency which involves efficient use of water and increased crop yields at reduced costs. An important factor involved in the efficient use of water is the delivery of specified amounts of water to the point of use at the times needed. Canal systems serving many distribution laterals need to respond faster and with greater flexibility of operation to meet the needs of modern irrigation practice. Automatic downstream control of canal check gates is one approach to achieve optimum efficiency of a canal delivery system and to nullify many of the limitations imposed by operating in the conventional manner.

A practical method to achieve automatic downstream control has been developed known as the EL-FLO (Electronic Filter Level Offset) plus RESET control system and is currently in operation on two canal systems in California which are the Corning Canal near Red Bluff with 12 check gate structures and the Coalinga Canal near Coalinga with 3 check gate structures. The EL-FLO relates an increase in demand from the turnouts and reaches downstream to a water level offset (the amount by which the water level for a positive flow lies below a target level). The upstream gate opening is directly proportional to this offset, so that a demand inflow identity is established. Sensing the offset involves a special filter to provide system stability for large and small changes in canalside demands [1]*. The RESET eliminates the residual water level offset and restores the water level back to the target level (selected at the maximum designed discharge of the canal reach being controlled).

Changes in canalside turnout demands are automatically coupled to the canal headworks in the EL-FLO plus RESET control system. The EL-FLO plus RESET control system is designed to accommodate complex irrigation water delivery schedules with a high degree

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* Numbers in brackets refer to literature cited.

of self-regulation and maintains near constant water levels in a canal system. The sustained water level oscillations inherent to automatic flow regulation schemes are eliminated through the use of an "electronic filter" or time delay circuit [2].

Although the EL-FLO plus RESET control method is based on the application of sophisticated control theory, the control elements are simple in design compared to the degree of self-regulation achieved. The method is general in principle and is applicable to many canal systems similar to the Corning Canal.

A treatise on control engineering which embraces many of the basic sciences would be inappropriate for this paper and beyond the capabilities of the author. However, the basic concept of automatic downstream control is briefly described. Automatic upstream control is also discussed in order to provide the basis for proper application of upstream and downstream control. The need for automatic downstream control and the general theory of the EL-FLO plus RESET control mode is then presented. Finally, the advantages, disadvantages, summary, and conclusions are offered. This paper does not include technical descriptions of the equipment necessary to implement the EL-FLO plus RESET automatic downstream control system.

Reference [2], expected to be published in August 1979, will describe the development of the EL-FLO plus RESET automatic downstream control system for the Corning Canal in greater detail. It will include laboratory and field verification tests, a technical description of each control element in the feedback path, and the procedure to calibrate the control system with selected control parameters. The contents of this paper summarizes parts of references [1] and [2]. Additional discussion has been included for the downstream control concept, the need for automatic downstream control, and the filter element to provide the basic fundamentals of the EL-FLO plus RESET automatic downstream control system and its application to the demand-oriented delivery systems such as the Corning Canal.

AUTOMATIC DOWNSTREAM CONTROL CONCEPT

The downstream control concept is "the transfer of the downstream water demands from the point of use to the upstream source of supply." Downstream control is applicable to demand-oriented delivery systems. Applying the downstream control concept to a main canal system of an irrigation project, figure 1(A), means the downstream water demands being delivered through the many canalside turnouts en route are transferred upstream to the canal headworks or the source of supply. <u>Automatic</u> downstream control automatically transfers the downstream

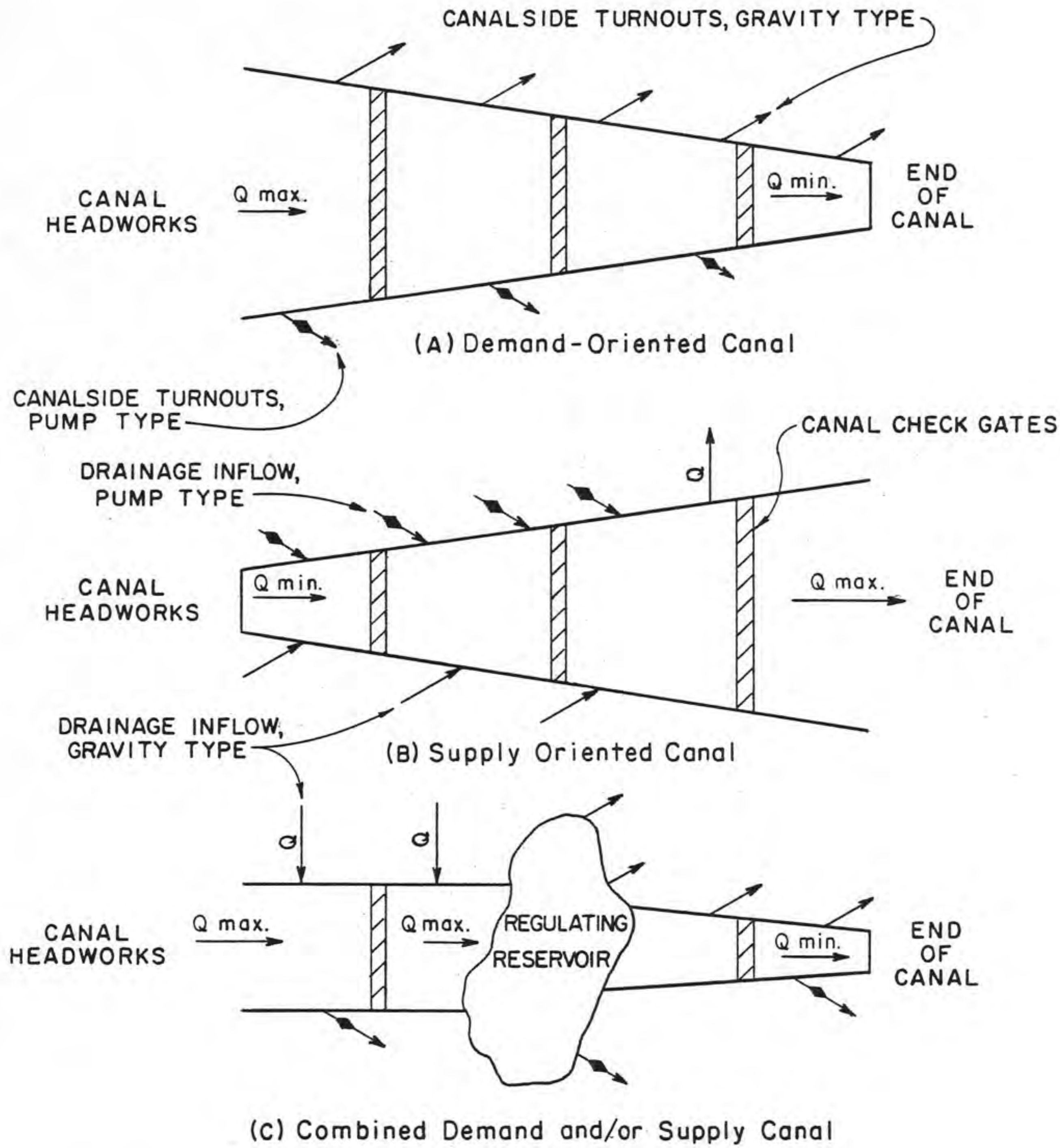


FIGURE 1 - SCHEMATIC PLANS OF (A) DEMAND-ORIENTED, (B) SUPPLY ORIENTED, AND (C) COMBINED DEMAND AND/OR SUPPLY-ORIENTED MAIN CANAL SYSTEMS

demands upstream through intermediate canal check gate structures to the canal headworks without supervisory intervention [3].

Main canal systems for irrigation projects are designed to deliver water to irrigation lands downstream from a source of supply upstream, figure 1(A). The main canal begins with a maximum designed flow capacity and usually ends with a much smaller capacity as water is delivered through the many canalside turnouts to project lands en route (typically the end capacity is about 10 percent of the beginning capacity).

An important factor involved in the efficient operation of an irrigation project main canal is the delivery of specified amounts of water to the point of use at the times needed. Sudden and unannounced variations in canalside demands or mismatches (when the demand is larger or smaller than the supply) must not be allowed to propagate into the downstream canal reaches that have the smaller carrying capacities. Serious shortages would cause objectionable water level drawdown and would disrupt service to water customers. Surplus water would cause flooding and trigger undesirable operation of the canal wasteways, wasting water into natural channels. The wasting of water as a result of operational errors is an inefficient use of the available water supply. Prompt action is required to adjust intermediate gates upstream and the canal inlet flow to maintain a balanced system and an efficient operation.

Automatic downstream control requires that a decrease in water surface elevation (modified by a filter and usually measured at the downstream end of the canal reach), an indication that canal demands have increased downstream, produce an increase in the upstream controlled gate opening. The increased upstream flow into the canal reach balances the increased downstream demand. Likewise, an increase in the water surface elevation (or a decrease in the downstream demand) decreases the upstream flow into the canal reach. Changes in the downstream canalside demands are, therefore, automatically transferred upstream.

To achieve optimum efficiency of the use of the available water supply, it is essential that irrigation main canals be operated as a demand-oriented delivery systems. Automatic downstream control insures sensible coupling of the irrigation demands and the canal inlet flow of a demand-oriented main canal system.

AUTOMATIC UPSTREAM CONTROL CONCEPT

The upstream control concept is "the transfer of water from the upstream source to points of delivery downstream." Upstream control is applicable to supply-oriented canals systems. Applying the upstream control concept to a main canal system means the source of water, collected from many canal inlet drains, for example, is transferred downstream to selected points of delivery. Automatic upstream control automatically transfers the upstream source of water downstream through intermediate canal check gate structures to the point of delivery without supervisory intervention.

Main canal systems for drainage projects are designed to collect water from many sources en route and deliver the water downstream to a holding reservoir, desalting plant, or to the ocean. The drain system capacity begins small and ends with a maximum design capacity as drainage inflows from project lands increase en route, figure 1(B).

The operation of a main canal for a drainage collection system requires all changes of the inflows to be delivered downstream. As the inflows vary, the intermediate check gate structures must be regulated to prevent flooding or serious water level drawdowns within the canal prism.

Automatic upstream control requires that an increase in the upstream water surface elevation (modified by a filter), an indication that canal inflows have increased, produce an increase in the controlled gate opening immediately downstream to increase the flow into the downstream canal reach. Likewise, a decrease in the water surface elevation upstream decreases the flow downstream. Changes in canal flow arriving at a check gate from upstream are, therefore, automatically transferred downstream.

COMBINED DOWNSTREAM AND UPSTREAM CONTROL

Main canal systems are sometimes designed to convey water from a source to a downstream regulating reservoir, figure 1(C). The main canal connecting the source to the reservoir usually has a constant designed flow capacity throughout its length. In this case, upstream control could be used to regulate intermediate check gates as changes of canalside turnout demands and/or inflows occur en route. However, applying the upstream control concept to a delivery system that is basically demand oriented will require a relatively large regulating reservoir and turnout demand at the end of the canal. The reservoir storage capacity will have to be designed to adequately regulate the largest anticipated mismatch for a sufficient period of time, i.e., the time required for a surge wave to travel the distance from the headworks to the reservoir to balance the mismatch.

In some conveyance systems, the regulating reservoir is located at an intermediate point, figure 1(C). In this case, upstream control could be applied to the upper canal reaches from the headworks to the reservoir. Downstream control would then be applied to the canal reaches downstream using the regulating reservoir as its source of water supply. Therefore, there are main canal systems where the design and operating criteria permit a combination of the downstream and upstream control concepts.

THE APPLICATION OF AUTOMATIC DOWNSTREAM CONTROL

The above dissertation on automatic downstream and upstream control concepts was deemed necessary in order to provide a basis for the application of the correct control concept to the Corning Canal system.

The Corning Canal is a demand-oriented delivery system, figure 1(A), and will be discussed further in subsequent paragraphs. Operating the Corning Canal can be accomplished by (1) manual, (2) local automatic, and (3) remote (manual and/or automatic) supervisory modes of control. The basic procedure of a manual operation involves (1) an order by the water user, (2) a change (increase or decrease) in the inflow of water at the head of the canal to meet that order, and (3) operation of the canal by having the "ditchrider" follow the wave by which the change is propagated downstream, making adjustments in the canal control structures such as check gates and canalside turnouts when the front of the wave arrives. The "ditchrider" is essentially performing downstream control for a demand-oriented delivery system. (A supply-oriented delivery system requires the "ditchrider" to follow the wave propagating downstream when the canalside inflow changes occur, making adjustments in the canal check gates when the front of the wave arrives.) An experienced operator can anticipate the water arrival at the scheduled time of the requirement within acceptable limits. Practically, there are difficulties in making proper adjustments.

In the remote manual supervisory mode of control, direct operational control is given to the "watermaster" in the central office at some remote location. The local automatic control mode is designed to sense and interpret changes in flow conditions and to make necessary adjustments "onsite" to meet the operating needs without supervisory intervention. In the remote automatic mode of control, the automatic control of the canal check gates is directed from the central office at some remote location without supervisory intervention.

Control of a canal operation may involve the use of a combination of two or perhaps all three modes of control [manual, local, and remote (manual and/or automatic) supervisory]. The relative merits of the three approaches depend on the circumstances of use. In some cases, one system will be better than another, or a combination will be even better [5].

The Corning Canal could have continued to be operated in the conventional mode, i.e., manual operation. However, as the irrigation distribution systems flow demands increased, each year of operation, the manual operation became increasingly more difficult without increasing the number of ditchriders. Remote manual supervisory control would have provided adequate control. However, the remote manual control requires 24-hour operator attendance at the central office, and the economics savings were considered to be marginal. The remote automatic supervisory (with manual control for backup in the event of equipment failures) several years ago was not considered to be feasible. In recent years, the availability of low cost minicomputers and microprocessors may make the remote (manual and automatic) supervisory control economically attractive if the selection of the control mode were made at the present time.

When the selection of the optimum control scheme for the Corning Canal was being studied in 1972, the local automatic control mode using the EL-FLO plus RESET automatic downstream control system provided the best economic savings estimated to be a 2:1 benefit to cost ratio. The selection of the EL-FLO plus RESET method was not limited to economic savings. The method has the capability to provide service on demand at a high degree of self-regulation. It requires the minimum of operating personnel coverage (day shift only and night standby). An alarm system for equipment failure for the local automatic mode must be an integral part of the control system. The control equipment must also operate at a high degree of reliability. To date, the reliability of the EL-FLO plus RESET control equipment has not reached a satisfactory level. Further development work is being conducted to improve reliability characteristics of the EL-FLO plus RESET control system. The majority of equipment failures have resulted from inadequate protection against electrical storms (lightning strikes), individual component failure because of insufficient quality control by the manufacturer, and loose connections at pin sockets.

THE NEED FOR AUTOMATIC DOWNSTREAM CONTROL

The Bureau of Reclamation and the laws under which it functions provide the means for owners of irrigable land to obtain financial and technical assistance in the development of irrigation projects. The landowners within the service area of the Corning Canal system, for example, form an irrigation or water district under the laws of the state of California. The Bureau works closely with the landowners or water users and the districts elected board of directors to develop the water supply and irrigation facilities to serve the irrigable lands. Reports are prepared describing the service area, the quantity of water supply required and its source, the plan of development, and the financial arrangements. These reports are reviewed by the local people, the state, and other agencies. After approval by the Secretary of the Interior, the final plan showing engineering and economic feasibility must be presented to the United States Congress for authorization.

The board of directors elected by the water users of the district has power to tax the water users and enter into a contract with the Bureau to construct, operate, and maintain the irrigation facilities. Before construction can start, the district must sign a contract agreeing to repay an appropriate share of the project cost, and Congress must appropriate the necessary funds. The board of directors of the irrigation district represents the landowners throughout these negotiations and transactions. However, before the contract can be executed, a favorable vote of the landowners is required.

The initial costs of the project facilities are amortized usually over a 40-year payout period and an annual operating and maintenance cost component is then added to determine the annual cost per acre-foot of water. The water users pay, through the irrigation district, for the constructed project facilities and its operation and maintenance costs. Therefore, the economic feasibility of providing "automation" becomes an important item when developing control schemes to achieve optimum operational efficiency for the Corning Canal.

The quantity of water made available to the water districts is based on the amount of water available from rain and snowmelt into the storage reservoirs for the normal years of precipitation. Carryover storage is provided for a historical dry cycle. However, in recent years, severe drought conditions have occurred in California, and the carryover storage was not sufficient to provide full service to all contracting water districts. A deficiency is then applied to each contracting entity based on the amount of water available in storage at the beginning of the irrigation season.

The above paragraphs describe, in simplified terms, the basic contractual arrangements of the water user, the water district, and the Bureau of Reclamation. The water user is entitled to receive his contracted amount of water each year (including the reduced quantity during drought years). The water user submits his order for water he needs 24 hours in advance to the water district headquarters. The water district accumulates the water orders from all the water users. The water users will receive their amount of water the next day providing the accumulated amount does not exceed the capacity of the distribution systems. The distribution laterals are not designed to provide service to all the water users at the same time because it would be too costly and is actually not required. When the daily demands exceed the capacity of the distribution lateral, the water users then must irrigate their lands on a rotational basis which means irrigation becomes a 24-hour operation. The rotation schedule is established by the water district through cooperation of the individual water users.

The water district, after accumulating the water orders for each canalside turnout, submits these orders to the Bureau of Reclamation's Corning Canal operating headquarters. The "watermaster" then checks to be sure the water district's accumulated orders have not exeeded the contracted quantities. There are also weekly and monthly schedules established in advance that the accumulated orders should not exceed by large amounts. If the orders are exceeding advanced schedules, the "watermaster" may require the water district to reduce its orders, particularly if water orders are exceeding the annual contractual amount. If the accumulated water orders are within proper limits, then the "watermaster" will accumulate the canalside turnout demand orders and submit the total demand for the Corning Canal inlet to the operators of the water storage facilities. Releases are then made from the storage reservoir, and the water supply will arrive at the Corning Canal inlet as to the scheduled time of delivery and in the quantity ordered including allowances for losses that occur in the conveyance system.

Therefore, the Corning Canal is operated as a demand-oriented delivery system. The demand begins with an advanced order submitted by the water user. The scheduled water will be available at the canal headworks at the time of the scheduled change. It then becomes the responsibility of the canal operator regulating a canal system serving many distribution laterals to match the downstream canalside demands or orders to the upstream available water supply at the canal headworks.

When canals are operated in the conventional manner, scheduling the water demand in advance as to time and quantity are important to the canal operator. The quantities of water ordered are released from the canal headworks with a lead time prior to the actual time of delivery. The arrival at the downstream turnout then coincides with the scheduled time of diversion. Water users must adhere to their announced schedules and maintain uniform diversions from the distribution lateral if the canal is to remain balanced.

Modern irrigation practices are straining the capabilities of a canal system operated in the conventional manner. The process of delivering water from the canalside turnout to its final applicathe requirement is the increase in the amounts of water being delivered by canal systems to municipal and industrial water users that require service on demand.

Automatic pipe distribution systems are becoming more prevalent. Pumping plants at canalside turnouts for pressure pipeline distribution laterals are being automated to reduce operational costs and maintain maximum pressure head in the laterals for better service to the water users. The pumping units are started and stopped from pressure-level sensors which respond to the actual diversions being made by the water users. An automated lateral is essentially a demand system limited only by the capability of the canal to respond. Since pumping units and the automatic devices are subject to power and equipment failure, the plant could shut down and the entire diversion would be rejected back into the canal. A sudden and unannounced increase of pumping at the turnout could cause serious shortages of water to the downstream water diverters. A sudden pump rejection could propagate into the lower reaches of the canal which usually have smaller carrying capacities and could trigger undesirable operation of the wasteways or cause flooding. The carrying capacities of the lower reaches in many canal systems are only about 10 percent of the initial reach or the design capacity of the canal headworks. A variation of inflow of 5 percent of the capacity in the initial reach of the canal could result in a 50 percent variation of flow in the last reach of the canal. Prompt corrective measures would be required to adjust the intermediate check gates and the flow at the canal inlet so as to protect the system.

Conventionally, operations personnel operate on-farm turnout valves to maintain the diversions in accordance with the schedule submitted in advance by the farmer. However, this responsibility is being relinquished to the farmer in order to reduce operating costs. For the most part, this arrangement is working out satisfactorily. However, it is only natural to expect the farmer to make last minute alterations in his irrigation schedules to facilitate other competing farm operations if no other controlling factor is involved. As a result, close control of diversions according to the announced schedule is sometimes not too close.

Sprinkler irrigation systems are steadily increasing in popularity. Through proper agricultural sprinkling, crop yields are increased, and better efficiency in water and land use is attained at reduced costs. Sprinkling for crop protection against frost and heat provides additional crop insurance to the farmer. Solidset sprinkler systems are readily adaptable to simple automatic switching devices which can be programmed as to the day and hour to transfer the irrigation from one section of land to another. Future automated sprinkler systems may include temperature and soil tensiometer sensors.

These sensors would activate irrigation of the crop for a preset period of time when air temperature exceeds the limits for frost and heat or when the soil moisture content in the plant root zone is at a low level. A fully automatic system would then be sensitive and respond immediately to the sudden changes in the weather. Many sprinkler systems require booster pumps to obtain the proper pressure head at the sprinkler nozzle. These pumps and the automatic programers are also subject to power and equipment failure as in the case of automated laterals. The changes in diversions caused by sensor activation or booster pump rejection would be reflected back into the distribution lateral and then to the canalside turnout without notification to the canal operator.

Increasing amounts of water are being delivered to M&I (municipal and industrial) customers along with irrigation water in canal systems. M&I use by its very nature requires water on demand. Many M&I distribution systems, like irrigation systems, have only minimal regulatory storage reservoirs. Therefore, a canal system may be required to deliver M&I water on demand, with a rate of supply which may vary by more than 50 percent of the mean daily demand.

The preceding paragraphs have pointed out how modern irrigation practices and new equipment currently being used can make optimum efficiency of water delivery in a canal system difficult to attain by canal operators, when operating in the conventional manner. Modernized and automated distribution systems, the way they are operated, and the techniques used to schedule and apply the water to the land, require significant variations in the daily diversion rate at a canalside turnout. Some of the major deviations from the daily schedule are caused by sudden changes in weather and by power and equipment failures. These deviations from an announced schedule cannot be predicted for a canal operator who requires lead time to make adjustments to the canal check gates and the inlet flow.

New techniques are available to predict, with greater accuracy, the time and actual quantity of water needed for irrigation. The guesswork and/or human intuition factors, which include safety margins, are being eliminated from irrigation scheduling procedures. As a result, higher irrigation efficiency is obtained through the efficient use of water. Specific amounts of water required for the crop at particular times of application can be derived on the basis of the very complex soil-water-plant relationships. The soil is characterized as to infiltration rate, permeability, and water-holding capacity. At the beginning of the irrigation season, the type of crop to be grown, the soil moisture content, and salinity conditions are established to start the soil moisture accounting and to estimate any leaching requirements. From the known soil moisture content and the estimated evapotranspiration, the timing and quantity of water needed to replenish the depleted plant-available soil moisture in the root zone can be predicted for the next irrigation. It is anticipated that a great deal of reliable and accurate scientific data on current soil and crop characteristics and weather conditions will be available in the future. With this advanced state-of-the-art and the use of automatic data processing, optimum scheduling of water application can be accomplished daily and perhaps hourly. There are several distinct advantages to predicting, with accuracy, the water applications based on the actual requirements in the plant-root zone. The farmer knows the specific quantities of water needed and when it should be applied to the crop. The canal operator can increase the operating efficiency of a conventionally operated canal by also knowing when these specific quantities should arrive at the point of diversion. Another advantage is that the timing and/or the quantity of the application can be altered to take into consideration other economic factors. Effective rainfall and other major environmental changes such as solar radiation can delay or eliminate the irrigation requirement. An increase in quantity or an earlier time of application may be required for unusually dry and windy weather. Also, the farm irrigation schedule may be revised to fit into the framework of other farm operations and provide the farmer with an economic return.

It is possible for the conventional canal to provide water service on demand through the application of better methods to predict water schedules. However, precise scheduling is very difficult to implement on a total system basis, and it is impossible to predict or anticipate some of the causes of turnout variation such as power and equipment failures. Some present canal systems require 24 to 72 hours advanced scheduling to change the canal flow at the canal-side turnout many miles downstream. The advantages of altering the timing and quantity of water application based on daily or hourly automatically processed scientific data would be nullified for these canals.

It is also logical that water should not be released from the reservoir into the canal system for irrigation or M&I service until there is a demand created. If there is not a demand for the water, it could be held in the reservoir for release at a later time or perhaps used somewhere else. Water held in the reservoir has economic value. It would be beneficial to the recreationist, increase the head for power generation, and decrease the energy required for relift pumping in the delivery systems. On a system basis, these advantages could add up to a significant total.

The Corning Canal is a typical canal system where modern irrigation practices, as previously discussed, are straining the capabilities of the conventional mode of operation. Deliveries are being made to 19 pipe distribution laterals. Seventeen of the lateral turnouts are of the pump type. Of the 17 lateral turnouts, 10 are automatic pressure pipe distribution systems consisting of a total of 30 automatically operated canalside pumping units ranging in size from 0.07 to 0.45 m^3/s (2.5 to 16 ft^3/s). Most of the lateral turnout valves to the farmers' lands are onfarm operated. A few sprinkler systems are in operation and more will be added in the near future. Practice scheduling techniques are not being used currently.

The annual delivery ultimately will reach 146.8 million m^3 (119,000 acre-ft). The water supply is used mainly for irrigation purposes.

The most troublesome problems deriving from the conventional operation of the Corning Canal are maintaining inlet flow to match the water demand and preventing unscheduled turnout diversion changes from passing into the lower reaches of the canal which have small carrying capacities. Difficulties in maintaining a balanced system were being experienced with the conventional mode or manual operation. The main cause is directly related to the large deviations from the announced schedules that are occurring at the 19 canalside turnouts. As the demands continue to build up in the future, the deviations will increase and the problems would have become even more difficult to handle properly with the conventional mode of operation.

The Corning Canal begins on the west bank of the Sacramento River near Red Bluff and extends southerly 33.8 km (21 mi) terminating near Corning, California. The canal begins with a capacity of 14.2 m^3/s (500 ft^3/s) and reduces to 2.5 m^3/s (88 ft^3/s) in the end reach. The canal section is of earth-lined construction with 2:1 side slopes. The canal, with a bottom width varying from 6.7 m (22 ft) to 3.0 m (10 ft) has an average invert slope of 0.00019 for a total drop of 6.4 m (21 ft) in 33.8 km (21 mi) or 0.19 m/km (1 ft/mi). The normal water depth varies from 2.2 m (7.2 ft) to 1.1 m (3.6 ft). There are 12 single-gated check structures spaced on an average of 2.6 km (1.6 mi).

The headworks consist of the Corning Pumping Plant, which has six centrifugal vertical-shaft pumps, three rated at 1.5 m^3/s (53 ft^3/s) and three rated at 3.3 m^3/s (115 ft^3/s). The pumping plant diverts its water from a settling basin just downstream from Red Bluff Diversion Dam. The pumps lift the water 18.0 m (59 ft) into the Corning Canal. At present, two of the small units are automatically started from a water level float sensor located just upstream from the first canal check gate 7.32 km (4.55 mi) downstream. The first unit is started when the water level is 0.06 m (0.2 ft) below the normal depth of 2.2 m (7.2 ft) and stopped when the water level is 0.09 m (0.3 ft) above. The second unit starts when the water level is 0.15 m (0.5 ft) below and stops when the water level is 0.15 m (0.5 ft) above the normal depth.

Automatic downstream control of canal check gates is one approach to upgrading the conventional mode of operation and achieving optimum efficiency of a canal system. Control of canal check gates from downstream water levels automatically insures sensible coupling of turnout diversions and canal inlet flow. The advantages of this concept are attractive and have great potential. The application of control theory has made it possible to design a suitable feedback system of relatively simple, standard components. This system will function with stability and will force the canal to respond immediately to large or small unannounced variations in canalside diversions without supervisory intervention [1].

GENERAL THEORY OF EL-FLO PLUS RESET

The feedback system of the EL-FLO plus RESET controller has been applied to automatic downstream control of canal check gates. The downstream control concept is basically that of a negative feedback relationship between the water level in the canal reach, usually measured at the downstream end, and the discharge into the canal reach through a motor-operated check gate at the upstream end. "Downstream control" in this context means that the control of the changes in canalside demands downstream will progress toward the head of the canal or to the source of supply. The control, although contrived through electronic sensors, "real-time" analog computers-comparators, and electrical-mechanical motorized gate controls, is like natural control in subcritical flow observed in backwater curves, i.e., the control is from downstream to upstream [1].

The signal generated by a change in canalside demand is transmitted nearly instantaneously from the downstream sensor to the upstream check gate. However, the speed at which the canal reach can respond to the signal to satisfy the change of the downstream canalside demand is very slow. The flow response time is relative to the time required for the change of discharge into the upstream end to traverse the canal reach and arrive at the downstream end through hydraulic transient wave action.

Rapid canal response times are necessary to insure sensible coupling of the canalside turnout diversions and canal inlet flow. Rapid response times are limited by canal flow stability considerations and to practical water level recovery characteristics. The design problem is how to achieve the best canal flow response and meet stability criteria that are chosen within limits [1].

The elements of the EL-FLO plus RESET feedback system are shown in the longitudinally compressed figure 2. The first element is the sensor that measures the water level in the canal reach at the downstream end. The water level sensor converts the vertical change of the water level to rotation of a potentiometer to produce a voltage signal output, YC. The output signal, YC, of the water level sensor is delayed by the electronic filter to produce a phase lag between the point of sensing and filter output. The delay limits the response of the total flow change within the period of potential oscillation of the hydraulic transient traveling between check structures.

The output signal, YF, of the electronic filter is transmitted to and received at the upstream check gate. The received YF is the input to the EL-FLO proportional controller and is used in solving the equation:

$$GP = K1[YT-YF] \tag{1}$$

where GP is the desired gate opening of the proportional mode of the feedback system, K1 is the proportionality factor of the "Gain" constant of the EL-FLO proportional controller, YT is the target value or the referenced input. The target value is the desired water level to be maintained for all steady-state flows.

The output signal, GP, of the EL-FLO proportional controller provides the input signal to the RESET controller and electronically performs the following integration:

$$GR = K2 \int_0^t GP \cdot dt \tag{2}$$

where GR is the desired gate opening of the reset mode of the feedback system, K2 is the proportionality factor or the "Gain" constant of the RESET controller, and t is time.

The total desired gate position, GD, is represented mathematically by the following equation:

$$GD = K1[YT-YF] + K2 \int_0^t [K1\ [YT-YF]\ dt \tag{3}$$

or

$$GD = GP + GR \tag{4}$$

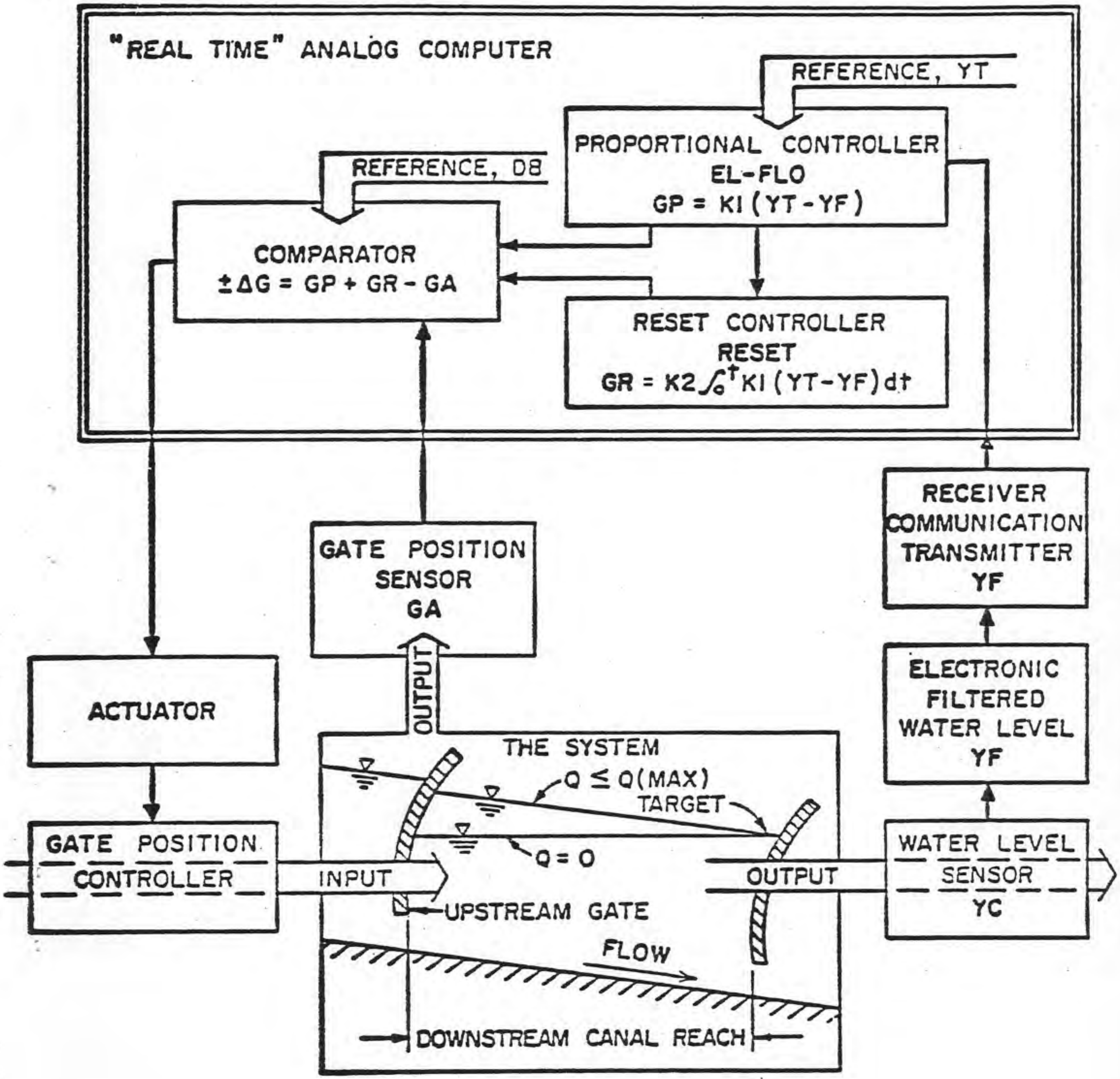


FIGURE 2 – EL-FLO PLUS RESET FEEDBACK CONTROL SYSTEM

The output signals of the EL-FLO and RESET controllers, GP and GR, are the inputs to the comparator unit. The comparator unit sums the two inputs to obtain the desired gate position, GD (equation (4)), and compares GD to the actual gate position,,GA, to obtain the error signal, $\pm\Delta G$, as follows:

$$\pm\Delta G = \Delta GP + GR - GA = GD - GA \qquad (5)$$

where GA has an opposite polarity to GP and GR. The value of GA is measured by a potentiometer driven by the check gate hoist shaft. If the error signal $\pm\Delta G$ is greater than the referenced input or gate movement deadband, DB, [typically 0.03 m (0.10 ft) of gate opening], the comparator unit will energize the raise or lower relay of the actuator which in turn energizes the gate motor to raise or lower the gate depending on the polarity of the comparator unit output signal. The gate will then raise or lower until the comparator unit difference or error signal output, $\pm\Delta G$ is zero, at which time the gate motion stops. The referenced input, DB, of the comparator unit is necessary because of the very fast rate of gate movement, GA, relative to the computed desired gate position, GD.

All measured and computed values of the feedback control system must be correctly scaled and calibrated if each element in the feedback path is to perform in accordance with equations (3) through (5).

The selection of proper control parameters is essential to the stable operation of the EL-FLO plus RESET feedback control system and to achieving desirable water level response characteristics. Control parameters are selected to eliminate instability inherent in automatic feedback control systems and to give a high degree of self-regulation, i.e., the fastest response to the change of canalside demands downstream with recovery of the canal reach to a new steady state without excessive overshooting of the inlet flows or deviation of the water levels. The system must function over a wide range of canalside demand changes from a rapid change of 50 percent of designed capacity of a canal reach to a small change of less than 1 percent.

Three control parameters used by the EL-FLO controller provide primary control action during the unsteady state flow conditions that occur immediately after a flow change downstream. These three control parameters are (1) the electronic filter "time constant," TF, (2) the water level "offset" (YT-YF) of equation (1), and (3) the proportionality factors or "gains," K1 and k2 of equations (1) and (2).

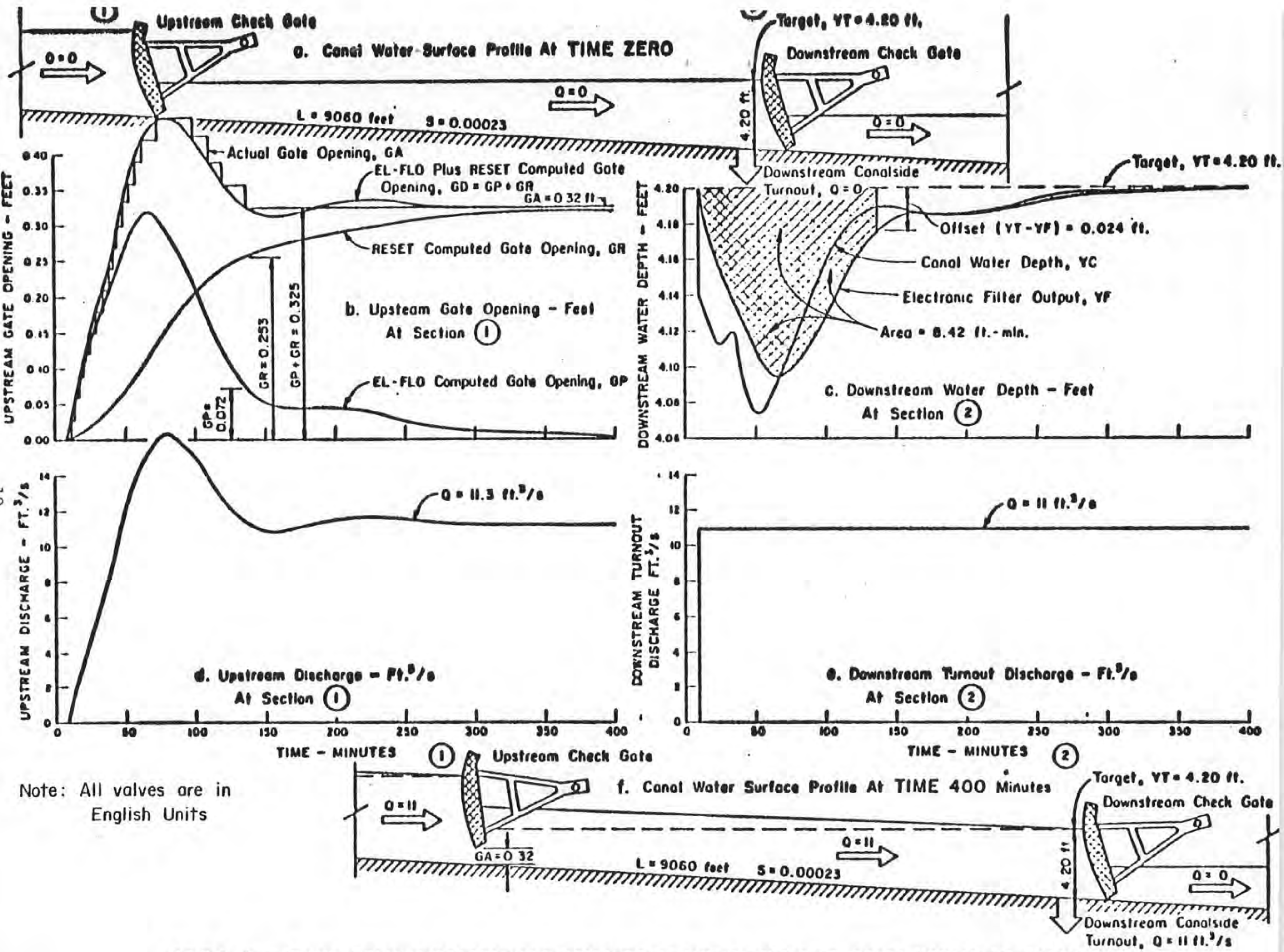


FIGURE 3 — CANAL REACH CHARACTERISTIC RESPONSE BY THE EL-FLO PLUS RESET METHOD OF AUTOMATIC DOWNSTREAM CONTROL (PROPORTIONAL MODE PLUS PROPORTIONAL RESET MODE OF CONTROL)

The "time constant," TF of the electronic filter, provides the stability of the control system by attenuating the critical frequencies of water level disturbances that tend to be amplified by the controller. The selection of the proper time constant is based on considerations of the hydraulic transient behavior of the open channel under study, the desired response of the control action for the system, or the amount of damping desired within a period of potential oscillation, as well as the desired magnitude of the "offset" from the target value.

The time constant, TF, and the magnitude of the offset, (YT-YF), are largely dependent on the length of the canal reach between check gate structures and the physical properties of the channel cross section. A long canal reach with a relatively small cross section will require a long time constant and a large offset to maintain control stability when recovering to the new steady-state flow conditions. The filter element is described in greater detail in subsequent paragraphs.

For stability, the downstream control concept requires that a decrease in the downstream water surface level (modified by a filter) indicating the downstream flow demands have increased, produce an increase of flow at the next canal check gate upstream, figure 3. Likewise, an increase in the water surface level, an indication that flow demands downstream have decreased, decreases the flow into the canal reach upstream. Changes of the downstream demand are, therefore, automatically transferred upstream.

The "offset" is an essential part of the proportional plus proportional reset mode of control and provides a smooth and continuous control action because of the coupling between the controlled variable, the downstream flow demand, and the inlet flow upstream after a flow change occurs downstream and a new steady-state flow condition develops at the target level, YT. Figure 3 illustrates a typical response of the EL-FLO plus RESET automatic downstream control system to a sudden increase in the flow demand downstream.

It should be noted, figure 3, how the electronic filter responds during the transient state. During steady-state flow conditions, the electronic filter output, YF, is the same as the canal water level, YC. The RESET controller does not sum the area within the dead band, ±RDB, and should be selected wide enough to provide good stability characteristics at the steady-state flow conditions. The primary function of the RESET controller is to eliminate the residual water level "offset" of the EL-FLO controller and thereby restore the canal capability for maximum flow and designed canalside turnout capacities. Observe that the EL-FLO controller provides the primary control response immediately after the flow change downstream has taken place. As a new steady-state flow condition level, YC. The RESET controller does not sum the area within the dead band, IRDB, and should be selected wide enough to provide good stability characteristics at the steady-state flow conditions. The primary function of the RESET controller is to eliminate the residual water level "offset" of the EL-FLO controller and thereby restore the canal capability for maximum flow and designed canalside turnout capacities. Observe that the EL-FLO controller provides the primary control response immediately after the flow change downstream has taken place. As a new steady-state flow condition develops at the target level, the EL-FLO controller influence approaches zero and the RESET controller provides the primary control response.

The three primary control parameters, (1) the filter "time constant," (2) the water level "offset" magnitude, and (3) the proportionality factors or "gains," K1 and K2, are interdependent and are selected by trial and error "on-the-bench" using a mathematical model of the canal and control system. Without the availability of the mathematical model, selection of the optimum control parameter values would be extremely difficult and is not recommended if the EL-FLO plus RESET control system is to function over a wide range (100 percent) of the canalside demands.

THE FILTER ELEMENT

The filter element is a necessary timelag compensator for automatic downstream control systems such as the EL-FLO plus RESET controller. The filter-time constant, TF, ranges from 100 to 4,000 seconds, depending primarily on the length of canal reach, to provide control stability. Effects of waves of high frequency are filtered out with a time constant of 100 seconds or more and, therefore, are not a problem with automatic downstream control systems.

The development of automatic downstream control actually started with the hydraulic filter. The hydraulic filter involves a small well with a very small diameter capillary tube inlet placed in the canalside stilling well shown schematically in figure 4 [6]. The water surface level, YF, in the small well would be measured for the input signals to the controller. The equation of continuity for the hydraulic filter is:

$$qf = \frac{ad\Delta hf}{dt} \qquad (6)$$

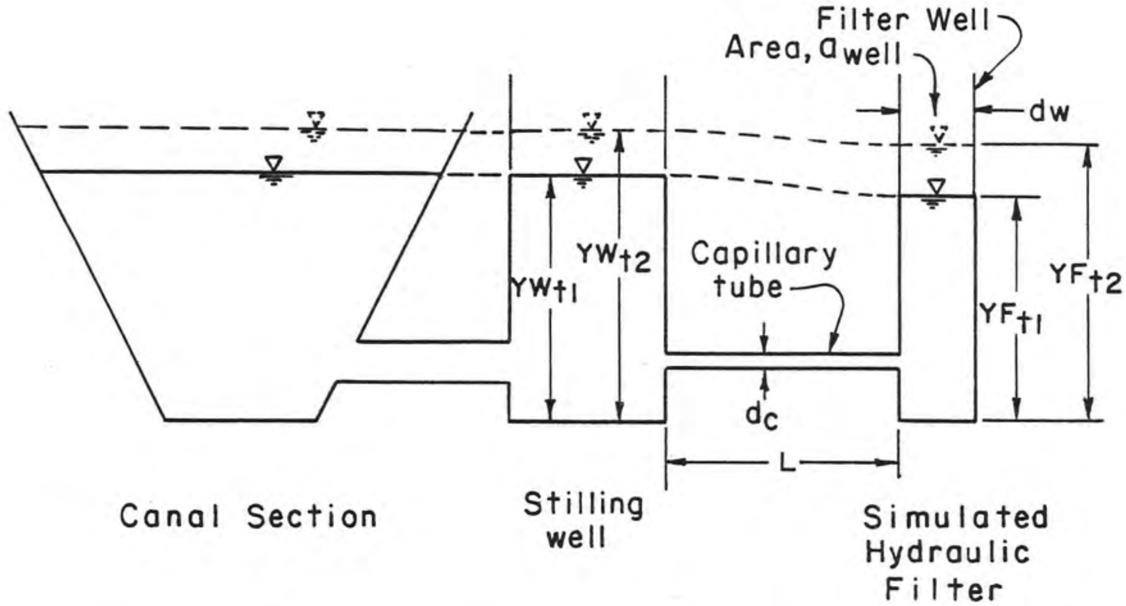


FIGURE 4-SCHEMATIC OF THE CANAL, STILLING WELL, AND THE SIMULATED HYDRAULIC FILTER CROSS-SECTION

where

- qf = The flow into the filter well
- a = The water surface area in the filter well
- Δhf = The change in the water level in the filter well
- dt = Change in the time corresponding to the filter well change

The energy equation for head loss across the capillary with entrance and exit losses neglected is:

$$\Delta y - \Delta hf = \frac{fL}{2gd_c}\left(\frac{qf}{\pi d_c^2/4}\right)^2 \tag{7}$$

where

- Δy = The displacement in canal depth from a steady state
- f = The friction factor
- L = Length of the capillary tube
- d_c = The inside diameter of the tube

For linear damping, flow through the capillary tube should be laminar. The friction factor is thus related to the Reynolds Number by:

$$f = \frac{64}{N_R} \tag{8}$$

where

$$N_R = \frac{(q_f/\pi d_c^2)}{4} \; \frac{d_c}{\nu} \tag{9}$$

ν = The kinematic viscosity of water

Equations (6), (7), (8), and (9) combine to give a differential equation for the hydraulic filter:

$$\frac{d\Delta hf}{dt} + \frac{1}{ak}(\Delta hf - \Delta y) = 0 \tag{10}$$

where

$$k = \frac{128\nu L}{\pi g d_c^4}$$

The initial conditions of control at time t equal to 0 will have the canal level and filter well level at the same elevation. Thus Δhf will be equal to 0 and the solution to equation (10) is:

$$\Delta hf = \Delta y \left(1 - e^{-t/TF}\right) \qquad (11)$$

where

$TF = ak$ = Time constant for the hydraulic filter

Δy = Canal level change

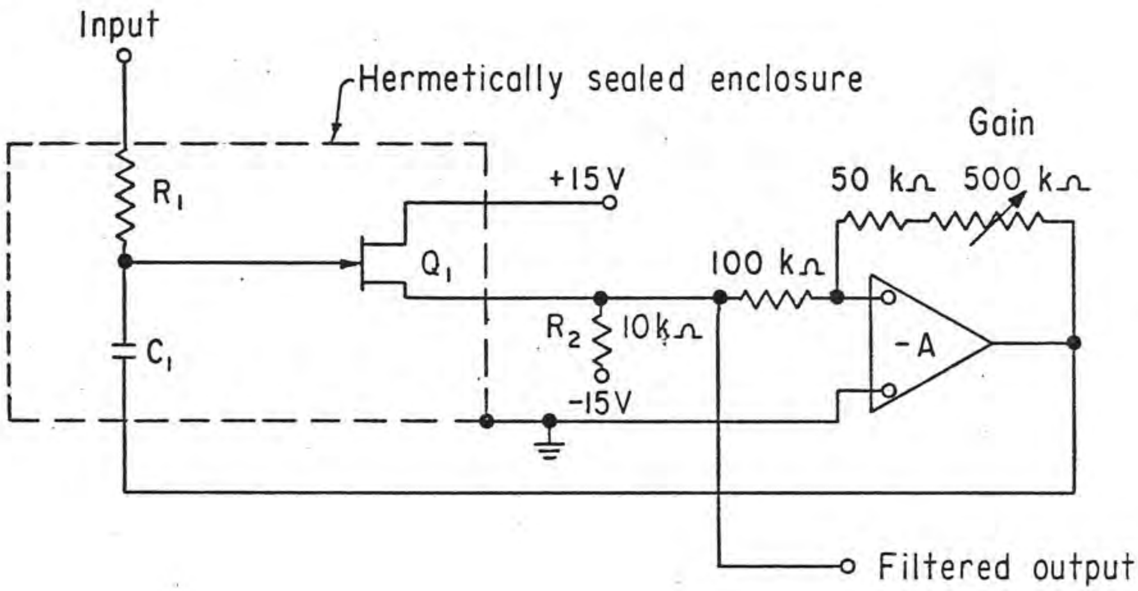
The time constant TF in terms of the physical dimensions of the filter is:

$$TF = ak = \frac{(\pi d^2 f)}{4} \frac{(128 \nu L)}{\pi g d_c^4} \qquad (12)$$

The long-term operation of the hydraulic filter did not prove to be reliable [2]. The small diameter capillary tube was susceptible to plugging up with sediment and debris. As a result, a decision was made to develop a reliable electronic time delay circuit to replace the more cumbersome and costly hydraulic filter well. A float-tape-pulley arrangement would still be required to sense the water level as input to an electronic filter.

The development of the electronic filter began with a suggested circuit design, figure 5, furnished by Professor James A. Harder, Professor of Hydraulic Engineering, Department of Civil Engineering, University of California at Berkeley. Professor Harder was the principal investigator for the University on the research contracts for investigating automatic downstream control of canal check gates sponsored by the Bureau of Reclamation, Mid-Pacific Region, which began in 1967 and ended in 1969.

The linear resistance of the laminar flow produced by the capillary tube represents the resistance, R1, and the surface area of the hydraulic filter well represents the capacitance, C1, of the analogous electronic RC circuit, figure 5. The time delay circuit requires long time constants (R multiplied by C) and typically ranges from 100 to 4,000 seconds. Time constants of this magnitude can be obtained using electrical elements consisting of a low-leakage capacitor, a good-quality resistor, a field effect transistor (FET), and an operational amplifier with a variable feedback



R_1 = 500 megohm
C_1 = 1 microfarad polystyrene
R_2 = 10 kΩ (or more - depends on FET type)
Q_1 = low leakage insulated gate, field effect transistor (FET)
A = operational amplifier

Time constant range: 1.5 to 5.5 times R_1 (R_1 in megohms)
Input range: 0 - 2.0 volts

Figure 5. - Single line diagram of original electronic filter circuit design.

resistor. The electrical circuit within the dashed area of figure 5 must be packaged in a hermetically sealed enclosure to shield the electrical high impedance characteristics from the influence of environmental humidity.

The mathematical model simulates the hydraulic filter using finite element method to solve for the new filter water level, YF, figure 4. Equation (7) gives the flow, Q_{tube}, through the capillary tube at time t_1:

$$Q_{tube,\ t1} = \frac{YW_{t1} - YF_{t1}}{k} \tag{13}$$

where

$$k = \frac{128\nu L}{\pi g d_c^4}$$

and at time t2:

$$Q_{tube,\ t2} = \frac{YW_{t1} - YF_{t2}}{k} \tag{14}$$

The equation of continuity for flow in the hydraulic filter well and capillary tube is:

$$Q_{well} = \frac{A_{well}(YF_{t2} - YF_{t1})}{DT} = \frac{Q_{tube,\ t1} + Q_{tube,\ t2}}{2} \tag{15}$$

where

Q_{well} = The average flow in the filter well
A_{well} = The filter well water surface area
$(YF_{t2} - YF_{t1})$ = The change in the water level in the filter well
DT = The change in time corresponding to the filter well change in water level

The sum of equations (13) and (14) combined with equation (15) gives the solution for the new filter water surface, YF_{t2}, as follows:

$$YF_{t2} = \frac{[CIDT\ (Yw_{t1} + YW_{t2}) - YF_{t1}(CIDT - 1)]}{(CIDT + 1)} \tag{16}$$

where

$CIDT = \frac{0.5 * DT}{TF}$ = The constant representing the simulated hydraulic filter

DT = The discrete time interval (seconds)

$TF = A_{well} * K$ = the filter well time constant (seconds)

YW_{t1} = The old measured stilling well water level

YW_{t2} = The new measured stilling well water level

YF_{t1} = The old simulated filter well water level

YF_{t2} = The new simulated filter well water level

The stilling well level and simulated filter well, YW_{t1} and YF_{t1}, must be replaced with the current values, YW_{t2} and YF_{t2}, respectively, before the real time computation at the next discrete time interval occurs.

The selection of the discrete time interval, DT, is very important, if the digital filter is used in a microprocessor to replace the electronic filter of the EL-FLO plus RESET control system.

It must be 0.5 second or less in order to define high-frequency sinusoidal wave, with a period of 1 second or less, caused by the surface winds. Therefore, the water surface sensor output, YWELL, is measured, and equation (16) is computed at intervals of DT equal to 0.5 second. The time interval, DT, could also be the same dt in equation (2). However, the equation (2) discrete time interval, dt, could be much larger (such as 60 seconds) without affecting the accuracy of the RESET output, GR.

THE ADVANTAGES OF EL-FLO PLUS RESET METHOD

Although the advantages are not limited to economic savings, the EL-FLO plus RESET control system can be justified on the Corning Canal with a 2:1 benefit to cost ratio. The EL-FLO plus RESET method of local automatic downstream control, because of its capability of providing service on demand at a high degree of self-regulation, will require the minimum of operating personnel coverage (day shift only and night standby) provided an alarm system for equipment failure is an integral part of the control system.

The EL-FLO plus RESET method makes use of control theory to match control and system characteritics so as to achieve satisfactory and stable regulation of canal check gates from downstream. It requires relatively simple electronic components which can be closely specified and readily obtained. Standard equipment components can be developed and only screwdriver adjustments would be necessary to insert the control parameters.

The advantages of the HyFLO method could be summarized as follows: (1) it is economically justified and has application for main canal systems like the Corning Canal, (2) it provides service on demand at a high degree of stable self-regulation, (3), it requires simple control equipment, and (4) it responds to emergencies such as sudden and abrupt changes of canalside diversions that may be caused by an emergency shutdown of canalside pump turnouts.

THE DISADVANTAGES OF THE EL-FLO PLUS RESET METHOD

The EL-FLO plus RESET method has an inherent delay in the total response at the headworks of the canal to changes in turnout demands. For canal systems that have a regulating reservoir at the headworks, like the Red Bluff Diversion Dam for the Corning Canal, the timelag would not be a problem. However, for a canal system that diverts water from a larger canal system, the time lag may impose operating difficulties unless the larger canal is also operated by automatic downstream control. If the lag is recognized in the design of the canal system its effects will be minimal. Long canal reaches between canal check gates require long-time constants for the filter element and large "offsets" in the canal water level. The large offsets could disrupt canalside delivery to gravity-type turnouts during the transient state.

The selection of the EL-FLO plus RESET control parameters could not have been accomplished successfully without the availability of a mathematical model of the canal and control system which requires a large computer facility to conduct studies "on-the-bench."

SUMMARY AND CONCLUSIONS

The downstream control concept is applicable to demand-oriented delivery systems such as the Corning Canal. The application of the EL-FLO plus RESET method to automatic downstream control provides an automatic response system between the demand downstream and the source of supply upstream. The controller has the capability to meet the demands of modern irrigation practice without supervisory intervention.

The implementation of the EL-FLO plus RESET control system on the Corning Canal has demonstrated that the method is alert to demand changes and is fully capable for taking responsible corrective action to contain emergency conditions. The initial response to a change in turnout demand downstream will begin to propagate rapidly upstream and reach the headworks after a moderate delay.

The proportional plus reset mode of control such as the EL-FLO plus RESET feedback control system offers a great deal of versatility and flexibility of operation to automatic flow regulation in canal systems. The large and rapid, as well as the small and slow, changes of canalside demands can be regulated smoothly by the proportional mode of control. Operational stability is maintained by the electronic time delay circuit element between the water level sensor and "real time" analog computer. The reset mode of control eliminates the residual water level offset of the proportional mode and maintains a nearly constant water level as flow demands change. If the EL-FLO plus RESET controller demonstrates a high degree of reliability, it will have application to and be economically justified for automatic flow regulation of many existing or proposed canal systems serving many distribution laterals having complex irrigation water delivery schedules.

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