PAP-281

AUTOMATIC DOWNSTREAM CONTROL OF CANAL CHECK GATES BY THE HYDRAULIC FILTER LEVEL OFFSET (HyFLO) METHOD

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A paper to be presented at the Fifth Technical Conference

U.S. Committee on Irrigation, Drainage, and Flood Control

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I.C.I.D.

October 8 and 9, 1970

Denver, Colorado

Question 28.2: Application of Automatic Facilities in the Operation and Maintenance of Irrigation and Drainage Systems

Not for Publication
Prior to Eighth Congress, I.C.I.D.
May 1972

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ABSTRACT

Main canal systems are required to respond faster and with greater flexibility of operation beyond what can be accomplished conventionally so as to meet the needs of modern irrigation practice. Automatic downstream control of canal check gates by the HyFLO method is a practical approach to upgrading the conventional mode of operation and achieving optimum efficiency in a main canal system. Work done under a research contract with the University of California at Berkeley and sponsored by the United States Bureau of Reclamation has developed the HyFLO method and its associated control parameters which are incorporated into the feedback control system. The hydraulic filter level offset (HyFLO) is utilized to relate the canal depths associated with downstream flows and turnout diversions to the canal inflow. It also establishes the primary control signal to sequentially and accurately adjust the upstream check gates to meet changes in demands. The HyFLO method is designed to accommodate changes in canalside diversions, that occur unannounced, with a high degree of self-regulation, that is, requiring virtually no supervisory intervention. Concurrently, the sustained water surface oscillations which plague many automatic flow regulation schemes are eliminated. The HyFLO method has been successfully tested "on-the-bench" and by a field application so as to confirm its applicability to many canal systems requiring immediate response to unscheduled canalside turnout demands.

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 recent research and development program with the University of California at Berkeley, sponsored by the United States Bureau of Reclamation, has culminated in a new and practical method of automatic downstream control of canal check gates which has great potential. Changes in canalside turnout demands are automatically coupled to the canal headworks in the Hydraulic Filter Level Offset (HyFLO) system. The HyFLO method relates the 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 that for zero flow). The upstream gate opening is directly proportional to this offset, so that a demand inflow identity is established. Sensing of the offset involves a special hydraulic filter well to provide system stability for large and small changes in canalside demands.

Although the HyFLO 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.

This paper discusses the need for automatic downstream control of canal check gates. It presents the theory of downstream control by the HyFLO method and its application.

THE NEED FOR AUTOMATIC DOWNSTREAM CONTROL

The primary responsibility of a canal operator regulating a canal system serving many distribution laterals is to match canal flow to the canalside turnout demand or orders. 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 system 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 application to the crops is becoming more complex and sophisticated. The thrust is towards higher irrigation efficiency which involves more efficient use of water and increased crop yields at reduced costs. Some of the factors involved are automatic pipe distribution systems, on-farm operated valves, sprinkler irrigation, and water applications based on predicted or measured soil moisture depletions. Implicit in this thrust is the requirement for water at the canalside turnout on a demand basis. Another factor contributing to the 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 in flow 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, (1), (2), (3).* Sprinkling for crop protection against frost and heat provides additional crop insurance to the farmer, (4), (5), (6). Solid-set sprinkler systems are readily adaptable to simple automatic switching devices which can be programmed as to 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, (7), (8).

* Parenthetical number refers to literature cited.

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 programmers 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 municipal and industrial (M&I) customers along with irrigation water in canal systems. Municipal and industrial 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, as to 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, (9). 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, (10), (14). 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 need 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 canalside 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.

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.

The remainder of the paper is devoted to the theory of downstream control by the HyFLO method including its applications.

THEORY OF DOWNSTREAM CONTROL AND THE HyFLO METHOD

The theory of downstream control 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 reach from a motor-operated gate at the upstream end. "Downstream control" in this context means that the control is from downstream towards the head of the canal. Thus the control, although contrived mechanically through sensors and motor controls, is parallel to the natural control (in sub-critical flow) observed in backwater curves, i.e., the control is from downstream to upstream.

Since the signal is transmitted from the downstream sensor to the gate over electrical lines, the response could be made nearly instantaneous from any location along the canal to its headworks, limited only by the speed of response of the motor-operated gates and by stability considerations. In the theory presented in this paper the response speed is assumed to be limited by stability considerations.

The general idea is understood best by considering how the system responds to very slow changes in the water surface when the flow in the canal is nearly zero. This is the so-called "horsetrough situation" where slow withdrawals (by the horse) are compensated for by flow from a float-controlled valve. "Slow" in this context means that the changes are slow relative to the time it takes for changes in the water level to traverse the length of the trough, through wave action. In a canal system, "slow" changes might well be measured in days, because of the time it could take for disturbance waves to die out while traversing the system. Such a "slow" system is stable for the very good reason that enough time has been postulated so that friction can damp out whatever instabilities arise.

Of greater interest is relatively more rapid response times and the design problem is how to achieve the best response according to criteria which are chosen within limits. Refer to figure 1 for the nomenclature used in the following discussion. The "target" water surface elevation at the downstream end is Y_o, whereas the actual water surface elevation is Y. The difference between them, $Y_o - Y = \Delta Y$ is called the "offset". The amount of the "offset" is measured by the sensor, and this information is passed through a filter, F, and an analog computer, A, resulting in a positioning of the upstream gate to the proper opening, which in turn controls the flow into the canal reach. For stability, an increase in sensed depth must produce a decrease in flow; thus a negative feedback system has been constructed. The point P is called the pivot point; in this vicinity the water surface elevation changes little with different discharges. For zero flow the water surface becomes horizontal, and the downstream water depth approaches the "target" value, Y_o.

One criterion to be chosen is the maximum "offset" which essentially establishes the location of the pivot point. If a "constant volume" is to be maintained in the reach, the "offset" is selected so that the pivot point will be near the center. To maximize the full-flow capacity of the canal, the offset should be small locating the pivot point as far downstream as possible. In either case interest lies in a rapid response

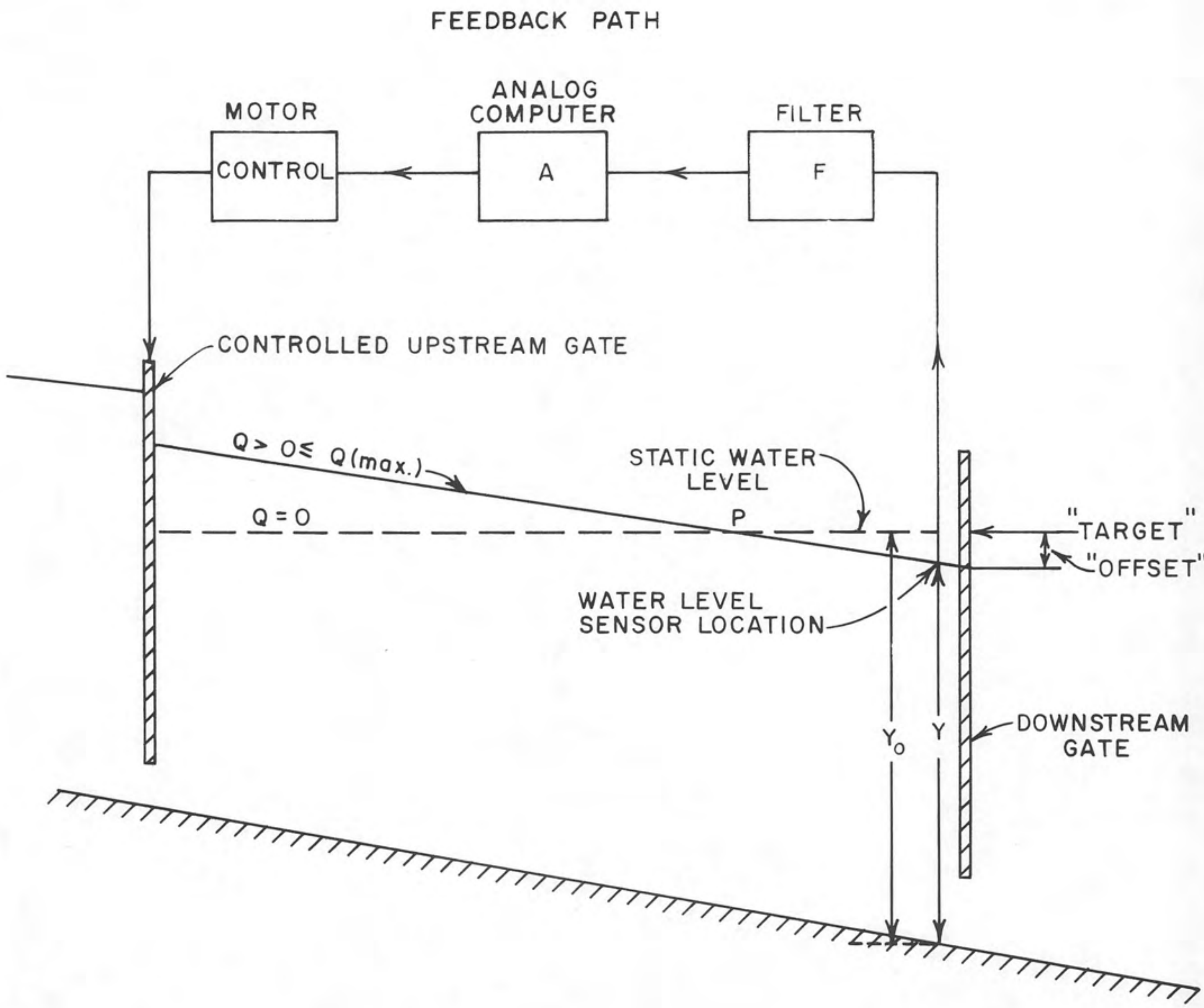


FIGURE 1 = SCHEMATIC OF DOWNSTREAM CONTROL BY THE H_y FLO METHOD so that the canal can recover from sudden loads (as occur when a user takes water) by refilling itself rapidly to a new equilibrium level, or can rapidly reduce the discharge through the upstream gate so that the canal reach does not overflow from a sudden rejection of flow by a user. These two criteria are not independent; the more rapid the response, the greater the offset that must be tolerated.

When operating with a small offset, the system is more sensitive to disturbances, and unless precautions are taken, it can go into an unstable mode in which waves travel back and forth in the reach with ever-increasing amplitude. Returning to figure 1, note that an initial fall in the water surface at the downstream end produces an increase in the flow at the upstream gate. This is negative feedback, for the action taken is to counteract the initial disturbance. The increase in discharge produces a positive surge which then traverses the canal to correct the drop in water-surface elevation; however, this takes a finite time--the time of travel of a shallow water wave. If the initial disturbance takes the form of an oscillation at a certain frequency, then by the time the compensating wave has arrived from upstream it will reinforce the disturbance, which by this time has reversed itself 180 degrees. Thus there will be a critical frequency at which disturbances will tend to be amplified--the frequency for which the canal represents a 180-degree phase shift which converts a negative feedback to a positive feedback. A similar phenomenon leads to the howling noted when a microphone connected to an amplifier is placed in front of a loudspeaker driven by the amplifier. The remedy in each case is to reduce the gain to below the point that sustains oscillation.

This remedy, while effective, reduces the sensitivity of the system for all frequencies, including the steady component, which is undesirable. A more sophisticated remedy is to reduce the gain of the system for the critical frequency, while maintaining full gain for longer periods and steady-state departures from equilibrium. This is the purpose of the filter. No advantage is obtained by passing frequencies higher than the critical, so the filter is given a low-pass characteristic.

The attenuation of the wave as it travels from the gate to the sensor must be taken into account when calculating the overall gain, as must the effect of multiple reflections. The condition for the amplification of a disturbance, however, can be stated simply in terms of the water surface response, at the sensor, caused by the operation of the gate, and initiated by some initial disturbance detected by the sensor. If the ratio of the response to the initiating disturbance exceeds unity, an initial disturbance, no matter how small, will grow in amplitude and may overtop the banks eventually.

Because of the fact that hydraulic friction is nonlinear in the velocity, the attenuation of a disturbance superimposed on a large steady flow is greater than that superimposed on a small one; however, the reflection effect is greater for the same reason, so the two influences on the overall gain tend to compensate. The calculation of the necessary gain and the filter parameters for the HyFLO method can be effected by the use of special computer programs developed at the University of California, Berkeley, and are described in greater detail in references number 12 and 13. One aspect of this calculation deserves special emphasis. When the gate operates in response to a change in the water-surface elevation at the downstream end of a reach, it causes, itself, a change in the water-surface elevation upstream from itself. This change is detected by the sensor in the upstream reach, which then operates the gate at its upstream terminus, and so forth, in a cascading action all the way to the headworks of the canal. It is important that the gain for an individual reach be limited so that this cascading action is not continuously amplified as it moves from one reach to another; it is usually permissible to set the gain at a value so that the water-surface disturbance in the upstream reach be the same as the initiating disturbance and to then adjust the filter parameters to control local instabilities.

When all parameters are calculated, the system operation is checked by a computer simulation of the system response to a small step-type disturbance. From this response, the provisional values of gain and filter parameters can be checked before the prototype installation is made. Enough adjustment is built into the gain and filter controls so that further adjustments can be made after field trials.

The simplest low-pass filter consists of a resistor and a capacitor element; in electronic terms, an RC filter. The requisite time constants, however, are rather long--on the order of half an hour. Such values can be obtained using electrical elements, consisting of Field Effect Transitor (FET) input operational amplifiers, special low-leakage capacitors, and sealed resistors, all packaged in a hermetically-sealed enclosure, so that the electrical properties can be shielded from the influence of environmental humidity. The decision to use a hydraulic analog for determining the time constant was based on the ruggedness of the mechanical elements. The HyFLO filter element consists of a capillary tube connected between the canal (or a normal stilling well) and a secondary well. The flow into or out of the secondary well is proportional to the difference in head across the capillary, since the flow is laminar, and the volume stored in the secondary well is proportional to the water-surface elevation in it. Thus the combination is an exact analog of an RC filter, but with the advantage that very long time constants are easily obtained. In practice the sensor is located in the secondary well, so the filter effect is ahead of the sensor.

After the gain and filter parameters are correctly chosen, the response of a single reach to a sudden demand (assumed to be at the downstream end near the sensor) will be similar to that shown in figure 2. In figure 2a the discharge at the lower end is shown as increasing suddenly by ΔQ_1 from Q_1. In figure 2b the water surface (at the downstream end) drops rapidly at first, and then recovers as the influence of flow from the upstream gate reaches the lower end. There is a small "overshoot" as the water surface recovers towards its new equilibrium Y_2, and as the transients die out. In figure 2c the flow through the upstream gate momentarily increases by slightly more than ΔQ_1, which is necessary to compensate for the fact that the gate does not open to its new steady-state position immediately.

THE APPLICATION OF THE HyFLO METHOD

The theoretical investigation defined the necessary control parameters for the HyFLO method of automatic downstream control of canal check gates. Untilizing the mathematical model, its feasibility was demonstrated

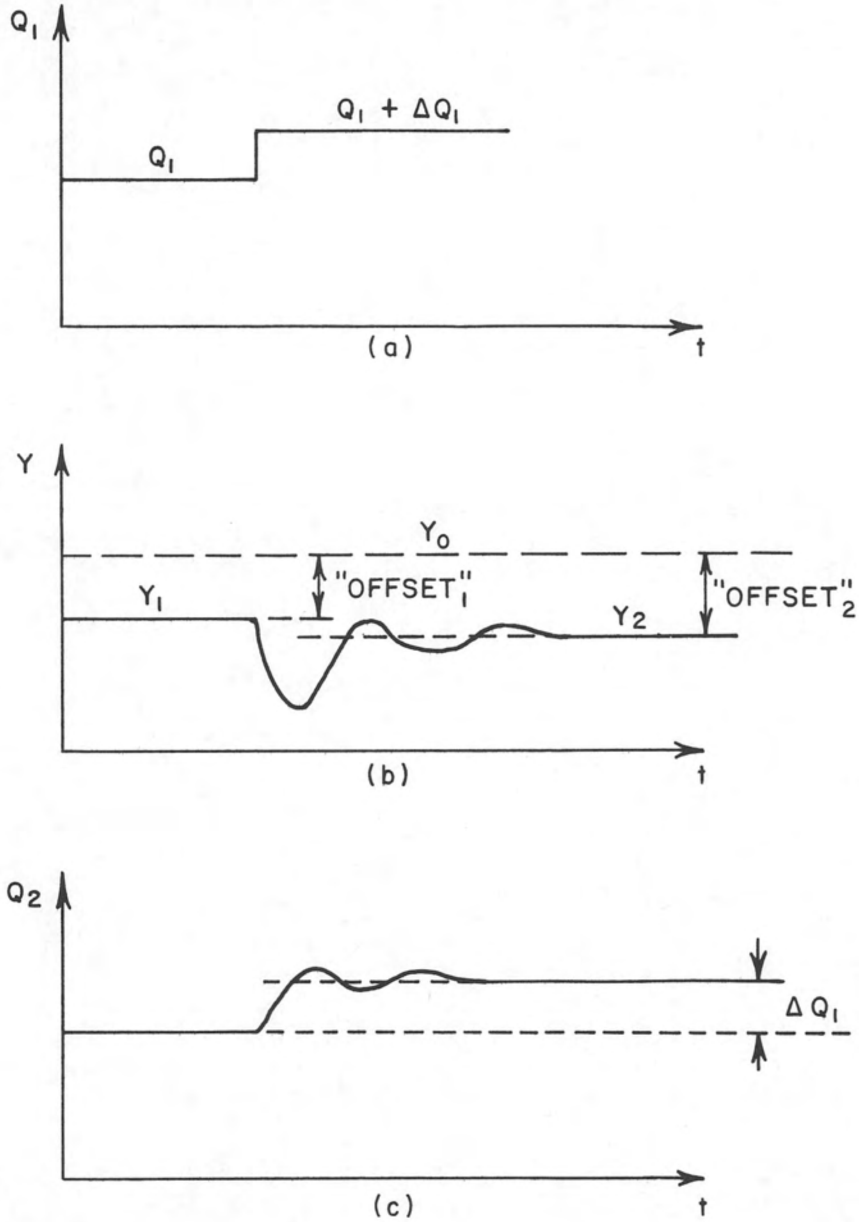


FIGURE 2 = THE RESPONSE OF A SINGLE REACH TO SUDDEN INCREASE IN DEMAND AT THE LOWER END.

"on-the-bench." Its applicability to canal systems that require immediate response was verified by a field scale application.

The Corning Canal, a recently constructed feature of the United States Bureau of Reclamation's Central Valley Project in California, was selected as an ideal canal system for field verification tests. At the present time, this canal is being operated in the conventional manner.

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. At the present time 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 2.5 to 16 cubic feet per second (0.07 to 0.45 cubic meters per second). Most of the lateral turnout valves to the farmers' lands are on-farm operated. A few sprinkler systems are in operation and more will be added in the near future. Precise scheduling techniques are not being used currently.

The annual delivery at the present time is 18,000 acre-feet (22.2 million cubic meters) but ultimately it will reach 119,000 acre-feet (146.8 million cubic meters). 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 are already being experienced even with the present demand only 15 percent of the ultimate. 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 will become more difficult to handle properly with the conventional mode of operation, (11).

The Corning Canal begins on the west bank of the Sacramento River near Red Bluff and extends southerly 21 miles (33.8 km) terminating near Corning, California. The canal begins with a capacity of 500 cubic feet per second (14.2 cubic meters per second) and reduces to 88 cubic feet per second (2.5 cubic meters per second) 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 22 feet (6.7 m) to 10 feet (3.0 m), has an average invert slope of 0.00019 for a total drop of 21 feet (6.4 m) in 21 miles, (33.8 km) or 1 foot per mile (0.19 m per km). The normal water depth varies from 7.2 feet (2.2 m) to 3.6 feet (1.1 m). There are 14 single-gated check structures spaced on an average of 1.5 miles (2.4 km).

The headworks consist of the Corning Pumping Plant, which has six centrifugal vertical-shaft pumps, three rated at 53 cubic feet per second (1.5 cubic meters per second) and three rated at 115 cubic feet per second (3.3 cubic meters per second). The pumping plant diverts its water from a settling basin just downstream from Red Bluff Diversion Dam. The pumps lift the water 59 feet (18.0 m) 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 4.55 miles (7.32 km) downstream. The first unit is started when the water level is 0.2 feet (0.06 m) below the normal depth of 7.2 feet (2.2 m) and stopped when the water level is 0.3 feet (0.09 m) above. The second unit starts when the water level is 0.5 feet (0.15 m) below and stops when the water level is 0.5 feet (0.15 m) above the normal depth.

Once the decision was made to utilize the Corning Canal system for a field scale application of the HyFLO method, several steps were taken before the actual prototype tests were conducted. It is appropriate to discuss these steps briefly to understand how the HyFLO method advanced from the theoretical "on-the-bench" investigation to the field installation.

The first step was to define the requirements of an adequate test program. It was felt that by automatically controlling the gates at Checks 1, 2, 3, and 4 from the respective hydraulic filter wells located at Checks 2, 3, 4, and 5, there would be provided an adequate length of canal and a sufficient number of HyFLO controllers in sequence to comprise a prototype confirmation. Refer to figure 3 for the Corning Canal Prototype Test Program Plan. Placing a practical limit on the number of checks involved funds and manpower available to purchase, fabricate and install equipment, and conduct an organized and well-controlled test program. Two wasteway structures, one at Check No. 3 and one at Check No. 5 were available within the test reach to release water to simulate a turnout variation. Simulating a turnout diversion by diverting water

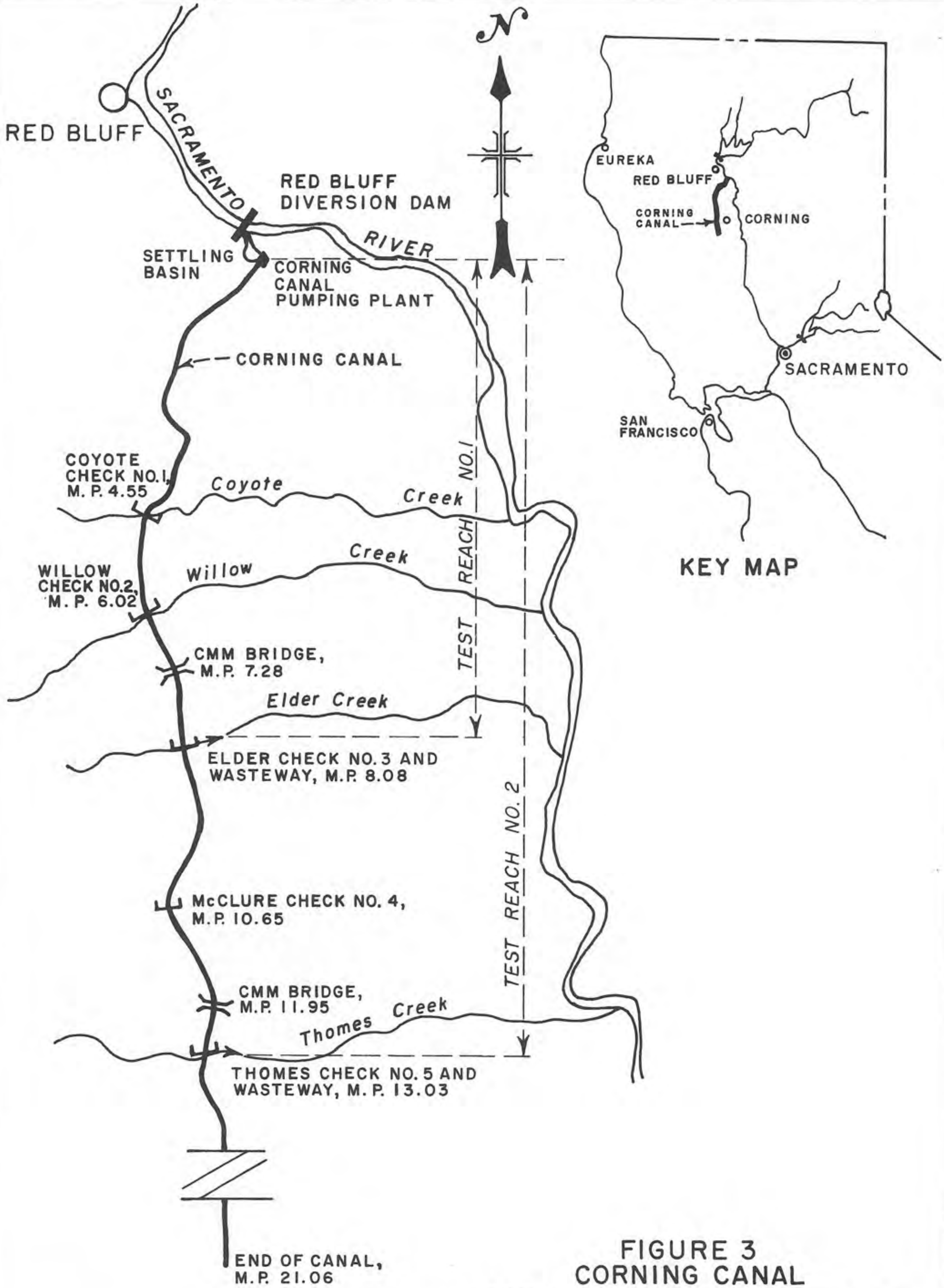
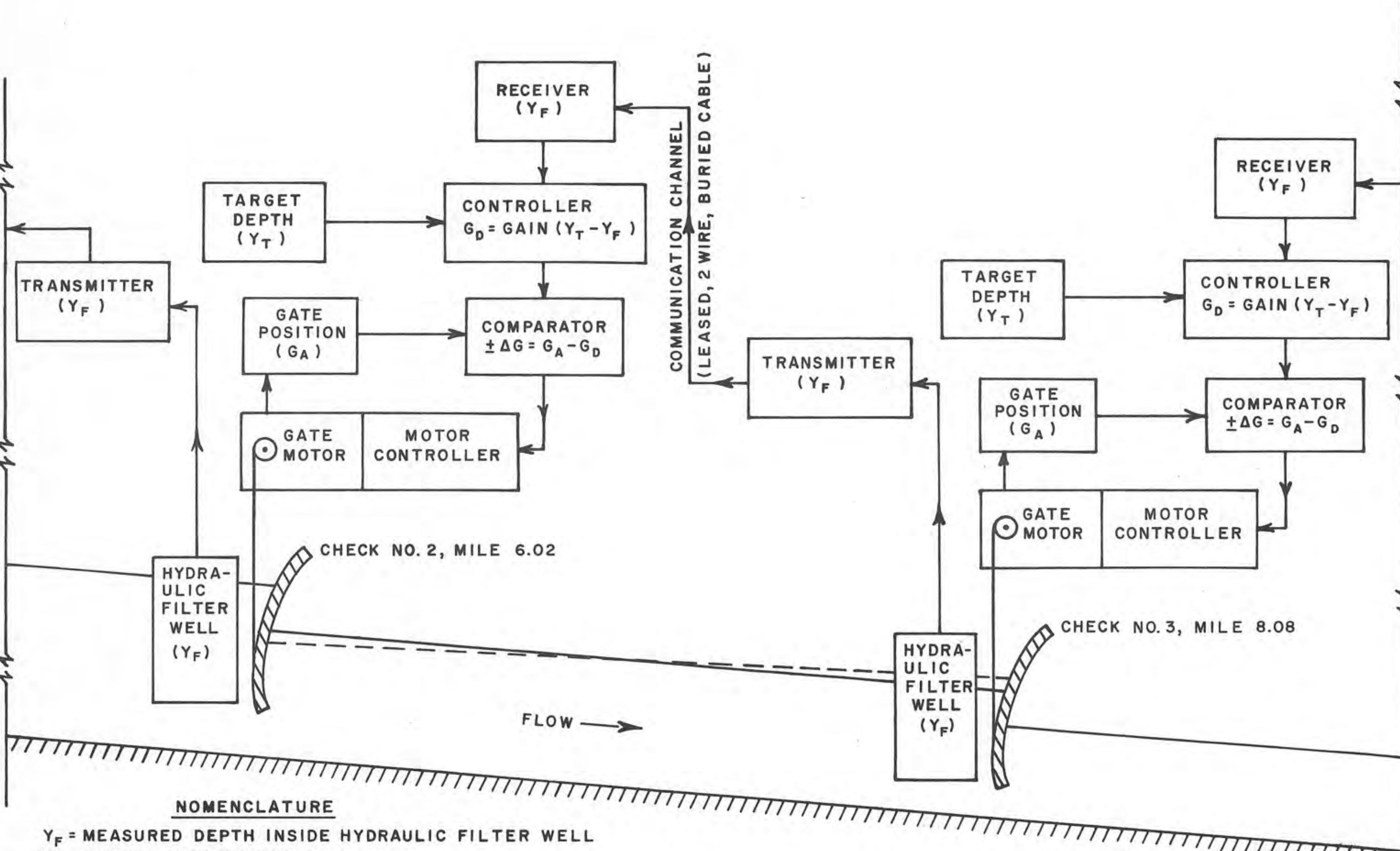


FIGURE 3
CORNING CANAL
PROTOTYPE TEST PROGRAM PLAN

through the wasteway structures was necessary because the tests were to be conducted during the month of March when existing canalside demands on the Corning Canal are either very small or nonexistent. Also, under these circumstances, initial flow conditions for the test runs could be zero and therefore much easier to define for the correlation of a later mathematical model simulation with the field data.

After the test length was defined, the control parameters for each HyFLO controller and the respective hydraulic filter wells were derived by applying the control theory and procedures developed in the theoretical investigation as discussed previously, (12). The original design of the Corning Canal was used to obtain the geometry necessary for computations. The control parameters selected for each canal reach in the test section were then checked on the mathematical model to ascertain their suitability. The next step was to purchase, and/or fabricate and then install the necessary equipment to physically reproduce the postulated HyFLO controller function. The prototype HyFLO equipment for control of a check gate consisted of three primary components: (1) hydraulic filter well, (2) transmitter and receiver, and (3) a real-time analog computer and comparator.

In reference to figure 4, the hydraulic filter well is located at the downstream end of the canal reach between two check structures (approximately 100 feet (30.5 m) upstream from the next downstream check). The changes of canal water levels are modified by the hydraulic filter principle discussed previously. The processed water level, (Y_F), being the primary signal was then transmitted over a buried 2-wire leased line



NOMENCLATURE

Y_F = MEASURED DEPTH INSIDE HYDRAULIC FILTER WELL
Y_T = TARGET DEPTH WHEN Q = 0
GAIN = PROPORTIONAILITY CONSTANT
G_D = COMPUTED DESIRED GATE OPENING
G_A = ACTUAL MEASURED GATE OPENING
$\pm \Delta G$ = DIRECTION AND AMOUNT OF GATE TRAVEL

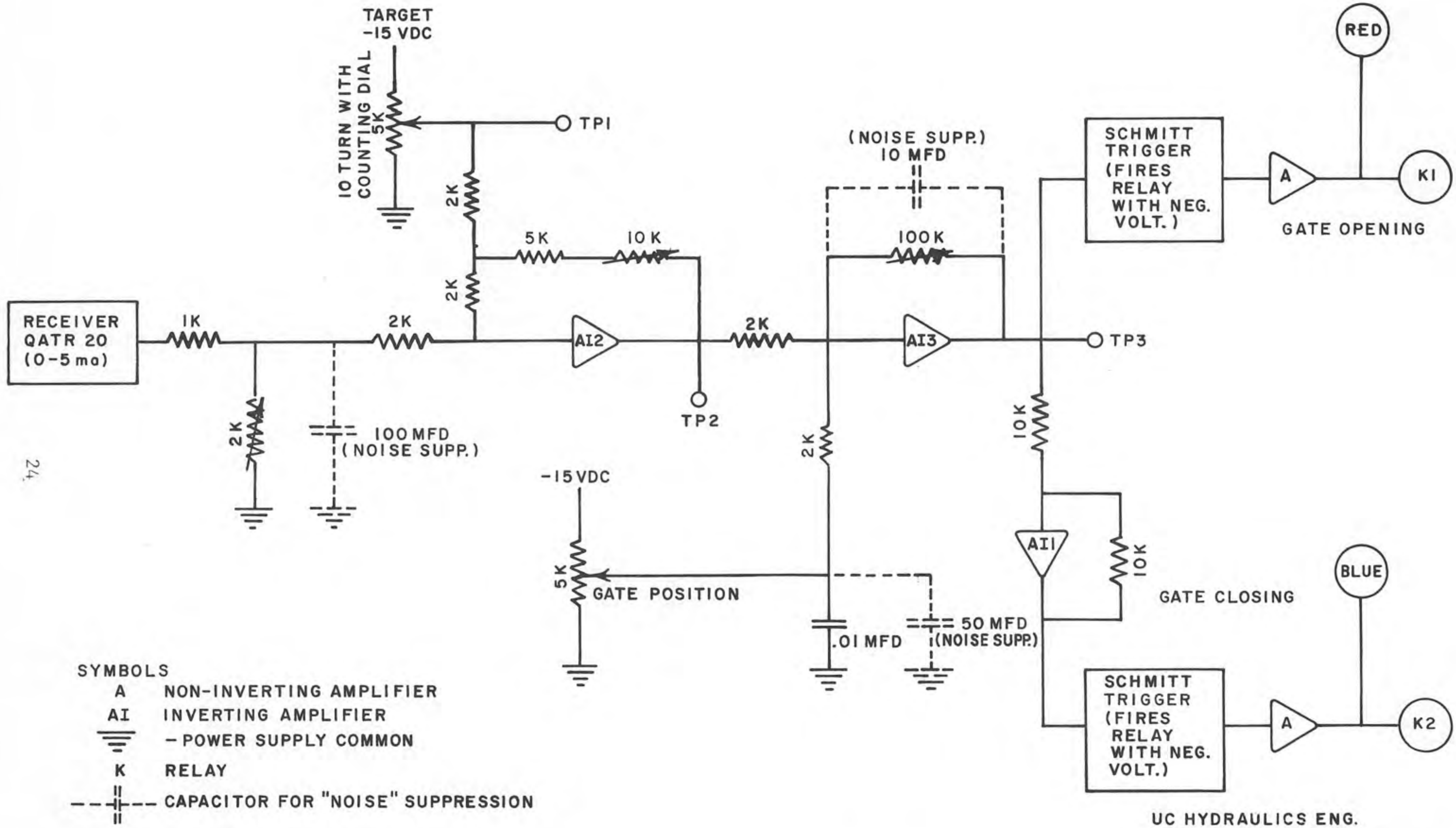
FIGURE 4

TYPICAL BLOCK DIAGRAM
CORNING CANAL PROTOTYPE EQUIPMENT
AUTOMATIC DOWNSTREAM CONTROL
BY THE
H_yFLO METHOD

to the receiver located at the next upstream check gate. The output of the receiver was the input to the real-time analog computer comparator unit. The input signal, (Y_F), was subtracted from an internal target level, (Y_T), to obtain the "offset" which was then multiplied by the GAIN or proportionality factor to get the desired gate opening (G_D). The desired gate opening (G_D), was then compared to the actual measured gate opening (G_A), to obtain the difference, $(\pm \Delta G)$. When the difference became greater than a preselected reference value, 0.1 foot (.03 m) of gate opening, the comparator circuit energized the motor controller. The gate then traveled in the proper direction (depending on whether the difference, $(\pm \Delta G)$, was positive or negative) until the difference between desired and actual gate opening was zero $(\pm \Delta G = G_A - G_D = 0)$. When the difference, $(\pm \Delta G)$, was zero, the comparator circuit then deenergized the motor controller to stop the gate travel. Those who are familiar with analog computer diagrams may be interested in reviewing figure 5 which shows the analog and comparator circuit used during the prototype tests.

Each of the control components operated continuously in a feedback network with the canal reach acting as one leg of the closed loop. Therefore, the desired gate opening, (G_D), was continuously computed on a real-time basis. Correct matching of voltage scales representing the various measured and computed valves and their calibration is essential if each component is to perform with correct results.

As part of the preparation for prototype tests, computer program runs using the mathematical model, (13), were made to predict the water



UC HYDRAULICS ENG.
RELAY CONTROL CK.
SINGLE LINE DIAGRAM

FIGURE 5

CORNING CANAL PROJECT

DRAWN M.S. DATE 4-19-69

level changes and gate movement that would be expected when simulated turnout diversions of specified flow quantities were made at the waste-way structures. The output of these computer program runs, defined as the predictor model, was plotted onto charts for field testing personnel for the purpose of ascertaining during the test runs whether or not the tests were progressing as planned, or if substantial deviations were occurring that might require shutdown of the canal system. The predictor model served a secondary but important function during the test runs as will be explained later.

The initial flow conditions for the test runs were zero and all gates were closed. The water levels existing in the hydraulic filter wells just prior to the start of the test run were designated as target levels since the flow in the canal was zero. The test runs began when the wasteway gates were opened to simulate a change in canalside turnout diversion and remained open for a period of time sufficient to establish a steady flow condition in the canal. The wasteway gates were then closed and the test run continued until all the upstream gates closed and the canal flows were zero.

It should be pointed out at this time that the objective of the prototype tests was to test the response of the HyFLO method and to compare it to the theoretical design. Not enough emphasis was placed on equipment reliability and the performance of the components as integral parts of a feedback system. As a result, problems in auxiliary equipment occurred during the test runs which caused the controllers at Checks No. 1 and 4 to become inoperative. The problems encountered included a pressure transducer sensor malfunction, a power supply failure, and pickup of extraneous "noise" signals which were not peculiar to the HyFLO method but common to many control systems. A delay in the test program would have been required to replace the defective components and provide protection against "noise" pickup within the electronics.

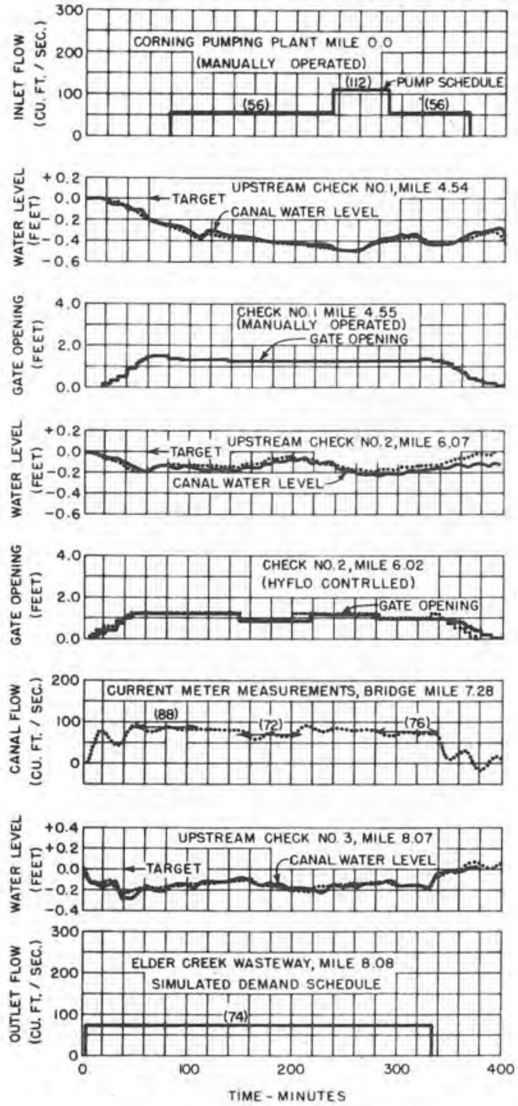
Rather than reschedule the test program for a later date, which would have been costly, the first and last of the four check gates equipped with HyFLO controllers (those gates at which the equipment problems occurred) were operated manually in accordance with the predicted output from the mathematical model, (13). The HyFLO controllers at the two intermediate checks operated satisfactorily.

Two prototype test runs of different flow conditions and number of canal reaches involved were conducted on the upper reaches of the Corning Canal on March 11 and 20, 1969, respectively (figure 3).

In TEST No. 1, a simulated flow demand was made by releasing 74 c.f.s. (2.1 cubic meters per second) (maximum) through Elder Creek Wasteway (at Check No. 3) (figure A). The wasteway gate was opened in one step, remained opened for 5½ hours, and then was closed in one step. The canal check gate (Elder Creek Check No. 3) remained closed throughout TEST No. 1. The response of the hydraulic filter well located immediately upstream of the Elder Creek Check No. 3 automatically controlled the gate opening at the Willow Creek Check No. 2, which is the next check structure upstream. As mentioned previously, the gate opening at the next check upstream, the Coyote Creek Check No. 1, was operated manually in accordance with the predictor model output.

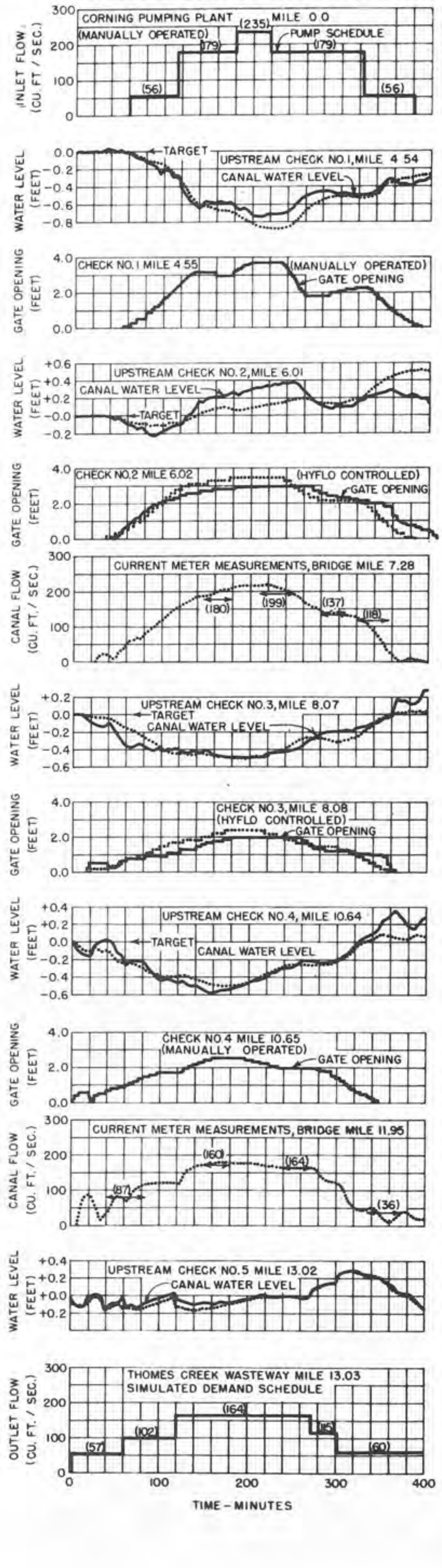
CORNING CANAL PROTOTYPE TESTS
FIELD DATA VERSUS MATHEMATICAL MODEL SIMULATION

FIGURE A - CORNING CANAL TEST NO. 1



FIELD DATA
MATHEMATICAL MODEL SIMULATION
(81) CURRENT METER MEASUREMENT

FIGURE B - CORNING CANAL TEST NO. 2



In TEST No. 2, a simulated flow demand was made by releasing 164 c.f.s. (4.6 cubic meters per second) (maximum) through the Thomes Creek Wasteway (at Check No. 5) (figure B). The wasteway gate was opened in three steps at 1-hour intervals and remained in the maximum position for 2½ hours. It was then closed in the same three steps with a 1/2-hour interval between the first and second step and a 2-hour interval between the second step and complete closure. The canal check gate (Thomes Creek Check No. 5) remained closed throughout and releases were not made in TEST No. 2 at the Elder Creek Wasteway (at Check No. 3). The gate at McClure Creek Check No. 4, the next check upstream, was operated manually in accordance with the predictor model output. The response of the hydraulic filter well, located immediately above the McClure Creek Check No. 4, automatically controlled the gate opening at the Elder Creek Check No. 3. The response of the hydraulic filter well located immediately above the Elder Creek Check No. 3 automatically controlled the gate opening at the Willow Creek Check No. 2. The gate at the Coyote Creek Check No. 1 was manually adjusted in accordance with the predictor model output for TEST No. 2.

In both TESTS No. 1 and No. 2, the pumping units at the canal headworks were started and stopped by pumping plant operators in accordance with the predictor model output. The pumping unit capacity and time of operation was calculated to maintain a relatively constant volume within the reach between Coyote Creek Check No. 1 and the pumping plant throughout the test runs.

Further field testing is being deferred until basic equipment problems such as the pressure transducer malfunction, power supply failure, and extraneous noise signals are resolved. Future field tests will be oriented towards establishing reliability and equipment standards for specifying equipment for a permanent installation. The prototype tests did emphasise the importance of equipment reliability and the necessity for an alarm monitoring system to alert the canal operators when the control system fails.

The objectives of the test program were achieved even though a portion of the original planned test schedule for prototype confirmation was revised. The response of the water levels and the gate movements were observed as the HyFLO controllers which were in operation responded to changes in simulated turnout diversions downstream. The necessary field data was collected to verify the theoretical analysis.

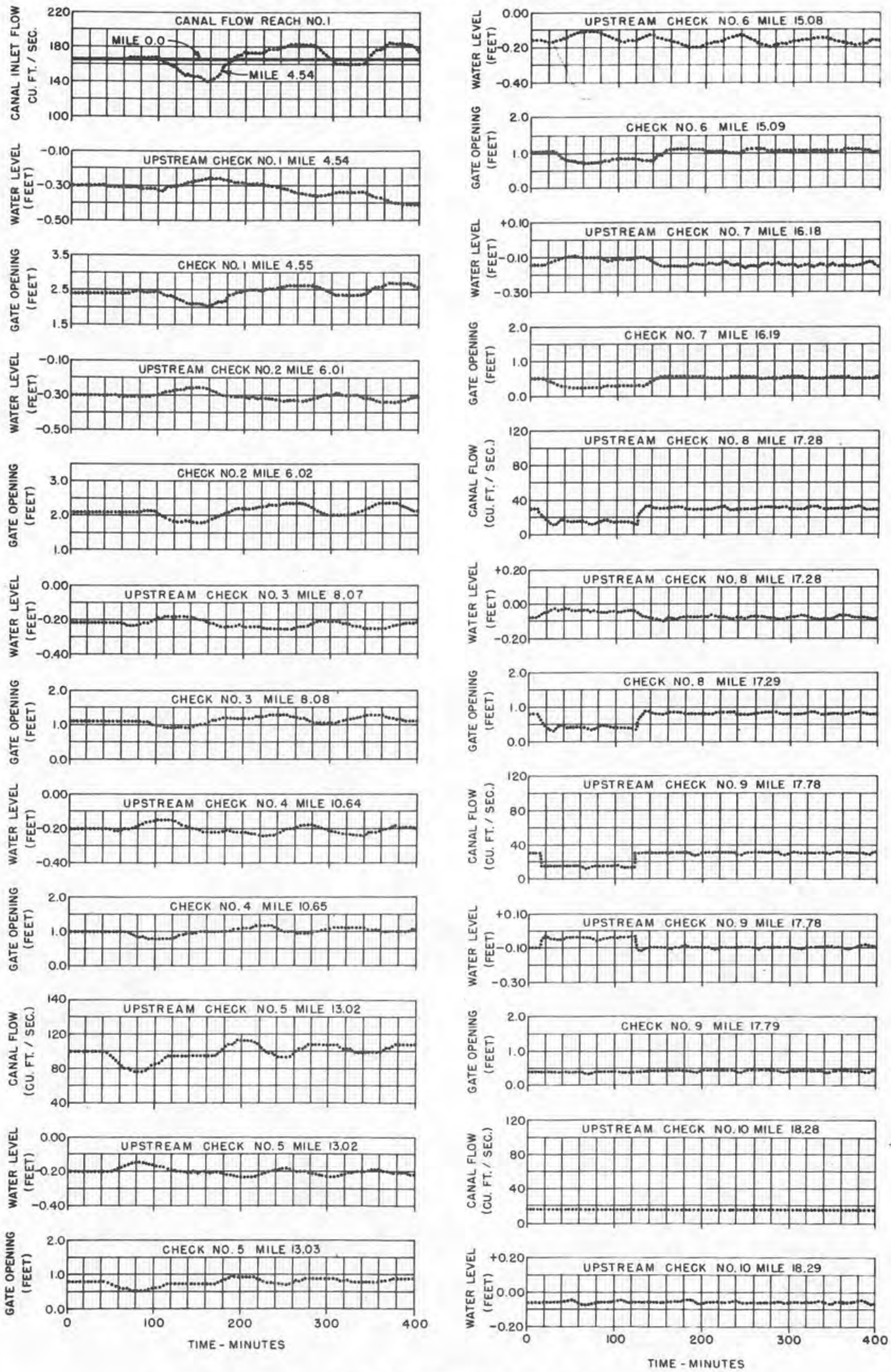
The test runs combined automatic and manual operation of canal gates. The HyFLO-controlled gates automatically responded to the actual flow conditions; the manual gate operation was based on predicted flow conditions which did not exactly match the simulated demands that actually occurred during the test runs. Therefore, the manual gate operation in one sense created a mismatch to the automatically-controlled gates. The HyFLO controllers that operated satisfactorily without supervisory intervention at the two intermediate checks were actually put under a more severe strain than originally planned, as a result of operating the upper and lower checks manually. These events do not lend themselves to an explicit demonstration of the successes achieved. However, the agreement between the field data collected during the test runs and the mathematical model simulation of actual field conditions shown in figures A and B provided complete verification of the mathematical model. Therefore, other flow conditions that might occur in the Corning Canal system can be simulated, and the performance of the HyFLO controllers (and other types of control systems) can be predicted with reasonable accuracy by the mathematical model.

Figure C displays results of a mathematical model simulation of the first 10 reaches of the Corning Canal equipped with HyFLO controllers, to illustrate the system response to a failure of a canalside turnout pump. The pump failure, rejecting 15 cubic feet per second (0.4 cubic meters per second), was assumed to occur above Check No. 9 at time equal to 10 minutes. This change represents 17 percent of the capacity in the last reach of the canal and 50 percent of the antecedent demand at this location. Power was restored after a period of 110 minutes and the pump was put back into operation. An emergency condition of this nature was actually experienced on the Corning Canal at this location before any automatic operation was implemented.

One of the more interesting indications of figure C is the ideal lack of response in the canal reach downstream from the pump rejection including the gate movement at Check No. 9. The canal flow and water-level variation at Check No. 10 and the gate movement at Check No. 9 are insignificant as a result of the HyFLO controller action in Canal Reach No. 9. The response of the hydraulic filter well just upstream of Check No. 9 has immediately, after rejection, lowered the gate at

CANALSIDE PUMP REJECTION SIMULATION
CORNING CANAL

FIGURE C - CANALSIDE PUMP REJECTION AT MILE 17.78



NOTE: THE SIMULATED PUMP REJECTION OCCURED AT MILE 17.78 JUST UPSTREAM OF CHECK NO. 9 AT TIME = 10 MINUTES OF A QUANTITY OF 15 CU. FT./SEC. THE SAME PUMP QUANTITY WAS TURNED BACK ON AT TIME = 120 MINUTES

.... MATHEMATICAL MODEL SIMULATION

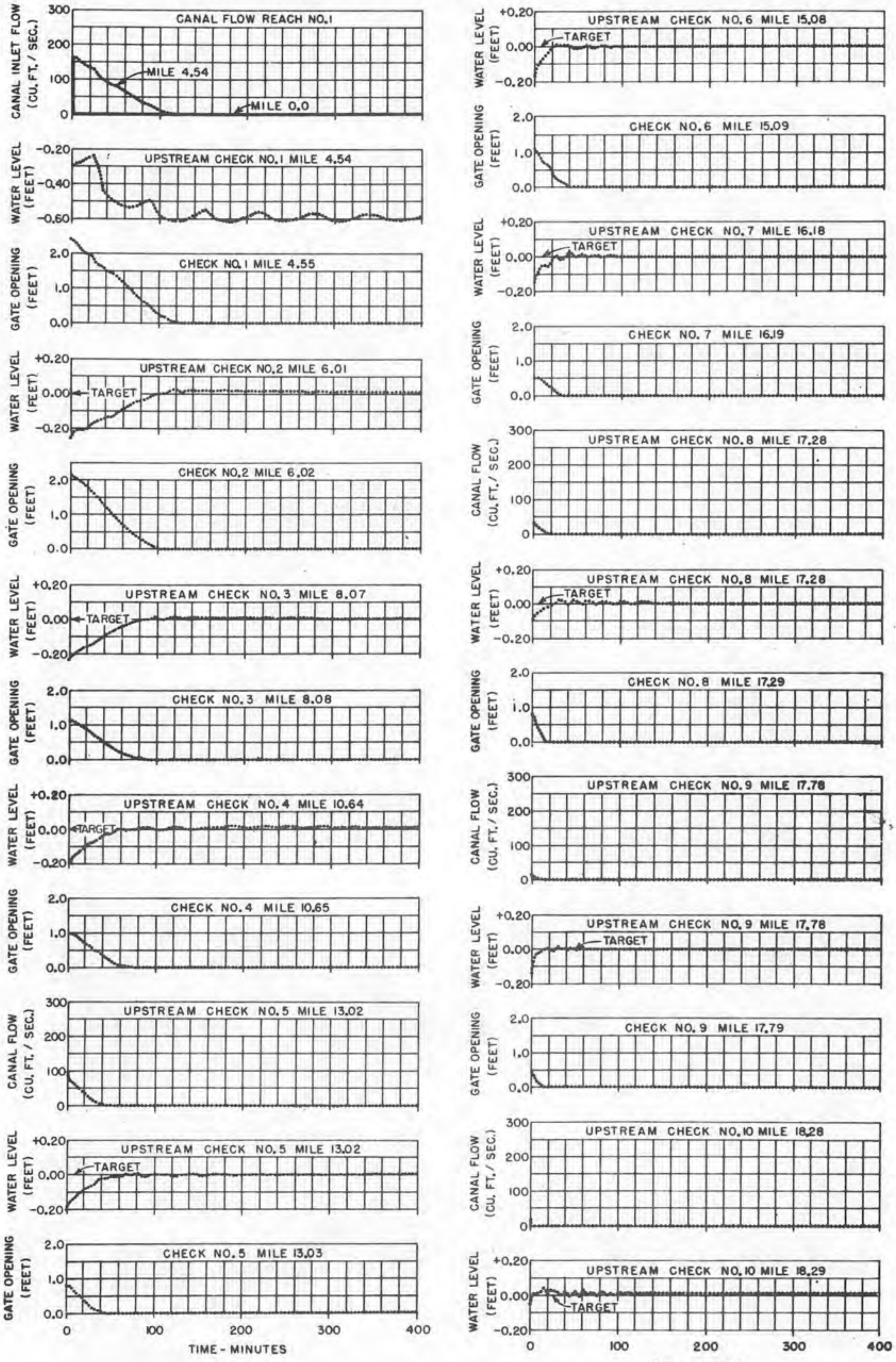
Check No. 8. As the pump rejection response cascades upstream to the next check structures, it becomes more and more delayed in satisfaction of the stability criteria as required to prevent oscillations. The surge wave height does not amplify as it progresses upstream and attests the proper selection of the proportionality factor, "Gain". The same observations are applicable when the canalside pump is returned to operation 110 minutes later. Practically all the canal reaches have returned to their original condition prior to the pump rejection after 400 minutes. Checks Nos. 1 and 2 have not quite completed the sequence because of the delay time involved.

Without the HyFLO controllers, the water levels in the canal reaches above Checks Nos. 9 and 10 would have risen at a rate of about 0.5 foot (0.15 m) per hour. This is a rather rapid rise considering that the designed freeboard for this canal is 1 foot (0.3 m). In fact, the canal operators did make the necessary adjustments in the canal check gates' openings manually in sufficient time to compensate for the actual canal-side pump rejection. The alertness of the canal operators may be credited with prevention of a serious condition. However, it would be unwise to anticipate that all of the emergency conditions either small or large, that may occur in the future, would be corrected successfully by manual operation.

It is of importance to consider what effects an area-wide power blackout would have on a canal system. Figure D illustrates the response of the same canal reaches as in figure C, if all of the canalside pump turnouts and the Corning Pumping Plant failed because of an area-wide

HEADWORKS AND TOTAL CANALSIDE PUMP FAILURE SIMULATION
CORNING CANAL

FIGURE D - AREA WIDE POWER OUTAGE CAUSING CORNING PUMPING PLANT AND ALL CANALSIDE PUMPING TO FAIL.



NOTE: THE INITIAL FLOW CONDITIONS ARE THE SAME AS FIGURE C AND TOTAL PUMP FAILURE OCCURS AT TIME ZERO.

.... MATHEMATICAL MODEL SIMULATION power outage. It is assumed that each canal check structure is equipped with standby generators that automatically start when the normal power supply fails to provide power for the HyFLO controllers and gate hoist motors. Figure D shows that all the check gates will be completely closed in a relatively short period of time by the HyFLO method without causing serious surge wave heights that might jeopardize the canal lining. The initial flow conditions for figure D are the same as shown in figure C (0 to 10 minutes). The entire canalside turnout rejection in figure D occurred at time zero and amounted to a total of 165 cubic feet per second (4.7 cubic meters per second) in Reach No. 1.

The mathematical model simulations have demonstrated that the HyFLO method is capable of providing control of relatively minor variations in canalside turnout diversions (figure C) as well as a major emergency condition as shown in figure D. Therefore, a high degree of control is attainable by the HyFLO method without supervisory intervention. It does function and control with stability using relatively simple and available equipment.

THE ADVANTAGES OF THE HyFLO METHOD

Although the advantages are not limited to economic savings, the HyFLO method can be justified on the Corning Canal with a 2:1 benefit to cost ratio at the present level of canal operating forces required to operate the canal system at 15 percent of its ultimate delivery capability. On an ultimate basis the justification is estimated to be about

10:1. The HyFLO method, 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 HyFLO method makes use of control theory to match control and system characteristics so as to achieve satisfactory and stable regulation of canal check gates from downstream. It requires relatively simple electrical and hydraulic 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, (12).

THE DISADVANTAGES OF THE HyFLO METHOD

The only significant drawback of the HyFLO method is the inherent delay in the total reponse 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 time lag 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.

CONCLUSIONS

Automatic downstream control of canal check gates by the HyFLO method adds to a canal system the capability to meet the demands of modern irrigation practice. It provides an automatically responsive system between the demand and the source of supply. The HyFLO method has been developed "on-the-bench" and confirmed by a field application to the Corning Canal. Field tests and mathematical model simulation have 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 theory is sophisticated but the control components are simple in design compared to the degree of self-regulation achieved. The HyFLO method is applicable to and economically justified for many existing or proposed canal systems.

ACKNOWLEDGEMENTS

Mr. Don Hebert offered a great deal of support and guidance throughout the course of this project. Mr. Dan Fults aided in the development and the usage of the mathematical model required for simulation studies. Appreciation is extended to Mr. Warren Carlson and the operating personnel of the Corning Canal for their assistance and cooperation during the field tests and to many others who contributed to the evolution of the HyFLO method.

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