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STUDY OF HYDRAULIC FILTER LEVEL OFFSET (HyFLO) EQUIPMENT FOR AUTOMATIC DOWNSTREAM CONTROL OF CANALS

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Engineering and Research Center

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16. ABSTRACT
The Hydraulic Filter Level Offset (HyFLO) system for automatic downstream control of canals was mathematically modeled, designed, and constructed by the University of California at Berkeley and the Bureau of Reclamation Office, Sacramento, California. The HyFLO system is a feedback control method that automatically adjusts the canal inflow from water level offsets caused by the canal outflow. Mechanical and electrical problems occurred in a field trial of the system, and the equipment was sent to the Engineering and Research Center, Denver, for testing and evaluating. The HyFLO equipment was installed in the laboratory to simulate one section of canal between two radial gates. After some equipment modification, the laboratory model satisfactorily simulated mathematical predictions of gate opening and water level changes in the canal section. Upon completion of the laboratory testing, the equipment was installed on one section of the Corning Canal near Red Bluff, California. The equipment is now controlling the flow satisfactorily.

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INTRODUCTION

A development program with the University of California at Berkeley, sponsored by the Bureau of Reclamation, produced a mathematical model and equipment for automatic downstream control of canal check gates.[1 2 3*] The feedback control system, named Hydraulic Filter Level Offset (HyFLO), automatically adjusts the canal inflow from water level offsets caused by the canal outflow (Figure 1). Changes in the position of the upstream gate are proportional to the offsets in water level, Figure 2.

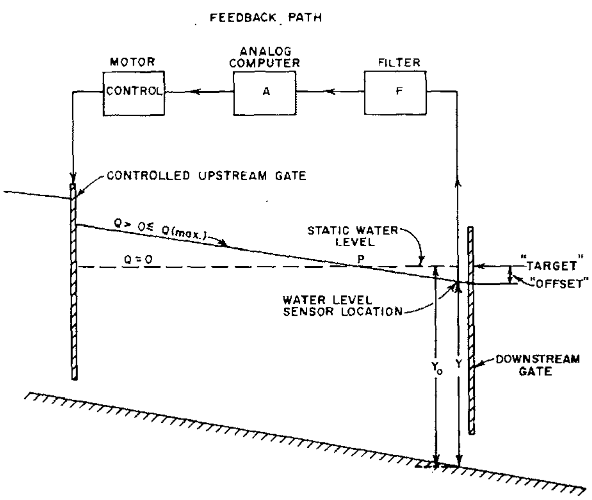


Figure 1. Schematic of downstream control by the HyFLO method.

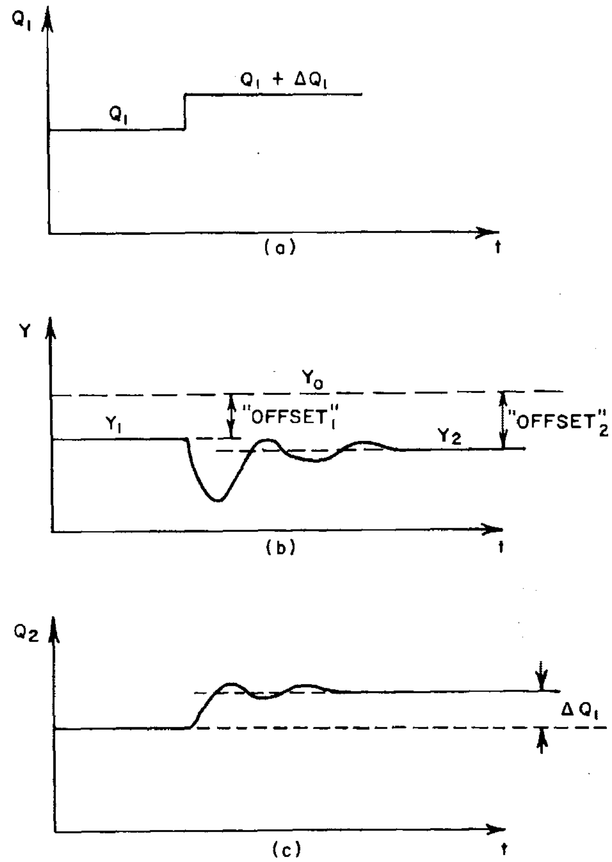


Figure 2. The response of a single reach to sudden increase in demand at the lower end.

The HyFLO method is a closed-loop control system in which the control action is proportional to the downstream water level. The response of the controller has to be in "real time" which is governed by the time constant of the canal section under control. The time response of the system is in the order of 2,000 to 3,000 seconds. Because of the long time constants, a hydraulic time delay circuit was designed for the HyFLO control system. The hydraulic filter includes a capillary damping tube open to the canal stilling well level and connected to a smaller secondary well. Flow into and out of the secondary well is computed to have a linear relation to the head across the capillary. A sufficiently long time constant necessary to control the canal flow was obtained easily with the hydraulic delay circuit. Field trial of the method was desirable to confirm the analytical studies.

Equipment was built to verify the mathematical model and the Corning Canal, Central Valley Project, California, was used for the test installation. A series of conditions were simulated on a digital computer using the mathematical model to predict the water level changes and gate movement for specified outflows. These outflows were repeated in the canal with the HyFLO equipment installed to control four radial check gates. During the test period, difficulties were experienced in the electronic circuitry so the test results were not entirely satisfactory. Since difficulties in the electronics were experienced during the field tests, the transmitters, receivers, and the analog computer-controller were sent to the Engineering and Research Center, Hydraulics Branch. Laboratory assistance was requested in resolving a transducer sensor malfunction, a power supply failure, and "noise" in the receiving and transmitting system. A laboratory simulation of a canal reach was constructed through the efforts of Electrical, Hydraulic Structures, and Hydraulics Branches.

*Numbers refer to References at end of text.

ANALOG COMPUTER-CONTROLLER

General

The computer-controller includes operational amplifiers for analog computing of the appropriate gate position, Figure 3. The input signal to the controller is the delayed signal output of the float-driven potentiometer in the hydraulic filter. The hydraulic filter must be located near the first check downstream from the controlled check. The voltage change of the float-driven potentiometer is converted to a variable 5- to 25-hertz signal, utilizing a voltage-to-frequency analog transmitter. The low-frequency signal is transmitted to an appropriate receiver at the controlled check structure.

The receiver converts the 5- to 25-hertz signal to a current output of 0 to 5 milliamperes. The output current is used to operate the analog computer-controller. Operation of the controller is as follows:

The initial conditions for the analog computer are entered via the operational amplifier feedback resistors and input potentiometer adjustment. A "target depth" adjustment must be made to define the "zero flow", starting point for the controller. The actual gate position is fed into the analog-computer to provide the necessary feedback for "anti-hunt" operation. The gate position is converted to a voltage suitable for operation of the analog computer by a potentiometer connected to the gate drive motor shaft.

The output of the analog computer operates into complementary Schmitt triggers. The Schmitt triggers operate when the positive or negative output voltage of the analog computer reaches a preset value. When the preset value is reached, the appropriate "Raise" or "Lower" Schmitt trigger operates and energizes the gate motor. The gate motor will run until the value of the analog computer output reaches an increased or decreased preset value. The output signal of the analog-computer is regulated from the feedback signal input of the gate position potentiometer. The gate will operate for a fixed time determined by the voltage "on" and "off" adjustments preset into the Schmitt triggers. The time between gate operations is proportional to the rate-of-change of the water level at the downstream gaging point. The "hydraulic filter" time constant provides the proper time for gate operations.

Modifications to Original Equipment

The operation of the analog computer-controller was improved by modifying the original equipment as follows:

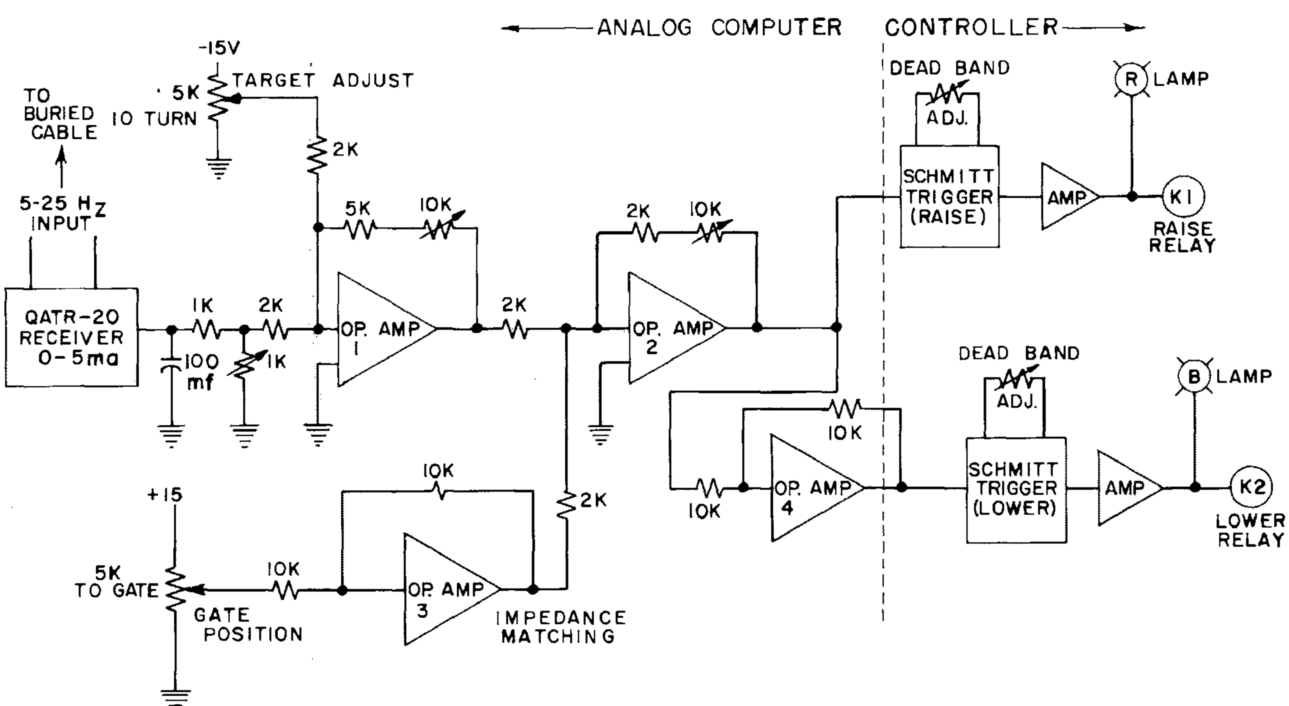


Figure 3. Analog computer-controller diagram.

a. Chassis and circuit commons were separated.

b. Linearity of the Schmitt triggers was improved by changing component values. Stability was improved with addition of capacitors.

c. An impedance matching amplifier was inserted between the gate potentiometer output and the analog computer input to prevent loading.

d. A 100-μf capacitor was inserted across the output of the Quindar QATR-20 receiver to improve its low-frequency performance while operating into operational-amplifier-type circuits.

e. A 0.001-μf capacitor was installed across resistor R27 in the QATR-20 receiver to prevent high-frequency self-oscillation due to operation into the first operational amplifier of the analog computer-controller.

f. RC networks were added across the coils of the transmitting and receiving relays to eliminate high-voltage spikes being produced by switching of the high-impedance coils.

g. Shielded wire was used to connect all inputs to analog computer-controller to reduce 60-hertz pickup.

LABORATORY SIMULATION

Equipment was installed in the Hydraulics Branch to simulate one section of canal between two radial gates (heavy dashed line), Figure 4. A steel tank representing the canal stilling well was connected to a metered water inflow and drain to change the water level manually. The hydraulic filter well or time delay circuit was installed in the well. The analog computer-controller, transmitter-receiver, and simulated gate hoist were placed on an adjacent table, Figure 5.

The voltage output necessary to operate the transmitter was developed in the hydraulic time delay

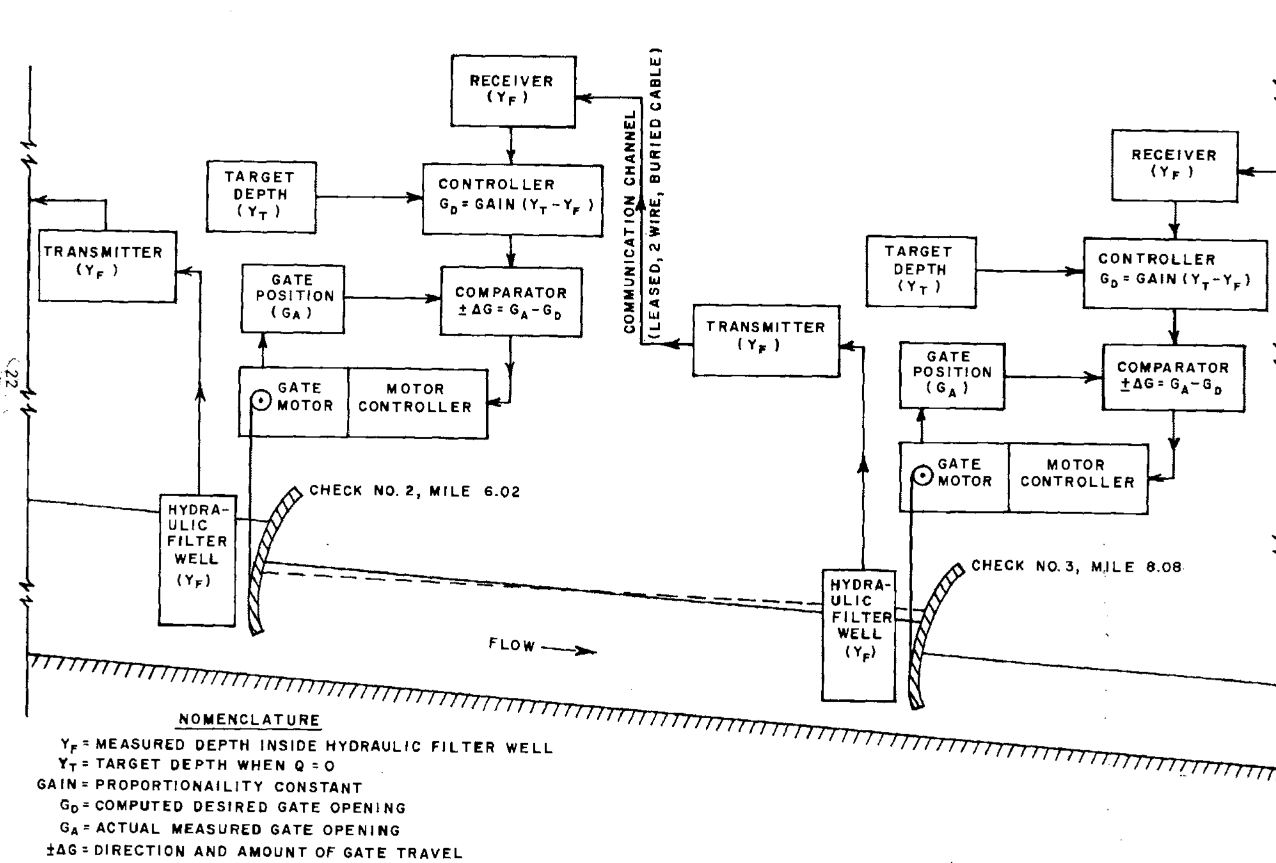


Figure 4. Block diagram Corning Canal prototype equipment.

Photo PX-D-70736

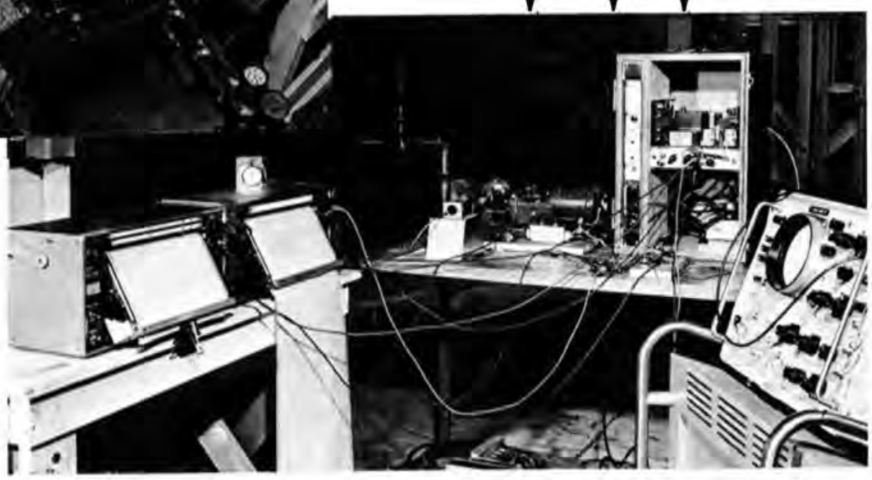


Photo PX-D-70737

Figure 5. Laboratory simulation of canal section.

circuit using a float-operated potentiometer. The movement of a 2-1/2-inch (6.3-cm) diameter float in the delay well was transferred by a perforated brass tape. to a 2-inch (5.1-cm) diameter pulley on the potentiometer shaft, Figure 6a. The voltage change in the potentiometer is a measure of the offset of the water level from a preset "target" level, Figure 1. The time delay between the change in the canal stilling well and the hydraulic filter well level was controlled by the ratio of the inside diameters of the filter well 4 inches (10.2 cm) and capillary tube, 0.13 inch (3.3 mm), and the 80-inch (2-m) length of capillary tube. Mathematical relationships given in the analysis were used to size the tube and well. The response of the system was limited by laminar flow in the capillary tube to minimize the potential oscillation of a wave traveling between two gate structures, Figure 4.

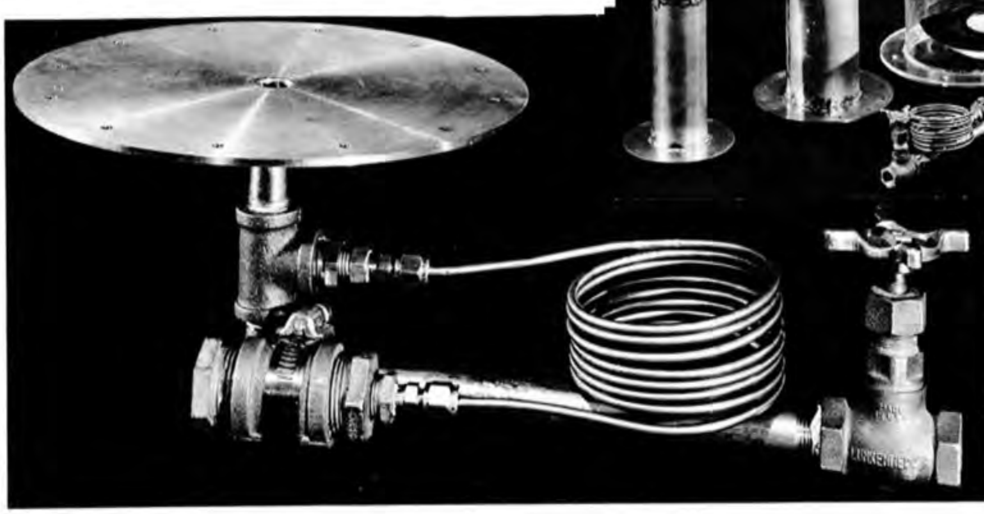
OPERATION

The main objectives of the simulation in the laboratory were to improve the performance and the reliability of the field equipment. Because difficulties had been encountered in the field, the laboratory problem included the developing and refining of the hydraulic

a. Float pulley on shaft of potentiometer, and perforated tape attached to float. Photo PX-D-70732

b. Assembled components. Photo PX-D-70730

c. Stilling well parts except 2-1/2-inch float in well. Photo PX-D-70731



d. Capillary damping tube and bypass drain. Photo PX-D-70733

Figure 6. Components of hydraulic time delay and water level sensor.

time delay circuit and water level sensor and improving the operation of the electronic controller. The input to the laboratory system corresponded to the input to the mathematical model. A water level change in the canal stilling well caused by a 50-cfs (1.4-cu m/sec) delivery from the section was computed from the mathematical model, Figure 7. The indicated change was manually controlled into and out of the laboratory stilling well. Records were made of the change in stilling well level, the water level in the filter well, and the indicated gate opening. The laboratory records were then compared to the predictions from the mathematical model.

CONTROL SYSTEM STUDY RESULTS

Hydraulic Filter

A continuous change in the output of the potentiometer with changes in the water surface level in the filter well is a desirable characteristic. Initial operation of the control system showed the 2-1/2-inch (6.3-cm) diameter float produced too small a force to smoothly drive the tape, pulley, and potentiometer. In the attempt to minimize the filter well size (4 inches, 10.2 cm) for ease of installation, the float was too

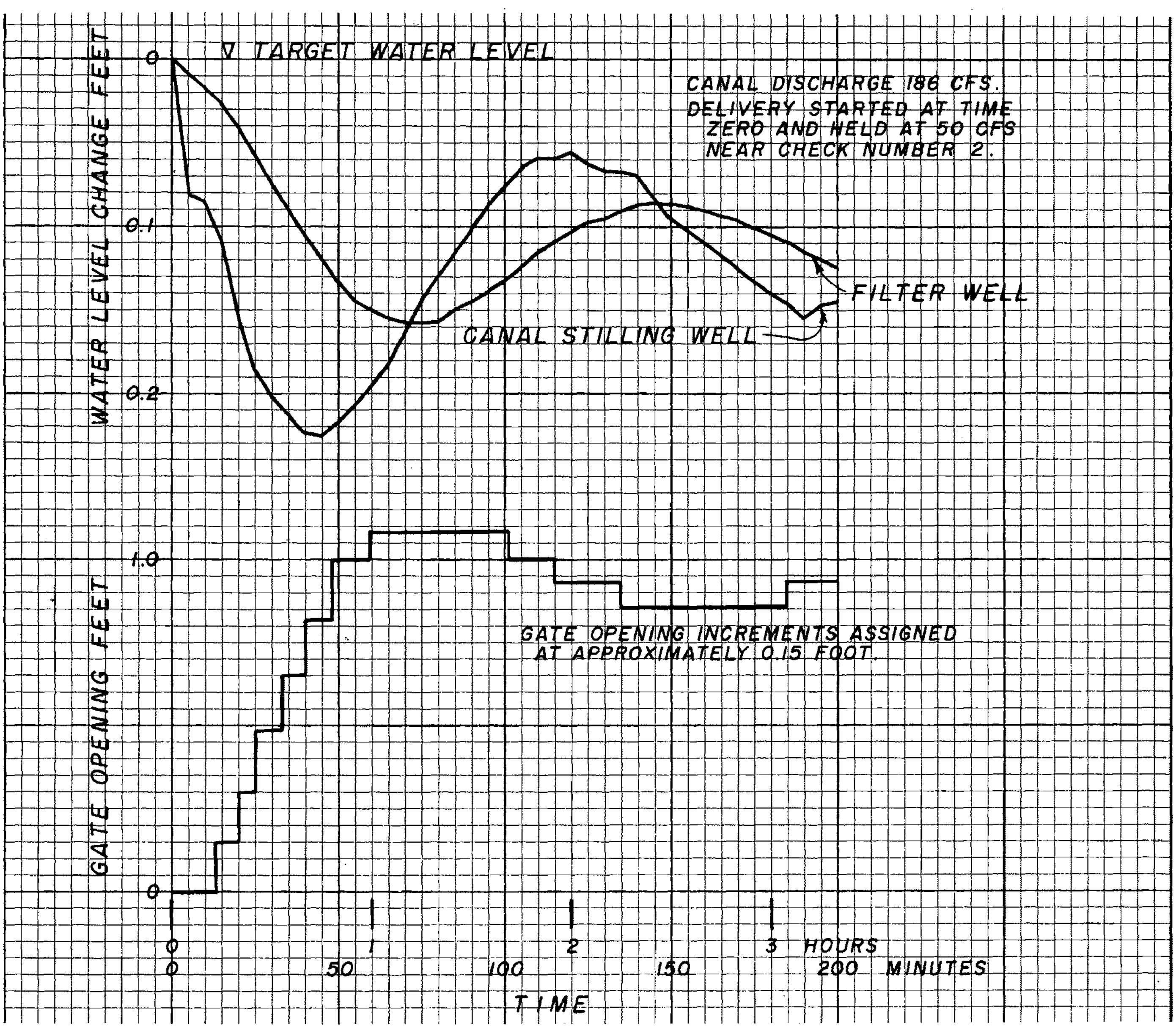


Figure 7. Transients predicted by mathematical model of Corning Canal.

small to overcome static friction. This resulted in not being able to repeat the target elevation.

A 0.15-foot (45.7-mm) step in gate opening was selected to prevent continuous operation of the hoist motors of the radial gates. The design of the control system provided this 0.15-foot step for a water level offset of 0.019-foot (5.7-mm). A water level change of 0.019 foot on the 2-1/2-inch-diameter float produced a force of about 0.6 ounce (17 grams). A 2-inch (5.1-cm) diameter pulley applied 0.6 ounce inches (43.2 gr-cm) to the potentiometer. Measurements of torque showed an 0.18-ounce (5-gram) weight at 1 inch was sufficient to turn the potentiometer shaft. The static friction became too large for reliable movements after the float, tape, and counterweight were added to the pulley, Figure 6a.

A study was then made to find a float size or a substitute means for measuring the water level with greater sensitivity. Because of the satisfactory resolution and sensitivity of a pressure transducer, a sensor was constructed to replace the float. A 1-psi strain-gage-type transducer was connected to a 1/8-inch (3.1-mm) outside diameter by 3/32-inch (2.4-mm) inside diameter brass tube. The tube and transducer pressure chamber were filled with distilled water. The tube was inserted into the filter well in place of the tape and float, Figure 8. For a computed time constant of 1,900 seconds in the laboratory hydraulic filter, the gate responded seven times in opening and two times in closing during operation, Figure 9.

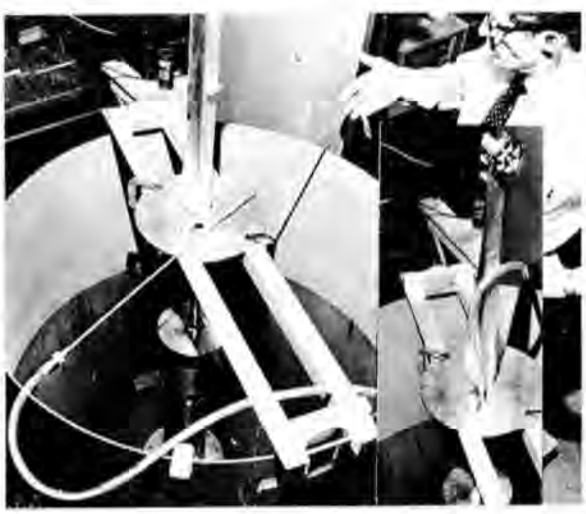


Figure 8. Water level sensing using water filled brass tube and pressure transducer. Photo PX-D-70735

Reversal of the time scale in the laboratory data was necessary because the maximum water surface elevation was also the maximum voltage of the system. Time references were placed at the right instead of the left of the recorder chart, the reverse of Figure 7.

The pressure transducer was an ideal water level sensor but required an additional high-stability signal conditioning circuit. Simplification of the system suggested that the float-potentiometer sensor be used but increased sensitivity be obtained by a larger float. The uniformity of the output of the potentiometer was measured for 5- and 12-inch (12.7- and 30.5-cm) diameter floats attached to the tape, Figure 10.

The 12-inch float, tape, potentiometer, and counterweight reacted to water level changes in the stilling well with a sensitivity equal to the pressure transducer. To accommodate the 12-inch float an unwieldy size of filter well would be necessary and cause difficulty in installation.

Because of the smaller size and good response a 5-inch float was selected for investigation and a 6-inch (15.3-cm) filter well was constructed to accommodate the float. Operation of the system using a computed time constant of 1,500 seconds produced seven steps in opening the gate and three steps in closing the gate, Figure 11.

The time of the gate opening was controlled by the sensitivity of adjusting the voltage of the Schmitt trigger. Variance in the order of plus or minus 0.03 volt in 1 volt of level was part of the cause of the shift shown by the time marks from the mathematical model placed near the recorded gate openings on Figures 9 and 11.

The potentiometer voltage output was not as uniform as that for the pressure transducer. Friction again caused a slight stepwise variation but the voltage steps were small. The reaction of the control appeared to be unaffected by the slight nonuniformity of potentiometer output.

Agreement between the mathematical model and laboratory simulation was better with the float than with the transducer in their respective stilling wells. The mathematical model computed the transients in Figure 6 from a time constant of 1,900 seconds. The filter well containing the transducer had a computed time constant of 1,900 seconds and a measured constant of 2,660 seconds for a 0.22-foot step function

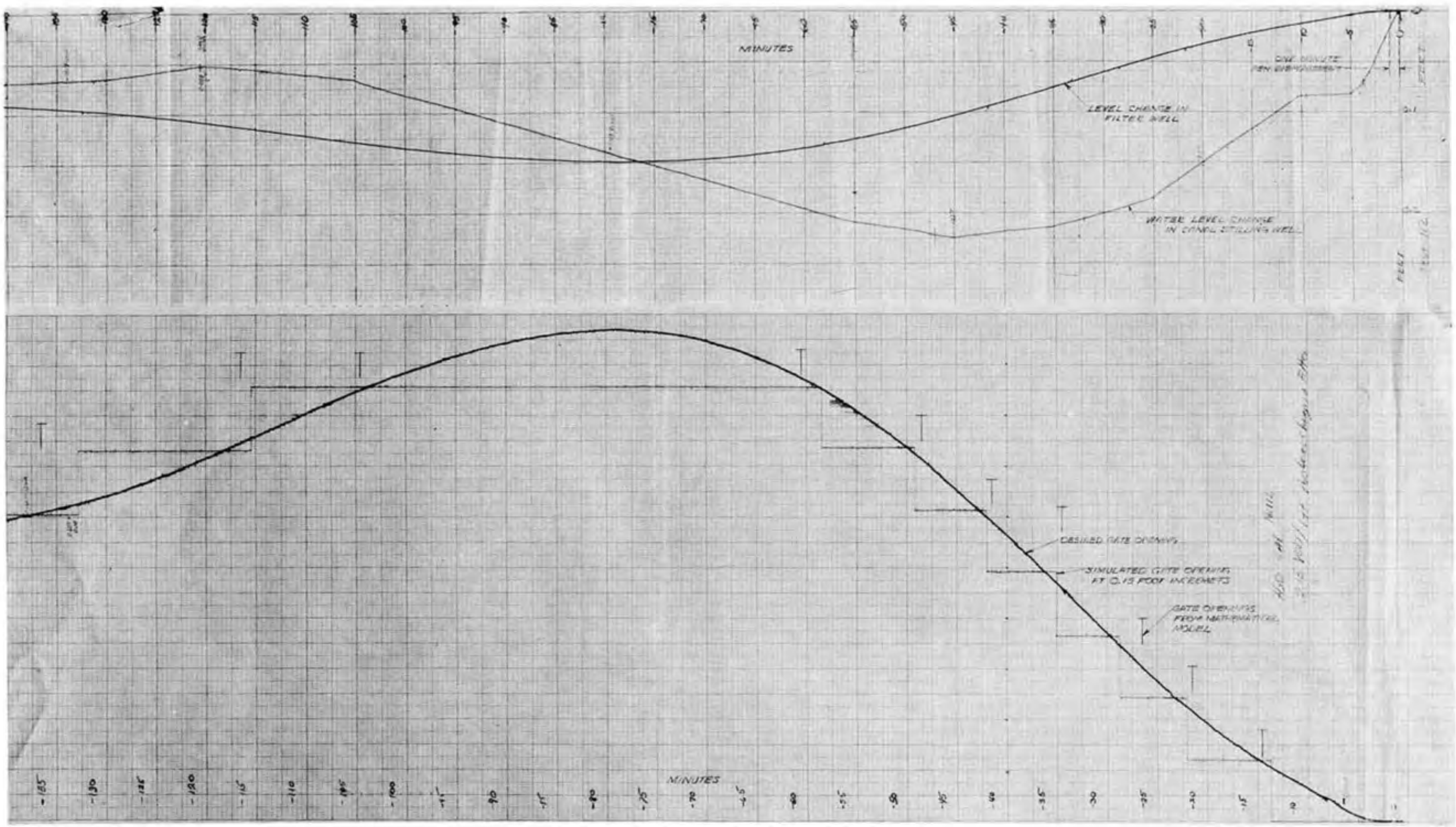


Figure 9. Laboratory simulation of mathematical model prediction of canal reaction to 50-cfs delivery near Check No. 2—Corning Canal (pressure transducer sensor).

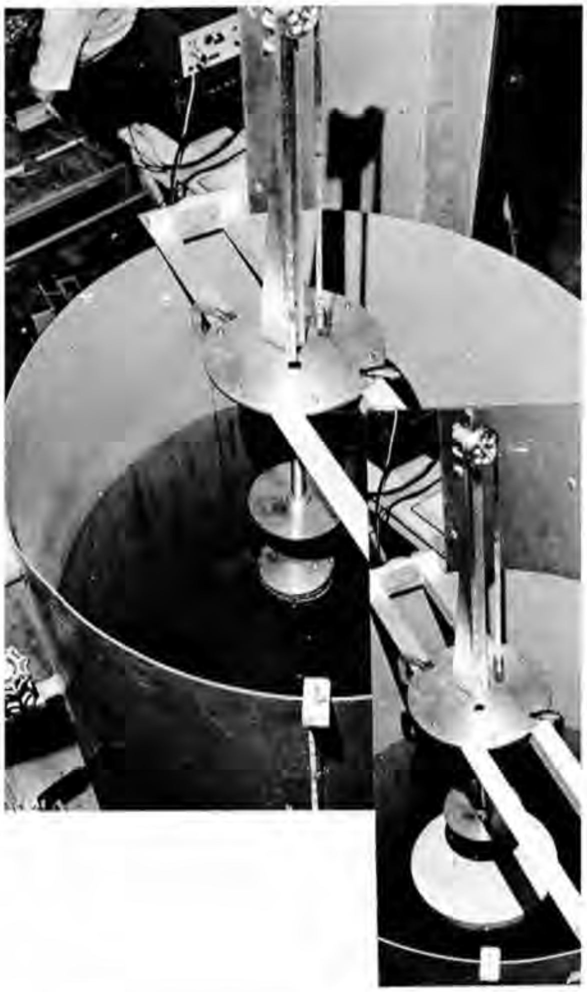


Figure 10. Five-inch and twelve-inch float actuated water level sensors. Photo PX-D-70734

in head. The filter well for the float had a computed time constant of 1,500 seconds and a measured constant of about 2,150 seconds for a 0.21-foot step function in head. The time constant of 2,150 seconds was closer to the mathematical model and thus the hydraulic filter with float gave better correspondence between theory and experiment.

Control Time Constant

Analysis.—Wave travel times in the sections of Corning Canal had been computed by personnel at the University of California.[3] These times were used with derived equations to compute the sizes of the stilling well and capillary damping tube, Figures 6c. and d. The equation of continuity for the filter is:

$$q_f = \frac{ad\Delta h_f}{dt} \qquad (1)$$

where

q_f	=	the flow into the filter well
a	=	the water surface area in the well
Δh_f	=	the change in the water level in the well
dt	=	change in time corresponding to the well change

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

$$\Delta y - \Delta h_f = \frac{fL}{2gd_c}\;\frac{qf}{\pi d_c{}^2/4}^{\;2} \qquad (2)$$

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:

$$f = \frac{64}{N_R} \qquad (3)$$

where

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

ν = the kinematic viscosity of water

Equations (1), (2), (3), and (4) combine to give a differential equation for the hydraulic filter:

$$\frac{d\Delta hf}{dt} + \frac{1}{ak}(\Delta hf - \Delta y) = 0 \qquad (5)$$

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 (5) is:

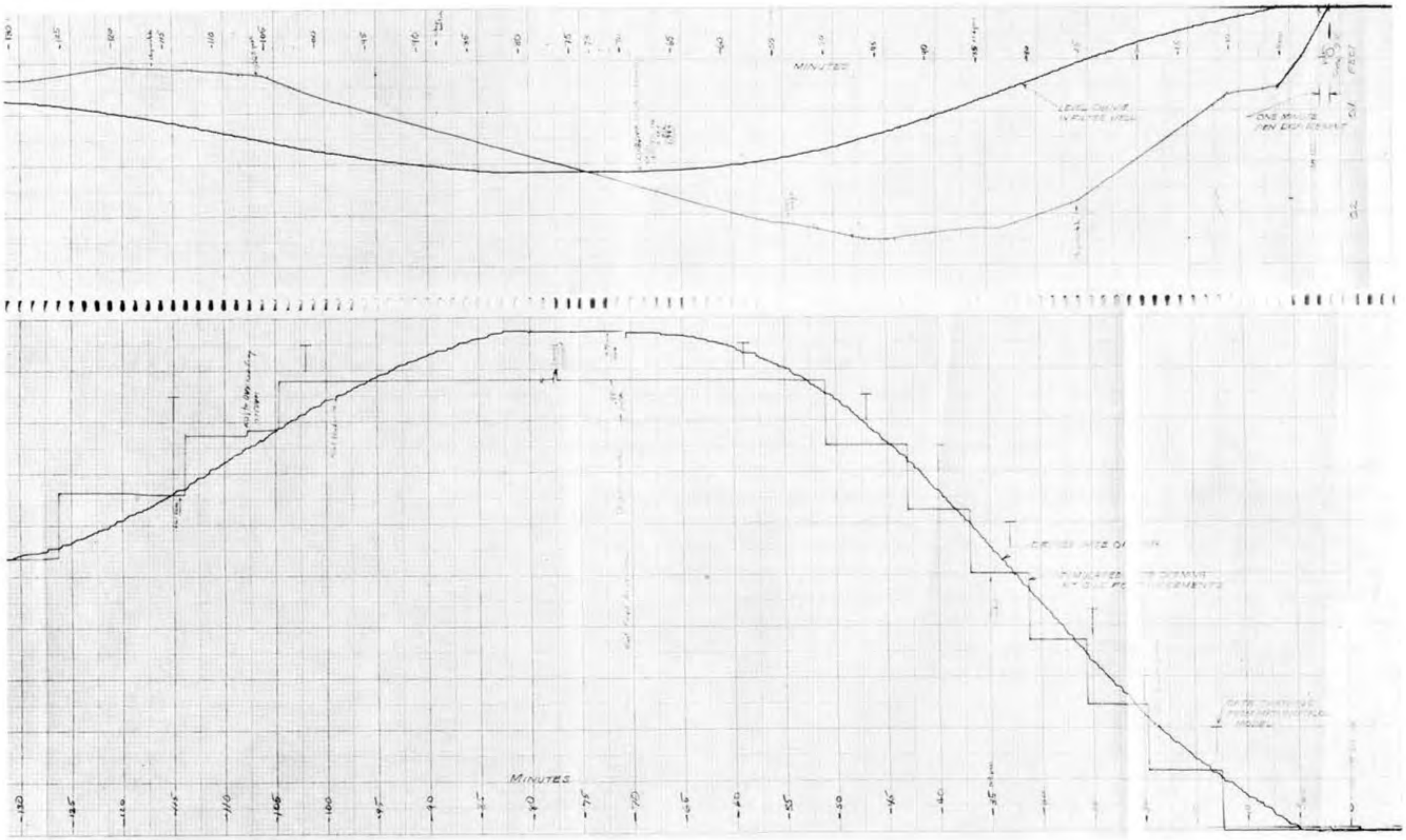


Figure 11. Laboratory simulation of mathematical model prediction of canal reaction to 50-cfs delivery near Check No. 2—Corning Canal (5-inch float sensor).

$$\Delta hf = \Delta y\ (1 - e^{-t/t_f}) \qquad (6)$$

where

$t_f = ak$ = time constant for the hydraulic filter

Δy = canal level change

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

$$\tau = ak = \frac{(\pi d^2 f)}{4} \frac{(128\nu L)}{\pi g d_c^4} \qquad (7)$$

$$\tau = ak = \frac{32\nu L}{g} d_f^2/d_c^4$$

Time constant measurements.—The time constant of the hydraulic filter was measured by monitoring the voltage output of the float-driven potentiometer and noting the time elapsed for the initial voltage to decrease to 63 percent of its value. The value of 63 percent of the maximum voltage is based on the following equation for the discharge of a capacitor:

$$T = V\max\ (1 - e^{-t/t_f})$$

Vmax = Maximum voltage output of potentiometer at t = 0

where

T = time t_f = filter time

for:

T = t_f the equation reduces to:

$$T = V\max\ (1 - e^{-1}) = V\max \left(1 - \frac{1}{e}\right)$$

$$T = V\max\ (1 - 0.3679) = 0.6321\ V\max$$

Major differences were found between the times for the filter to reach 0.63 of a step function as computed and measured in the laboratory. The indicated time constant varied with the size of the step function, Figure 12.

For the capillary tube (0.9-inch (22.8-mm) long by 1/32-inch (0.8-mm) inside diameter), time constants for small step functions were in closer agreement to the computed value. Computations of Reynolds Numbers from measured data showed that near turbulent flow conditions were present for the larger steps. Thus, conventional analysis does not appear to account for the excess entrance and turbulent losses occurring in the tube. Time constants associated with small steps or ramp variations normally encountered in the level change in the canal stilling well would be more closely computed by Equation 7.

Table 1 is a summary of the computed and measured times for a series of capillary tubes used in this study. The time constants apply to both the 4- and 6-inch filter wells. Data were taken throughout the study of the HyFLO control as filter well configurations were changed to provide desired time constants.

Fears were expressed that debris from the canal water passing from the stilling well to the filter would plug the capillary tubing. Because of the probability, studies of the HyFLO control system included a plastic bag submerged in the stilling well to supply clean water to the filter, Figure 13. Time constants in Table 1 indicate that no appreciable change was caused by the addition of plastic bag and tubing.

Stilling well measurements.—Use of the canal stilling well and a larger float (12 inches or more) was suggested as a possible substitute for the control hydraulic filter. Limited studies were made of the time constants of the laboratory well, Table 2.

For the three tubes cited, Reynolds Numbers near the transition range of 2,000 occurred for step ΔH values of 0.2 foot. Excess losses were evidenced by the lack of agreement between the computed and measured time constants.

CONCLUSIONS

Completion of the laboratory studies showed:

1. The HyFLO system equipment with slight modifications was capable of automatically controlling a gate supplying water to a canal section. Modifications included improving electrical components of the computer-controller and increasing the size of the hydraulic filter to accomodate a 5-inch float in place of a 2-inch float.

2. The control would supply water on demand from a delivery assumed to be located near the downstream end of a canal section.

3. A hydraulic time delay circuit can provide a delay of sufficient length to minimize oscillations when changes are made in canal flows.

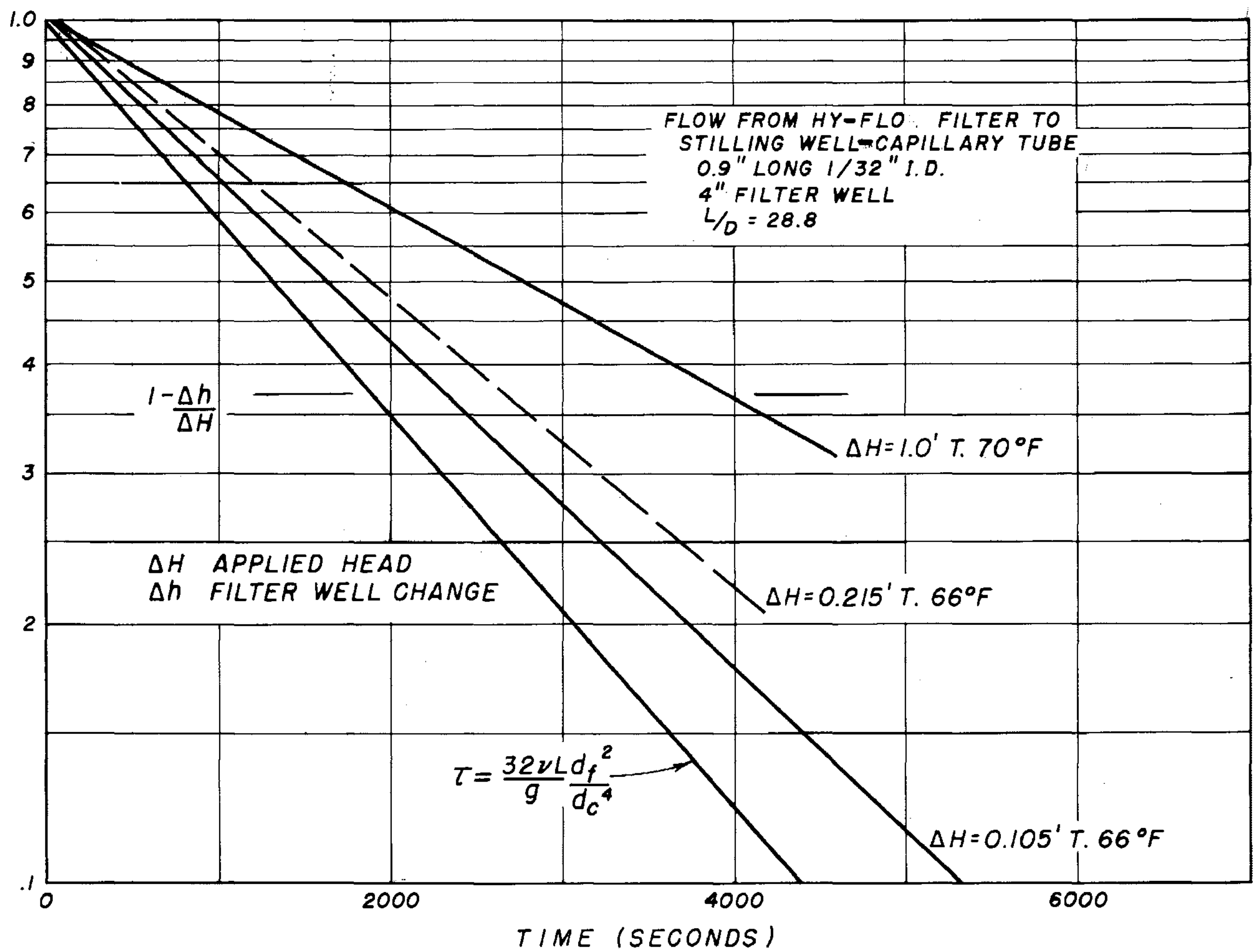


Figure 12. Time constant measurements HyFLO filter with pressure transducer sensor.

4. The laboratory model satisfactorily simulated predictions of gate opening and water level changes in the canal section. Exact correspondence was not obtained between the mathematical model predictions and the laboratory simulation because of the voltage sensitivity of the Schmitt triggers in the controller and actual filter time constants larger than computed from equations in the mathematical model.

5. Additional studies of the hydraulics of the time delay circuit should be made to produce an analysis to account for the loss across the capillary tube in excess of that predicted by equations from the mathematical model.

6. Additional analytical and experimental studies should be made of the system time constant to determine the range of variance for satisfactory flow control.

7. The addition of a plastic bag containing clear water will assist in keeping the capillary tube clean and the hydraulic time delay operating. The time constant of the delay was not appreciably changed by the addition of the bag and connecting tubing.

8. Substitution of a stable electronic time delay would allow use of a large float in the stilling well and would eliminate the maintenance necessary to assure satisfactory operation of the hydraulic time delay.

9. A float, tape, pulley, and potentiometer combination is a simple and satisfactory way of sensing water level and transferring information to the analog-computer. A 5-inch float produced a satisfactory force to operate the sensor. A larger float would be desirable for long-term operation of the mechanical parts as friction increases with age.

Table 1

SUMMARY OF FILTER WELL TIME CONSTANTS

Capillary tube: Inside diameter (inches)	Capillary tube: Length (inches)	Computed time constant (seconds)	Step ΔH (feet)	Measured* time constant (seconds)	Remarks	
		4-inch (10.2-cm) Diameter Stilling Well (pressure transducer sensor)				
1/32 (0.8 mm) L/d = 28.8	0.9 (22.8 mm)	1,900	1.0	3,940	Flow out of filter well water temperature	70° F
			0.22	2,660		66° F
			0.10	2,285		66° F
0.13 (3.3 mm) L/d = 625	8 0 (2 m)	490	1.0	870	Out, Temp	66° F
			1.0	930		59° F
		2-1/2-inch Float Sensor				
1/32	0.9	1,900	0.18	5,400	Out, Temp	72° F
			0.11	5,280		72° F
			0.2	**4,650	In, Temp	72° F
			0.11	5,350		72° F
		6-inch (15.3-cm) Diameter Stilling Well (5-inch float sensor)				
3/32 (2.4 mm) L/d = 307	28.8 (73 cm)	1,500	0.22	2,180	Out, Temp	78° F
			0.20	1,980	In, Temp	78° F
	5-inch (12.7-cm) Float, Plastic Bag, and 12 feet of 3/8-inch Plastic Tubing					
		1,500	0.21	2,190	Out, Temp	70° F
			0.21	2,120	In, Temp	70° F

*Time required to reach 0.63 of ΔH.
**Cause not determined.

10. A pressure tranducer has greater sensitivity to water level changes, but stable signal conditioning equipment and transducer are required for continued satisfactory operation.

11. Before general use is attempted, of the HyFLO system, a careful study should be completed of the operating characteristics of a single canal controlled by multiple units.

APPLICATIONS

Upon conclusion of these laboratory studies, the filter and a modified comparator were returned to California and installed to control the Corning Canal section simulated in the laboratory. An initial trial period of about 6 months prior to this report resulted in satisfactory control of flow in the section.

Figure 13. Hydraulic time-delay 6-inch stilling well and plastic bag for clean water supply. Photo PX-D-70738

Refinement of the HyFLO downstream control equipment and method is possible. Further study of the hydraulics of the filter should be made to produce an analysis to account for the excess loss in the capillary damping system. A study of a stable electronic time delay could result in the elimination of the hydraulic time delay. The electronic delay would allow use of a large float and potentiometer mechanism to increase reliability and reduce maintenance costs of the control equipment. Time constant studies in an operating canal should include the allowable variance to maintain satisfactory control of the flow.

The HyFLO method of downstream control and equipment of increased reliability should have general use in existing and proposed water systems of the Bureau. Before general use is attempted, a careful study should be completed of the operating characteristics of a single canal controlled by multiple units of HyFLO equipment.

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Table 2

SUMMARY OF STILLING WELL TIME CONSTANTS

Tube size: Inside diameter (inches)	Tube size: Length (inches)	Computed time constant (seconds)	Step ΔH (feet)	Measured* time constant (seconds)	Remarks
0.44 (11.2 mm)	600 (1,525 cm)	2,440	1.0	7,440	Copper tubing $T = 70^{\circ}$ F
			0.2	4,570	$T = 71^{\circ}$ F
0.44 (11.2 mm)	504 (1,281 cm)	2,060	1.0	5,660	Saran plastic $T = 69^{\circ}$ F
			0.5	4,760	
			0.2	3,800	
0.88 (22.4 mm)	540 (1,372 cm)	–	0.2	700	Garden hose $T = 70^{\circ}$ F

*Time required to reach 0.63 of ΔH.
Stilling well diameter 34.5 inches (87.7 cm).

7-1750 (3-71)
Bureau of Reclamation

CONVERSION FACTORS–BRITISH TO METRIC UNITS OF MEASUREMENT

The following conversion factors adopted by the Bureau of Reclamation are those published by the American Society for Testing and Materials (ASTM Metric Practice Guide, E 380-68) except that additional factors (*) commonly used in the Bureau have been added. Further discussion of definitions of quantities and units is given in the ASTM Metric Practice Guide.

The metric units and conversion factors adopted by the ASTM are based on the "International System of Units" (designated SI for Systeme International d'Unites), fixed by the International Committee for Weights and Measures; this system is also known as the Giorgi or MKSA (meter-kilogram (mass)-second-ampere) system. This system has been adopted by the International Organization for Standardization in ISO Recommendation R-31.

The metric technical unit of force is the kilogram-force; this is the force which, when applied to a body having a mass of 1 kg, gives it an acceleration of 9.80665 m/sec/sec, the standard acceleration of free fall toward the earth's center for sea level at 45 deg latitude. The metric unit of force in SI units is the newton (N), which is defined as that force which, when applied to a body having a mass of 1 kg, gives it an acceleration of 1 m/sec/sec. These units must be distinguished from the (inconstant) local weight of a body having a mass of 1 kg, that is, the weight of a body is that force with which a body is attracted to the earth and is equal to the mass of a body multiplied by the acceleration due to gravity. However, because it is general practice to use "pound" rather than the technically correct term "pound-force," the term "kilogram" (or derived mass unit) has been used in this guide instead of "kilogram-force" in expressing the conversion factors for forces. The newton unit of force will find increasing use, and is essential in SI units.

Where approximate or nominal English units are used to express a value or range of values, the converted metric units in parentheses are also approximate or nominal. Where precise English units are used, the converted metric units are expressed as equally significant values.

Table I

QUANTITIES AND UNITS OF SPACE

Multiply	By	To obtain
	LENGTH	
Mil	25.4 (exactly)	Micron
Inches	25.4 (exactly)	Millimeters
Inches	2.54 (exactly)*	Centimeters
Feet	30.48 (exactly)	Centimeters
Feet	0.3048 (exactly)*	Meters
Feet	0.0003048 (exactly)*	Kilometers
Yards	0.9144 (exactly)	Meters
Miles (statute)	1,609.344 (exactly)*	Meters
Miles	1.609344 (exactly)	Kilometers
	AREA	
Square inches	6.4516 (exactly)	Square centimeters
Square feet	*929.03	Square centimeters
Square feet	0.092903	Square meters
Square yards	0.836127	Square meters
Acres	*0.40469	Hectares
Acres	*4,046.9	Square meters
Acres	*0.0040469	Square kilometers
Square miles	2.58999	Square kilometers
	VOLUME	
Cubic inches	16.3871	Cubic centimeters
Cubic feet	0.0283168	Cubic meters
Cubic yards	0.764555	Cubic meters
	CAPACITY	
Fluid ounces (U.S.)	29.5737	Cubic centimeters
Fluid ounces (U.S.)	29.5729	Milliliters
Liquid pints (U.S.)	0.473179	Cubic decimeters
Liquid pints (U.S.)	0.473166	Liters
Quarts (U.S.)	*946.358	Cubic centimeters
Quarts (U.S.)	*0.946331	Liters
Gallons (U.S.)	*3,785.43	Cubic centimeters
Gallons (U.S.)	3.78543	Cubic decimeters
Gallons (U.S.)	3.78533	Liters
Gallons (U.S.)	*0.00378543	Cubic meters
Gallons (U.K.)	4.54609	Cubic decimeters
Gallons (U.K.)	4.54596	Liters
Cubic feet	28.3160	Liters
Cubic yards	*764.55	Liters
Acre-feet	*1,233.5	Cubic meters
Acre-feet	*1,233,500	Liters

Table II

QUANTITIES AND UNITS OF MECHANICS

Multiply	By	To obtain
MASS		
Grains (1/7,000 lb)	64.79891 (exactly)	Milligrams
Troy ounces (480 grains)	31.1035	Grams
Ounces (avdp)	28.3495	Grams
Pounds (avdp)	0.45359237 (exactly)	Kilograms
Short tons (2,000 lb)	907.185	Kilograms
Short tons (2,000 lb)	0.907185	Metric tons
Long tons (2,240 lb)	1,016.05	Kilograms
FORCE/AREA		
Pounds per square inch	0.070307	Kilograms per square centimeter
Pounds per square inch	0.689476	Newtons per square centimeter
Pounds per square foot	4.88243	Kilograms per square meter
Pounds per square foot	47.8803	Newtons per square meter
MASS/VOLUME (DENSITY)		
Ounces per cubic inch	1.72999	Grams per cubic centimeter
Pounds per cubic foot	16.0185	Kilograms per cubic meter
Pounds per cubic foot	0.0160185	Grams per cubic centimeter
Tons (long) per cubic yard	1.32894	Grams per cubic centimeter
MASS/CAPACITY		
Ounces per gallon (U.S.)	7.4893	Grams per liter
Ounces per gallon (U.K.)	6.2362	Grams per liter
Pounds per gallon (U.S.)	119.829	Grams per liter
Pounds per gallon (U.K.)	99.779	Grams per liter
BENDING MOMENT OR TORQUE		
Inch-pounds	0.011521	Meter-kilograms
Inch-pounds	1.12985×10^6	Centimeter-dynes
Foot-pounds	0.138255	Meter-kilograms
Foot-pounds	1.35582×10^7	Centimeter-dynes
Foot-pounds per inch	5.4431	Centimeter-kilograms per centimeter
Ounce-inches	72.008	Gram-centimeters
VELOCITY		
Feet per second	30.48 (exactly)	Centimeters per second
Feet per second	0.3048 (exactly)*	Meters per second
Feet per year	$*0.965873 \times 10^{-6}$	Centimeters per second
Miles per hour	1.609344 (exactly)	Kilometers per hour
Miles per hour	0.44704 (exactly)	Meters per second
ACCELERATION*		
Feet per second^2	*0.3048	Meters per second^2
FLOW		
Cubic feet per second (second-feet)	*0.028317	Cubic meters per second
Cubic feet per minute	0.4719	Liters per second
Gallons (U.S.) per minute	0.06309	Liters per second
FORCE*		
Pounds	*0.453592	Kilograms
Pounds	*4.4482	Newtons
Pounds	$*4.4482 \times 10^5$	Dynes

Table II—Continued

Multiply	By	To obtain
WORK AND ENERGY*		
British thermal units (Btu)	*0.252	Kilogram calories
British thermal units (Btu)	1,055.06	Joules
Btu per pound	2.326 (exactly)	Joules per gram
Foot-pounds	*1.35582	Joules
POWER		
Horsepower	745.700	Watts
Btu per hour	0.293071	Watts
Foot-pounds per second	1.35582	Watts
HEAT TRANSFER		
Btu in./hr ft^2 degree F (k, thermal conductivity)	1.442	Milliwatts/cm degree C
Btu in./hr ft^2 degree F (k, thermal conductivity)	0.1240	Kg cal/hr m degree C
Btu ft/hr ft^2 degree F	*1.4880	Kg cal m/hr m^2 degree C
Btu/hr ft^2 degree F (C, thermal conductance)	0.568	Milliwatts/cm^2 degree C
Btu/hr ft^2 degree F (C, thermal conductance)	4.882	Kg cal/hr m^2 degree C
Degree F hr ft^2/Btu (R, thermal resistance)	1.761	Degree C cm^2/milliwatt
Btu/lb degree F (c, heat capacity)	4.1868	J/g degree C
Btu/lb degree F	*1.000	Cal/gram degree C
Ft^2/hr (thermal diffusivity)	0.2581	Cm^2/sec
Ft^2/hr (thermal diffusivity)	*0.09290	M^2/hr
WATER VAPOR TRANSMISSION		
Grains/hr ft^2 (water vapor) transmission)	16.7	Grams/24 hr m^2
Perms (permeance)	0.659	Metric perms
Perm-inches (permeability)	1.67	Metric perm-centimeters

Table III

OTHER QUANTITIES AND UNITS

Multiply	By	To obtain
Cubic feet per square foot per day (seepage)	*304.8	Liters per square meter per day
Pound-seconds per square foot (viscosity)	*4.8824	Kilogram second per square meter
Square feet per second (viscosity)	*0.092903	Square meters per second
Fahrenheit degrees (change)*	5/9 exactly	Celsius or Kelvin degrees (change)*
Volts per mil	0.03937	Kilovolts per millimeter
Lumens per square foot (foot-candles)	10.764	Lumens per square meter
Ohm-circular mils per foot	0.001662	Ohm-square millimeters per meter
Millicuries per cubic foot	*35.3147	Millicuries per cubic meter
Milliamps per square foot	*10.7639	Milliamps per square meter
Gallons per square yard	*4.527219	Liters per square meter
Pounds per inch	*0.17858	Kilograms per centimeter

GPO 840-399

ABSTRACT

The Hydraulic Filter Level Offset (HyFLO) system for automatic downstream control of canals was mathematically modeled, designed, and constructed by the University of California at Berkeley and the Bureau of Reclamation Office, Sacramento, California. The HyFLO system is a feedback control method that automatically adjusts the canal inflow from water level offsets caused by the canal outflow. Mechanical and electrical problems occurred in a field trial of the system, and the equipment was sent to the Engineering and Research Center, Denver, for testing and evaluating. The HyFLO equipment was installed in the laboratory to simulate one section of canal between two radial gates. After some equipment modification, the laboratory model satisfactorily simulated mathematical predictions of gate opening and water level changes in the canal section. Upon completion of the laboratory testing, the equipment was installed on one section of the Corning Canal near Red Bluff, California. The equipment is now controlling the flow satisfactorily.

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Bur Reclam Rep REC-ERC-72-3, Div Gen Res, Div Des, Jan 1972. Bureau of Reclamation, Denver, 15 p, 13 fig, 2 tab, 3 ref

DESCRIPTORS—/ downstream/ *control/ automation/ *automatic control/ irrigation canals/ *canals/ hydraulics/ damping/ timing circuits/ control systems/ water levels/ water level fluctuations/ offsets/ analog computers/ laboratory tests/ test results/ simulation/ mathematical models
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