THE UNIVERSITY OF CALGARY

A COMPARISON OF IRRIGATION UPSTREAM AUTOMATIC CONTROLLERS

by

Michael A. Schaalje

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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies for acceptance, a thesis entitled, "Comparison of Upstream Automatic Controllers" submitted by Mr. Michael A. Schaalje in partial fulfilment of the requirements for the degree of Master of Engineering.

Supervisor, Dr. D.H. Manz
Department of Civil Engineering

Dr. I. Muzik
Department of Civil Engineering

Dr. J.D.M. Belgrave
Department of Chemical Engineering

(DATE) July 15/91

ABSTRACT

Many types of automatic controller systems exist for use in irrigation conveyance systems. Some of these controllers were developed in the field by irrigation canal operations personnel. Other controllers were carefully engineered using computer modeling and/or prototypes to develop and improve the controllers.

Although computer modelling has been used in the past to develop specific automatic controllers, computer models have not been used extensively for the comparison, engineering design and applicability to operations of upstream automatic controllers. This thesis was initiated to investigate the possibilities of using the Irrigation Conveyance System Simulation (ICSS 2) model to simulate and compare the operations of three automatic upstream controllers. The controllers chosen were the Littleman, EL-FLO and Proportional + Integral + Differential (PID) controller. Comparisons of the three controllers were accomplished by evaluating the maximum water level overshoot and undershoot from the desired water level, the cumulative error during the simulation from the desired water level and by visually evaluating the response of the water level and controller during an entire simulation using graphs.

This investigation found that all of the controllers investigated successfully controlled the upstream water level to varying degrees. Of the three controllers the PID controller seemed to hold the most promise for use as a general purpose controller algorithm.

The comparison of the three upstream automatic controllers was successful. This research should be extended to include the comparison and development of downstream controllers, system controllers and demand oriented control systems.

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NOMENCLATURE

C	Controller action response
CMS	Cubic Metres Per Second
e	Error between desired and actual water levels
G	Change in gate position
GA	Actual gate position (EL-FLO controller)
GDB	Gate deadband (EL-FLO controller)
GP	Calculated Proportional Gate Position (EL-FLO controller)
GR	Calculated Reset Gate Position (EL-FLO controller)
HRS	Hours
K_d	Differential Gain Constant (PID controller)
K_p	Proportional Gain Constant (PID controller)
K_i	Integral Gain Constant (PID controller)
M	Metres
mm	Millimetres
M/min	Velocity Metres per Minute
RDB	Reset deadband (EL-FLO controller)
T_r	Reset time constant (PID controller)
YF	Actual water level (EL-FLO controller)
YT	Preset water level (EL-FLO controller)

1.0 INTRODUCTION

The purpose of an irrigation conveyance system is to deliver water in a controlled manner from sources upstream to users downstream. Users of irrigation conveyance systems are typically farms, however municipalities have made use of these systems to supply their potable water needs.

Once the water is delivered, the user may allow the water to flood the field by gravity, it may be pumped from a dugout adjacent to the canal or directly from the canal or flow into large storage reservoirs for use as a potable water supply for municipalities. The different ways in which the water is used also prescribes the accuracy of the delivery of flow required. For example an irrigation system which uses a pump to irrigate crops through a sprinkler system can deal with very little variation in the required delivery. Too much water may cause flooding of the field; too little water will cause the pump to shut down.

Due to different users and user requirements the operation of an irrigation conveyance system can be very complex. Standard operational procedures have been developed to deal with these complexities. In some cases automatically controlled equipment has been included in the operational procedures of a particular irrigation conveyance system.

Many types of automatic controller schemes exist for use in irrigation conveyance systems. Some controllers were developed in the field by canal operations personnel, while others were carefully engineered using prototypes or computer models. No known initiative, however, has been launched to evaluate and compare the response of automatic controllers in differing locations and under a variety of flow conditions.

By having the ability to evaluate automatic controllers engineers and planners will be able to choose the most appropriate type and configuration. Additionally, the ability to evaluate the performance of the automatic controller may provide economic justification for constructing the automatic controllers where none was available before. Finally the ability to evaluate and design for the impact which the automatic controller has on the conveyance system will assist in making economical and accurate deliveries to the end user.

2.0 OBJECTIVE OF RESEARCH

The objective of this thesis is to compare the operation and quality and range of control of different upstream automatic controllers used in irrigation conveyance systems using computer simulation techniques. Evaluation of these criterion will assist designers and managers in making both operational and economical decisions about the use of automatic controllers.

The automatic controllers used for this demonstration are the Littleman, EL-FLO and PID controllers. Only the PID controller will be developed sufficiently to be used to test its effectiveness under varying flow conditions.

3.0 THE DEVELOPMENT OF AUTOMATIC CONTROLLERS FOR USE IN IRRIGATION CONVEYANCE SYSTEM

The regulation of flow through irrigation conveyance systems to the end users is accomplished through a series of inline control or offline control structures. The inline control structures are constructed within the main canal and are used to control the depth of water or flow through the structure. Offline control structures are used to deliver water from the main canal to the end users.

In broad terms, the methods used to operate these control structures are known as Upstream control, Downstream control and Dynamic Regulation. Both the Upstream and Downstream control systems may be used within a manually, partially or fully automated conveyance system. The Dynamic Regulation requires complete automation of the conveyance system.

Automatic controls have been developed which control the water level or flow rate using one of the above control methods.

3.1 IRRIGATION CONVEYANCE CONTROL SYSTEMS

The following discussion describes the three different control methods in detail. This discussion is followed by descriptions of automatic control methods starting from elementary control theory.

3.1.1 Upstream Controlled Systems

Upstream controlled systems are often referred to as supply oriented systems. This system controls the level of the water upstream of the depth control structure. This method requires that adequate water be available upstream of the depth control structure to supply water to the immediate upstream diversion as well as all diversions downstream. Of necessity it can be seen that it is preferable to deliver more water than required to satisfy the needs of all diversions. The excess water is wasted at the end of the canal system into some type of drainage system.

Manz (1987) describes the operation of a manual upstream control system. Figure 1. shows the system used for the example. This example is as follows:

1. The canal operator, (ditchrider), receives notice from the farmers that water is required.

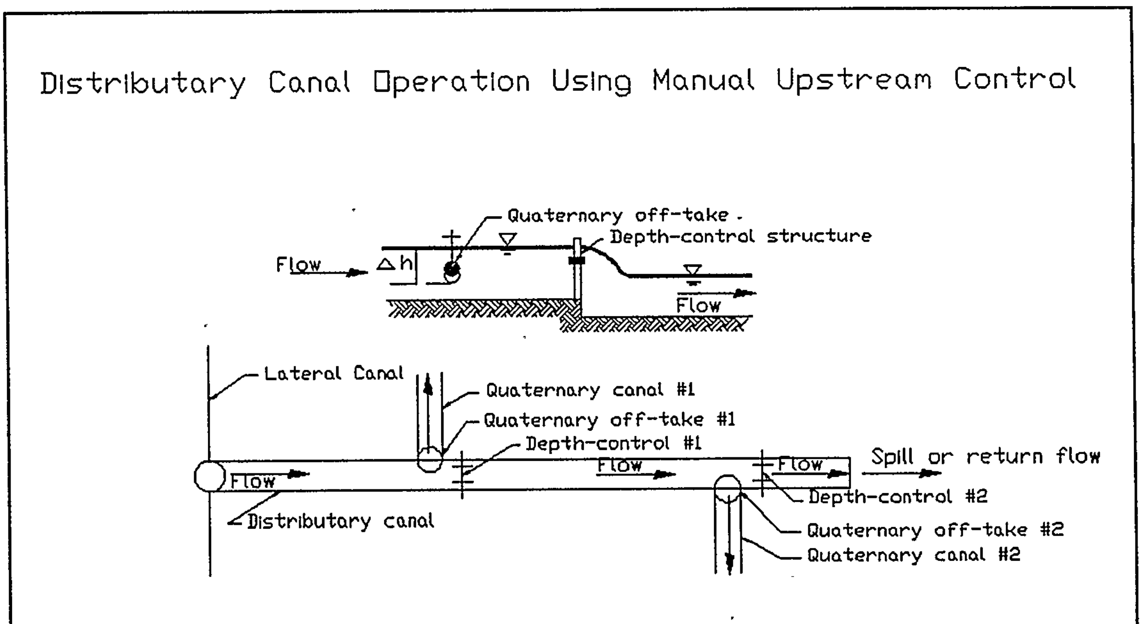


Figure 1. DISTRIBUTARY CANAL SCHEMATIC (MANZ 1987)

2. The canal operator generates an estimate of the farmers' actual water requirements.

3. The canal operator estimates the magnitude of distributed losses which will occur while the water is transferred from the distributary off-take to the quaternary off takes.

4. The canal operator estimates the magnitude of the required release into the distributary canal.

5. The canal operator operates the primary distributary off-take and diverts water into the distributary canal. The actual amount diverted into the canal will likely differ from his objective due to imprecise distributary off-take operations.

6. The canal operator will operate the depth control structures immediately down stream of the quaternary off-takes to ensure that there is adequate depth of water in the canal to operate the quaternary off-takes.

7. The water actually released into the canal will be reduced by unknown distributed loss rates, which are a function of the canal's hydraulic and hydrologic characteristics at the time the canal is operated and by the backwater effects caused by the operation of the depth control structure.

8. When the operator is sure that steady-state conditions are achieved at the quaternary off-takes, delivery will be made to the farmers.

9. The farmers are ready to accept this delivery and extract their water application needs from the delivery.

10. Water delivered to the farmers in excess of their needs may be spilled by the farmers into some available drainage system.

11. Water not delivered to the farmers is allowed to spill down the distributary canal.

12. As the spilled water passes down the distributary canal,

the volume of water is reduced by additional distributed losses incurred while enroute.

13. Spilled water which reaches the end of the canal is ejected into an available drainage system and is called surface return flow.

The canal operator may attempt to reduce excessive spill. The steps used are as follows:

14. After a period of time, a farmer may report to the canal operator an excess delivery of water. (With the use of sprinkler irrigation systems, excess deliveries are preferred to shortfalls.)

15. The canal operator will assess the farmer's report and reduce the delivery to the farm.

16. Additional distributary flow will occur.

17. The canal operator assesses the spill.

18. The canal operator reduces the diversion into the distributary canal by operating the primary distributary off-take.

19. After a period of time, the canal operator will reassess the spill and may repeat step 18.

The manual process of controlling a canal can be a laborious task as evidenced from the above example. Both automatic and manual upstream control systems operate in the same manner.

3.1.2 Downstream controlled systems.

Downstream controlled systems are referred to as demand oriented systems. The water level downstream of the depth control structure is controlled. Thus as water requirements downstream change the upstream control structures compensate to maintain the preset water depth.

Downstream control is used infrequently in manual operations. The manual downstream controlled delivery systems which are used are mostly closed pipelines. A typical pipeline system is shown in Figure 2. Water delivery from this type of system operates much like a municipal water distribution system. When the valve is opened at one or more of the quaternary off-takes water is available immediately for the duration desired. The volume of water available is limited by the capacity of the pipeline. This capacity is determined by the available head at the lateral, entrance, exit and friction losses.

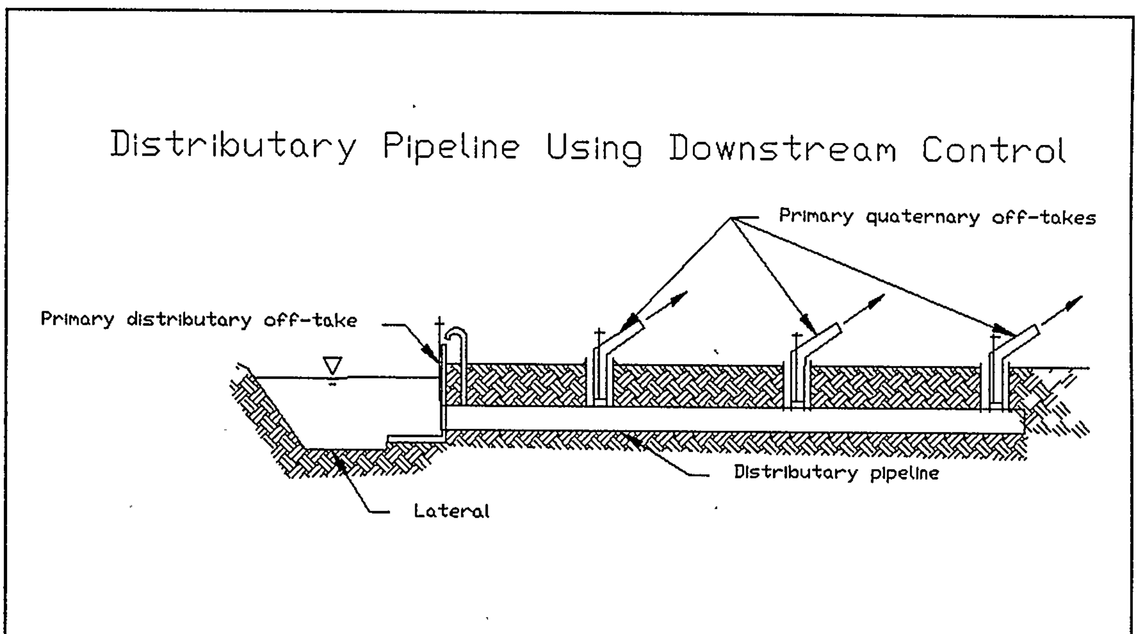


Figure 2 Distributary Pipeline Schematic (MANZ, 1987)

Automatic downstream control of open channel irrigation conveyance systems have been researched for a number of years. Specifically Buyalski(1979), Merriam and Dedrick(1977) and Zimbelman (1981) describe examples of automatic downstream control of irrigation channels. Automatic downstream control incorporates a water level sensor(s) placed in the reach below the control mechanism. The output from the sensor(s) is compared to the desired water elevation. The gate position is then changed according to the results of the depth comparison.

3.1.3 Dynamic Regulation

Dynamic regulation of irrigation conveyance systems involves a combination of upstream and downstream control. This type of control requires that some or all of the control structures be coordinated. Control of each structure is based on the supply conditions, the status of the depth control and diversion structures along with data on planned deliveries.

Examples of a dynamically regulated system include the California Aqueduct and the Canal de Provence in Southern France. Devries and Amorocho(1973) describe the operation of the California Aqueduct.

3.1.4 Operational Constraints

When dealing with operations of an open channel conveyance system physical and hydraulic constraints come into play.

Unlike pressurized systems water delivery is not instantaneous. The time required to complete a water delivery is dependent on the dynamics of the flow resulting from the upstream and downstream flow adjustments.

Control of gates, whether manual or automatic, must attempt to minimize the fluctuations in water levels. This is mostly due to the fact that quick draw down of the canal water level may cause failure of the canal due to excess pore pressure in the canal's banks. (For example the recommended rate of drawdown in the Saint Mary's River Irrigation District (SMRID) is 200 mm (8 inches) per 24 hours.)

3.2 ELEMENTARY AUTOMATIC CONTROL THEORY

Classical control theory textbooks describe classical automatic control theory in the context of process control. In many process control applications responses to a stimulus applied to the system is almost instantaneous. It is also assumed that continual adjustment of the system stimulus is possible. In applying these concepts to irrigation conveyance systems instantaneous response to the adjustment of a gate (the stimulus) does not usually occur. This is due mostly to the time required for the surge wave to propagate down the channel, usually called lag time. Also continual adjustment of the gate mechanism is not appropriate as this mode of operation may shorten the life of the mechanism considerably.

Control systems may be classified into one of two categories, these are open and closed loop systems. Brighouse and Loveday (1987) define an open loop system as one in which "the output is set by a reference input but where the control action is independent of the effect produced at the output." An example of an open looped system is one of a speed control for a motor. (Figure 3) The speed may be set using the control dial marked in graduations of 100 revolutions per minute. As no means of monitoring the speed of the motor is available, if the load on the motor increases or decreases the speed may fluctuate from the setting.

The closed loop systems utilize feedback to monitor the effect produced by the controller. Figure 4. shows the speed controller modified for feedback control. A change in speed of the motor will be sensed and will produce an error signal. This signal is used to adjust the controller output. If the speed of the motor falls below the preset speed the error is positive thus increasing the controller output and finally the speed of the motor. Vice versa if the speed is higher than the preset value.

Open loop systems are used when low accuracy is required or conditions being controlled are not subject to excessive variations. Closed loop systems are used when accuracy is important and variations in the controlled conditions are excessive.

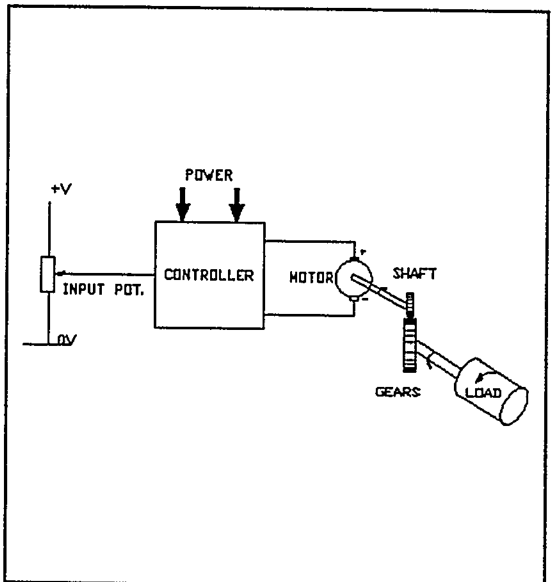


Figure 3 Open Loop Control System

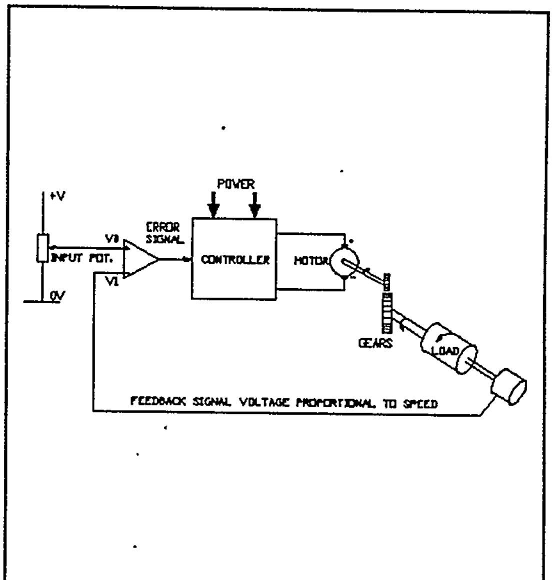


Figure 4 Closed Loop Control System

All automatic controls used in irrigation and drainage are closed loop systems.

3.3 AUTOMATIC CONTROL SYSTEMS FOR IRRIGATION AND DRAINAGE

Many irrigation systems in North America have, in the past, been designed for, or retrofitted with, automatically controlled structures to regulate water depth or flow through the structure. The types and methods of control for automatically controlled structures are diverse. Automatically controlled structures have been developed in the field (by trial and error), using prototypes and with the use of computer models.

The following presents descriptions of some of the automatic control methods for irrigation and drainage systems. The control methods discussed include:

- Two Position Control
  - Pumping Systems
- Floating Controllers
  - Dual Acting Controlled Leak System (DACL)
  - Neyrtec
  - Littleman Control (SOT/SRT)
- Proportional Control
  - Classical approach
- Proportional + Reset
  - Classical approach
  - EL-FLO Controller
- Proportional + Rate
  - Classical approach
- Proportional + Reset + Rate
  - Classical approach

- Rate Controller
  - Canal Automation for Rapid Demand Deliveries

3.3.1 Two Position Control

Two position control is the simplest of all of the controls to understand. The USBR (1973) states that "Because of the simplicity, two position controls are probably the most widely used mode of feedback control". This type of control either turns the controlling element On or Off. The best example of a two position control is that of a pumping installation. In this application the pump is turned on when the water level reaches a preset level, and is turned off at a different predetermined level. The complexity of this type of control can be increased by adding more pumps and more level controls.

A typical application for this type of control includes pumping water into an irrigation or drainage system from a lower canal or reservoir.

3.3.2 Floating Control

Floating control is the term given to automatically controlled structures which rely on some type of float to sense the water level and either directly control the position of the gate or activate limit switches to control the gate movement. Floating controls which directly affect the movement of the gate include the Neyrtec and the DACL system. The floating controls which control the position of the gate via a floating device opening and closing switches include the Little Man and the Hy Flo controls.

Some floating controls were designed in the field by canal operators. Designs of these controller vary considerably, however they all perform basically the same functions of controlling the upstream or downstream water surface.

3.3.2.1 Neyrtec Gate Floating Controls

The Neyrtec gates are able to control the upstream or downstream water levels or deliver a constant flow rate. The Neyrtec gates are commercially available.

The operating principles of the Neyrtec gate as described by Goussard (1987) are based on floats which are rigidly attached to a radial gate. The floats operate in wells or tanks whose water level varies as a function of both the upstream and downstream water levels. As the water level changes so do the float levels. The equilibrium of the radial gate is independent of hydraulic forces from the canal, therefore the radial gate is easily adjusted as the floats change levels. A system of floats and counter balances may be devised to control the gate based on the water level in the well. Figure

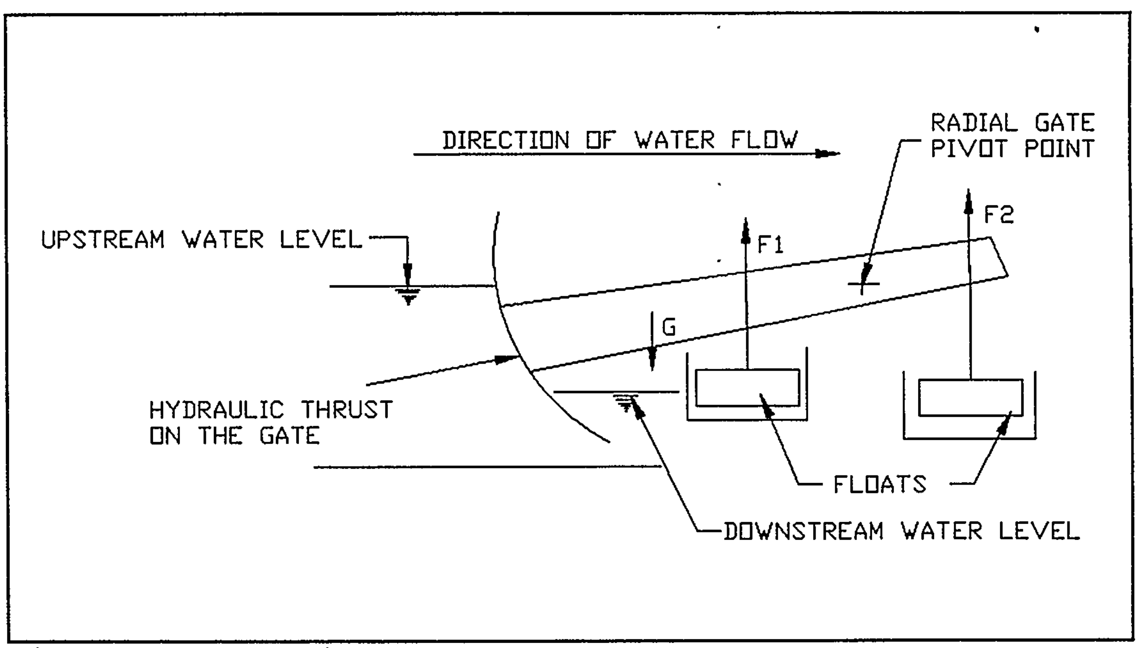


Figure 5 Schematic of the Neyrtec type gates

5 shows a schematic of the Neyrtec gate.
The Neyrtec gates are available in three configurations. These are the AMIL upstream water level control, AVIS and AVIO downstream water level control and composite control gates for flow control.

3.3.2.2 Dual Acting Controlled Leak Floating Control

Clemmens (1987) describes the operation of the Dual Acting Controlled Leak system (DACL). This control system offers precise control and uses no power. The justification for the use of this type of control system as stated by Clemmens is that:

> "In general, existing water-level control devices for canal gates are capable of controlling water levels to within about 20 to 30 mm. Canal flow rate control devices can generally control flow rates to within 5 to 10%. In many cases, this level of control is not precise enough for the regulation of a flexible irrigation delivery system. To date, electrical control devices have not demonstrated a better ability to control water levels than mechanical devices."

The DACL controller is shown in Figure 6. This apparatus includes two valves which control the water level in the float chamber. The valves are installed in a stilling well. As the level in the stilling well rises valve A opens and valve B closes. This has a net effect of adding water to the float chamber thus closing the gate. If the water level falls valve A closes and valve B opens thus lowering the level in the float chamber and raising the gate. At the desired water level no change of water level in the float chamber is required, thus valve A lets in only as much water as can be discharged by valve B.

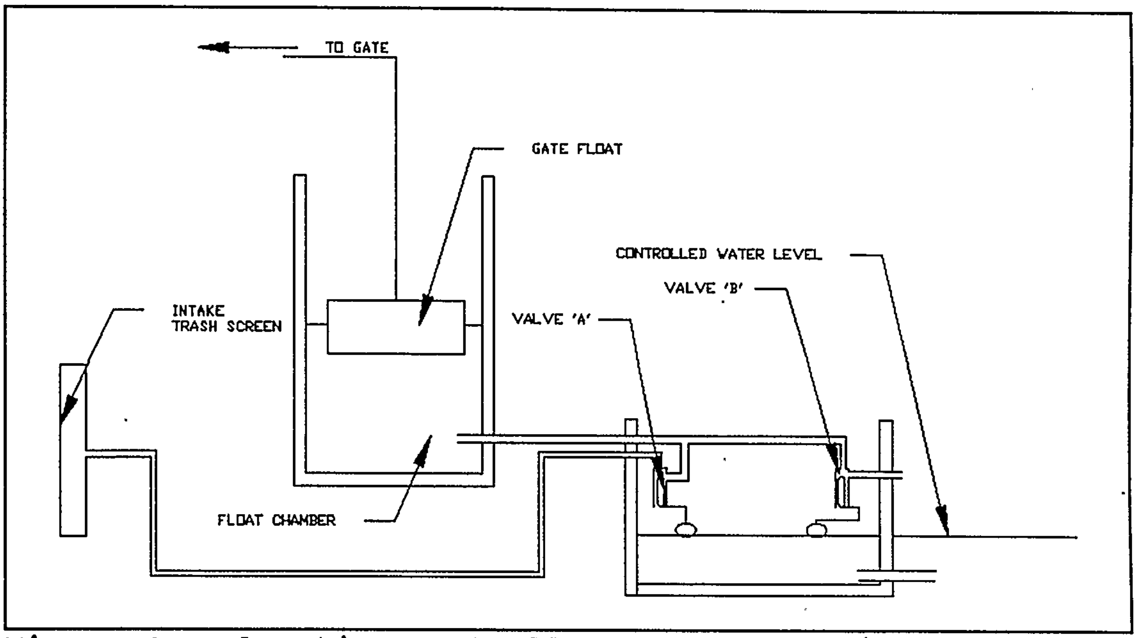


Figure 6 Dual Acting Controlled Level Operation

Clemmens reports that the DACL controller system can maintain water levels to +- 2 mm, and that generally any initial overshoot is within +- 2 mm.

This exceedingly close regulation of water level is very impressive. However this regulation of water level only occurs near the sensor. Control of the water level to within these tolerances may not occur anywhere else in the reach. The DACL controller is of a continuous nature and should indeed control water levels to a much finer degree than the discretized electronic controllers. The reason for this is that discrete electronic controllers only make adjustments after a preset deadband is reached.

3.3.2.3 Littleman (SOT/SRT) Floating Controls

Floating controls which control the gate indirectly replace most of the hydraulic equipment with electronic. This electronic equipment usually includes limit switches, timers and electric motors.

When the water level deviates from a preset level by a predetermined amount the gate is adjusted. This adjustment occurs at a predetermined rate. The amount by which the water level is allowed to deviate from the preset level is referred to as the deadband. Continuous adjustment is allowed outside of the deadband until the water level either returns to within the deadband or the fully opened or fully closed gate positions are reached.

It is interesting to note that according to the USBR (1973) "there are very few successful applications of unmodified single speed floating controls on Reclamation projects". Typically the motors used to automate these types of structures reacted too fast. Nelson (1980) indicates that a rapidly moving control gate will behave like a two position controller. The water surface will cycle about its preset level and the gate will reverse directions frequently. Designers of these gates have modified these gates using timers. The timers modify the control action by allowing the gate to operate a predetermined time then stopping all gate movement for a predetermined time. This sequence is repeated continuously. This type of controller is referred to as the set operate time/set rest time (SOT/SRT) controller. The net result of this type of controller is a slowing of the gate movement. Nelson notes that " a completely stable gate position for uniform flow is seldom achieved by this modification because, as the gate moves a predetermined amount in each cycle, it seldom arrives at the exact position required." He further states that a controller which makes two small adjustments per hour is usually considered satisfactory.

Two types of Littleman control cited in the USBR (1973) are the Columbia Basin type and the Friant Kern type. Each of these controllers function similarly despite the differences in design. Both controllers are float controllers modified using SOT/SRT.

Gray describes the operation of the Columbia Basin type Littleman. (Figure 7) This operation is summarized as follows:

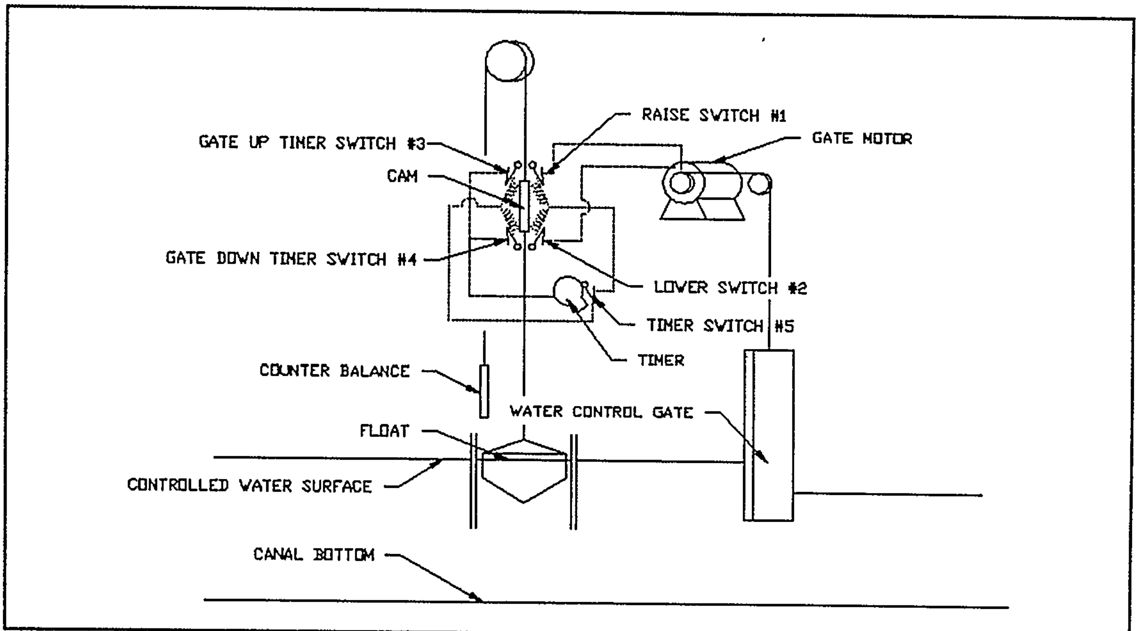


Figure 7 Operation of Littleman Controller

- When cam rises due to rising water level, the raise microswitch, 1 and the timer microswitch 3, are closed. The time actuates microswitch 5 so that in conjunction with microswitch 1 the motor operates a preset time during any period.

- When the cam falls due to falling water level, the lower microswitch 2 and the timer microswitch 4 are closed. Again the timer actuates microswitch 5 so that in conjunction with microswitch 2 the gate operates only a preset amount of time during the period.

The ratio of operating time to non operating time is set depending on the length of the upper pool; the head difference between the upper an lower pool and the discharge.

Gray found that while the above setup eliminates most of the oscillation, in some pools the closing of the gate caused velocity shock waves or surges which cause fluctuations in the water surface. These surges affected the operation of the gate. By allowing a longer gate closing time these fluctuations were minimized. Figure 8 shows this modification. The difference between this and the previous setup is the addition of a timer. Thus microswitch 3 and 4 instead of activating the same timer activate different ones to give a different gate opening and closing rate.

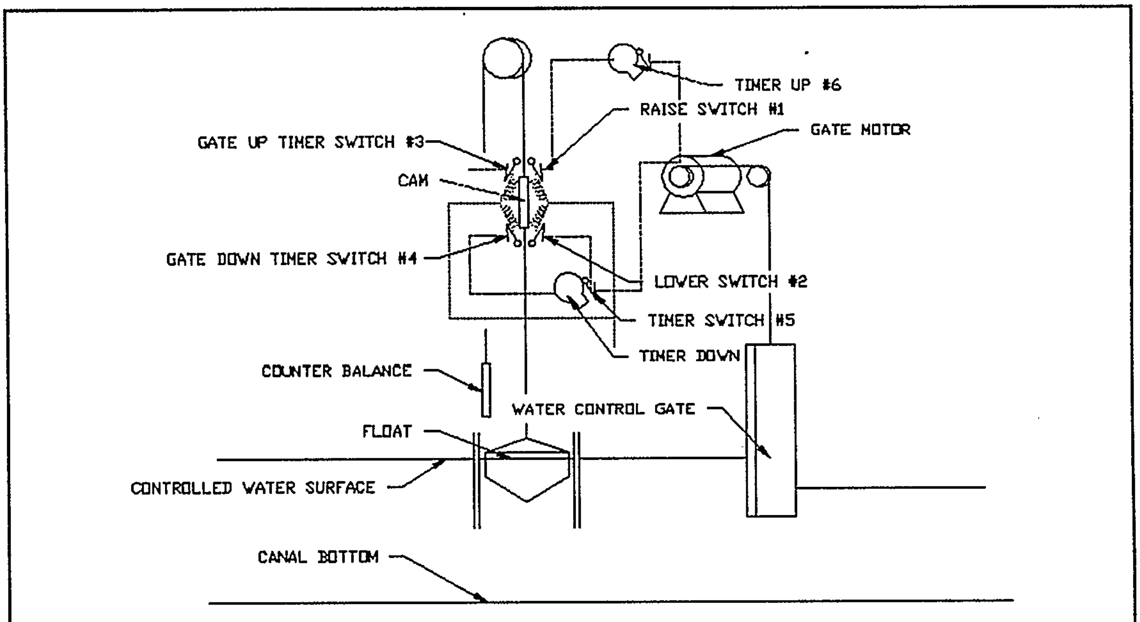


Figure 8 Littleman Controller UP/DOWN Timer Modification

Gray made one more modification to the Columbia Basin type Little Man. At the downstream end of the Columbia Basin small short pools exist. These pools experienced surges due to changes in flow. It was found that the Little Man as previously described was not sensitive enough to disengage from the microswitches, thus overshooting the desired water level. The modification as shown in Figure 9 was made. The modification and operation of this system is described by Gray as follows:

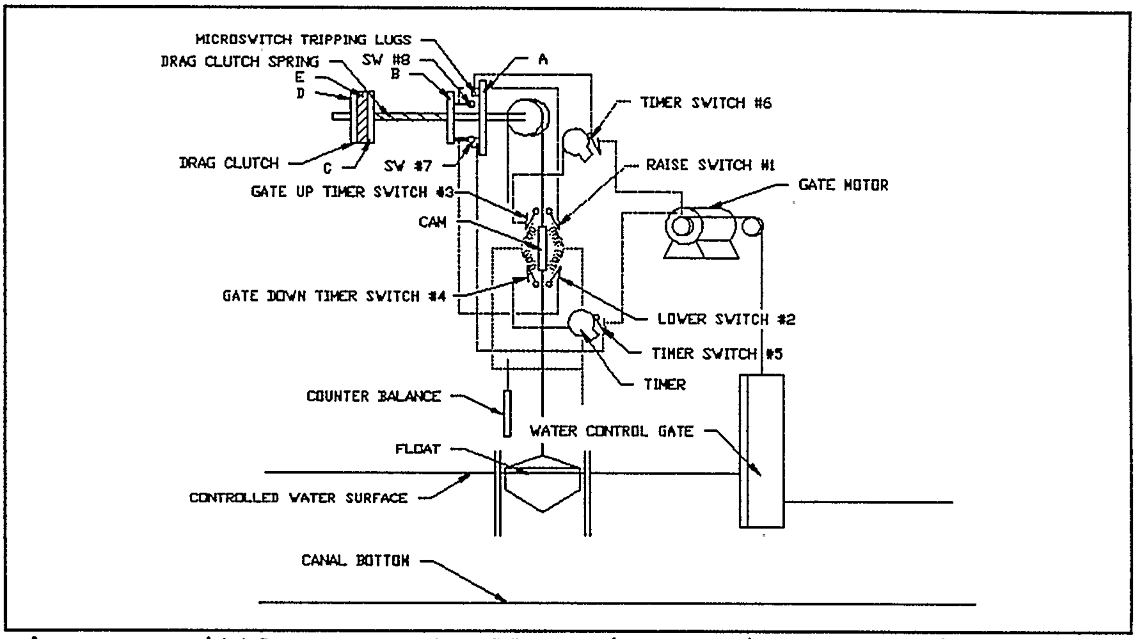


Figure 9 Littleman Controller with Anti Hunt Device

The pulley (A) supporting the float, tape, cam and counter-balance was mounted, free to rotate, on a stationary shaft and positioned by use of collars fixed to the shaft for alignment. Microswitch tripping lugs were welded to one face of the pulley. A separate circular plate (B) free to rotate on the same shaft was mounted opposite the pulley and separated from it by a collar. Microswitches (7) and (8) were attached to this plate. Also on the same shaft a drag clutch was installed which allows motion of the circular plate but stops residual motion when motivating force is removed. The drag clutch arrangement consists of a spring located between the circular microswitch plate and free to rotate pressure plate (C) separated from a stationary collar plate (D) by a fibrous clutch plate (E). The loading of the spring is adjusted by changing the position of the stationary collar plate (D) using a set screw. The operation of the control device is as follows:

When the water surface in the canal is being raised, the float actuated pulley rotates to a position that causes the proper tripping lug to close gate opening microswitch (7) which in series with microswitch (1) causes the gate to open effecting a loss of water in the pool. When the point is reached where the pool begins to lose elevation, microswitch (7) is immediately opened by the reversal action of the pulley and even though microswitches (1) and (3) are still closed, there is not gate action. As the pool continues to lower, microswitch (8) becomes closed but no gate action takes place until the vertical cam causes microswitches (2) and (4) to close. (Gray)

Other modifications made to these floating type controllers includes proportional speed controllers, and set operate time/variable rest time (SOT/VRT) controllers.

The proportional speed controller incorporate variable speed motors. As the water level moves farther away from the set point the rate on control action increases. As the water level approaches the set point the rate of control action decreases.

The SOT/VRT controllers strongly resemble proportional control according to the USBR (1973). These controllers increase the width of the deadband each time the gate moves. Increasing the deadband results in the variable rest time of the controller.

The floating control type mechanisms offer coarse regulation of canal flows. Although the SOT/VRT controller resembles the action of a proportional controller it is very difficult to implement the reset and rate actions on these controllers. These actions further refine the movement of the controller to more accurately adjust the water level to the preset level.

3.3.3 Proportional Control

Using proportional control, the output of the controller is directly proportional to the error. The action of the proportional controller may be described mathematically as:

$$C=K_p e$$

Where:

Where:	C	is the control action
	K_p	is the controller proportionality gain constant
	e	is the error between the desired and the actual water level

For high accuracy and rapid response high values of K_p must be used. As most systems contain delay elements, (inertia of a rotating load) too high a value of Kp will cause instability. The cause of the instability is due to the delay elements causing a swing from positive to negative correction values. In most cases this instability will decrease with each positive to negative transition, eventually settling to a steady state. In other cases however, the positive to negative swings may not diminish and may actually grow in magnitude (Figure 10). This situation is not desirable.

3.3.4 Proportional + Reset Control

Two types of Proportional + Reset control exist. These are the classical Proportional + Integral controller and the EL-FLO controller. Both controllers may be configured as an upstream level, downstream level or flow rate controller.

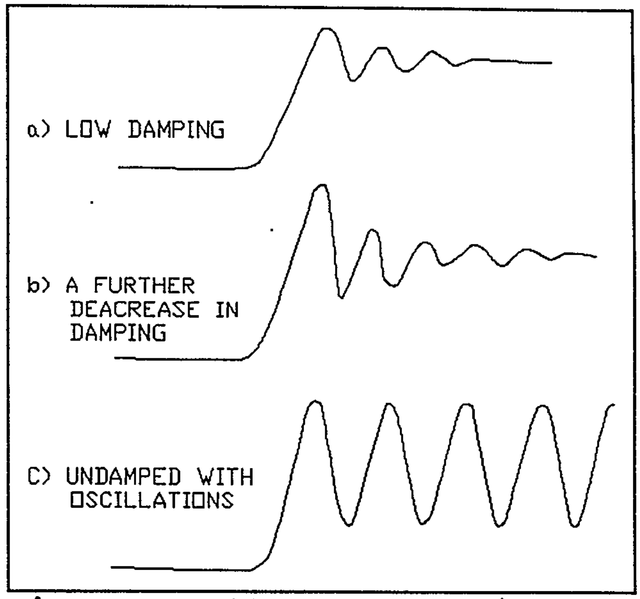


Figure 10 Effects of Damping

The differences in operation of between the two controllers are subtle. In both the classical and EL-FLO controllers the Proportional + Reset control (Proportional + Integral) controls the water level based on the current error between the actual water level and the desired water level plus the summation of all of the errors to that point in time. However the result of this calculation is interpreted differently. The EL-FLO controller interprets the result as an actual gate position. The classical approach interprets the result as a correction in gate position. These interpretations present two different philosophies for the automatic control of irrigation conveyance systems. The first philosophy controls the gate directly as in the EL-FLO controller. The second uses the error in water levels to calculate a gate movement which will bring the actual water level closer to the desired water level. This philosophy, in essence, controls the water level.

The following discussion describes both the classical control method and the EL-FLO control method.

3.3.4.1 Proportional + Reset Control

Integral control is proportional to the integral of the error. This is expressed as:

$$C = K_i \int e \, dt$$

Where: C is the correction term
K_i is the integral proportionality constant
e is the error
t is the time increment.

This equation may be expressed in terms of discrete events as follows:

$$C = K_i \sum e \, \Delta t$$

Where: C is the nth control action
K_i is the integral proportionality constant
e is the error at time step i
dt is the sampling time step

Integral control will make corrections as long as any error exists.

This type of control is usually used in conjunction with proportional control as described in 3.3.4 above. This is written as:

$$C = K_p e + K_i \int e \, dt$$

Together this control action provides a faster initial response to changes in the system than just proportional control. Settling time is also improved, however, there is an initial tendency to overshoot the setpoint.
The above equation has also been written in the form:

$$C=K_p\left(e+\frac{1}{T_r}\int e\,dt\right)$$

Where: T_r is the reset time.

The reset time has special significance in that it is the time it takes for each repeat of proportional action. For example, if a step change in error occurs at time zero and the error remains constant, the change in output would then be:

$$C=K_p\left(e+\frac{1}{T_r}\sum e\Delta t\right)$$

At time zero the response of the controller is Kp e. At time one the response is 2 Kp e and so on. The response is for this function is shown in Figure 11.

3.3.4.2 EL-FLO Proportional + Reset Control

Proportional + reset controllers have been researched extensively by Buyalski. Buyalski's first attempt at automating a canal gate was the Hydraulic Filter Level Offset (HyFLO) controller. It was found, however, that operation of this controller caused the hydraulic filter to become inoperative due to water and air transported debris. To alleviate this the Electronic Filter Level Offset (EL-FLO) controller was developed. The EL-FLO controller substitutes hydraulic level filters of electronic ones.

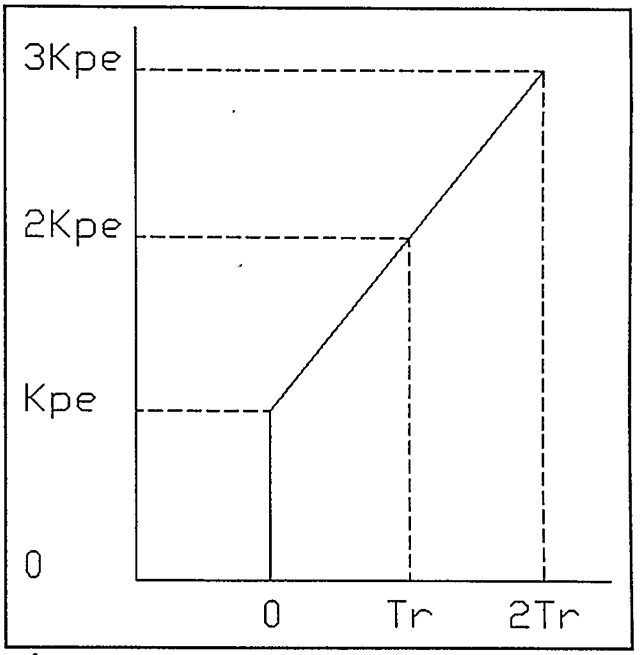


Figure 11 Controller response to Tr.

Buyalski (1979) describes the use of an EL-FLO controller for the Yuma desalting plant. Figure 12 shows the upstream proportional + reset controller used in this project. The operation of this controller is as follows:

- The water level is sensed by YWELL and is fed into the water level filter. This filter eliminates any short duration water fluctuations.

- The output from the water level filter is YF.

- The proportional gate position (GP) is calculated by comparing the actual water level (YF) to the preset water level (YT) and multiplying by a gain factor, K1.

- The reset gate position (GR) is calculated by summing (YF-YT) over time and multiplying by the gain coefficient K2. If the difference (YF-YT) is within the reset controls deadband (RDB) no summation takes place.

- The required gate position is calculated by adding GP+GR.

- The change in gate position (Δ G) is calculated by subtracting the required gate position from the actual gate position (GA)

- ΔG is fed into the gate position controller if Δ G is greater than the gate movement deadband (GDB) then the gate is moved by the amount Δ G.

The water surface level YWELL is modified to eliminate the frequent changes in water elevation which may be caused by wind action, waves due to gate movements etc. The filtering action may be accomplished hydraulically as shown in Figure 13. The capillary tube dampens water level changes in the filter well, thus eliminating short duration fluctuations in water level. In the EL-FLO system the capillary tube and filter well are replaced by analog electronic equipment which simulate these components actions.

Buyalski (1979) has also seen the need to incorporate gate deadband modifications into the EL-FLO system. These modifications are a result of frequent gate movements occurring during steady state flow. This type of behaviour drastically reduces the life of the gate control machinery. Buyalski describes the operation of the GDB modification as follows:

> " The gate movement deadband, GDB, is not actually changed. The gate, however, is not allowed to travel the full distance of the deadband, GDB. If the gate movement direction is opposite to the last gate movement, the gate travel distance is reduced by 5 percent. The 5 percent reduction continues as long as each gate movement is in the opposite direction of the previous gate movement until a minimum value of 40 percent of the deadband, GDB, is reached."

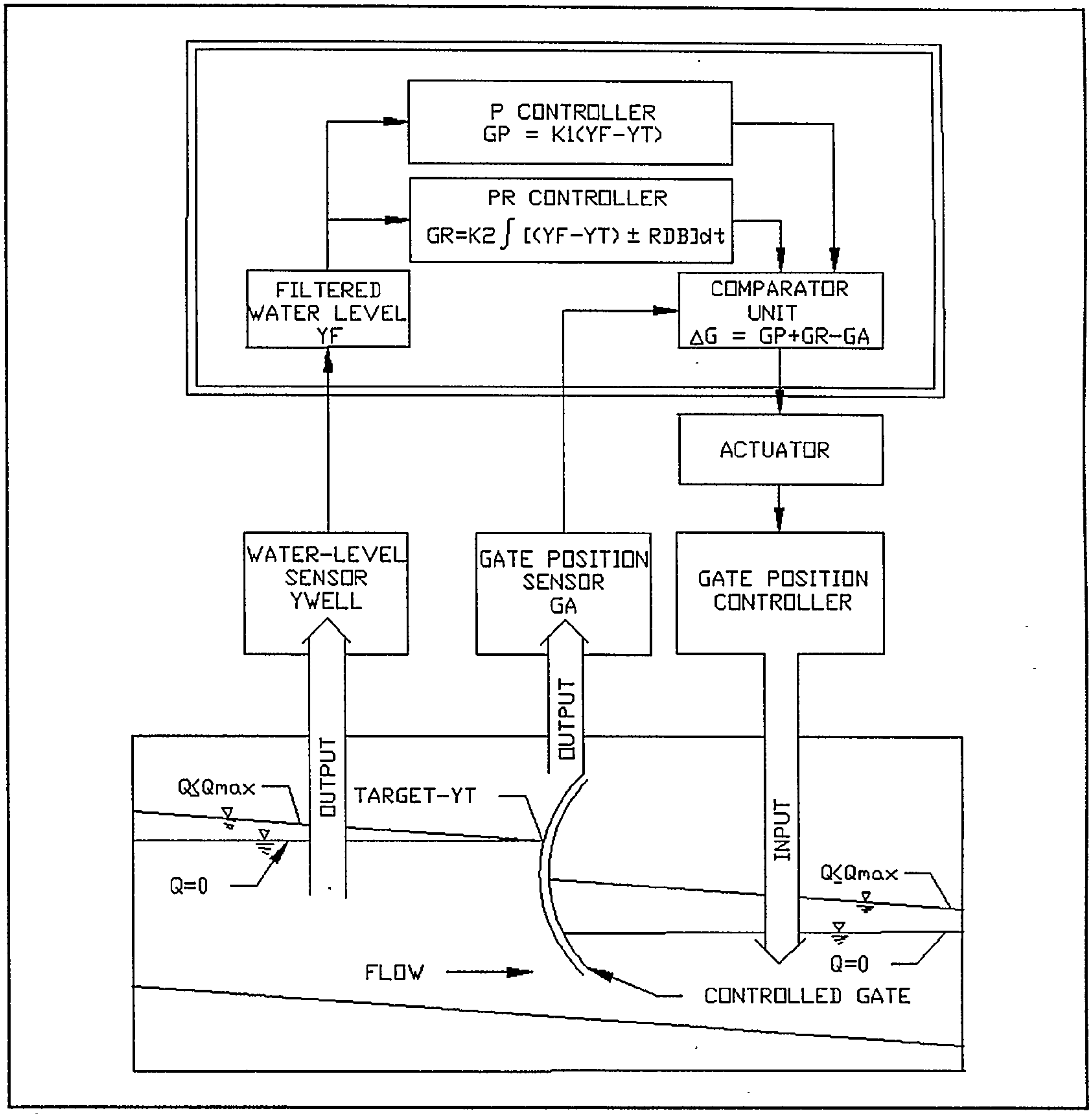


Figure 12 Upstream Proportional Control (Buyalski 1979)

This gate controller algorithm with its modifications has been implemented in the field. For the most part this controller seems to control the water surface sufficiently.

The filtering out of the reset action until it is within the reset deadband has the effect of slowing the initial response to a disturbance. As the reset action will dominate near the

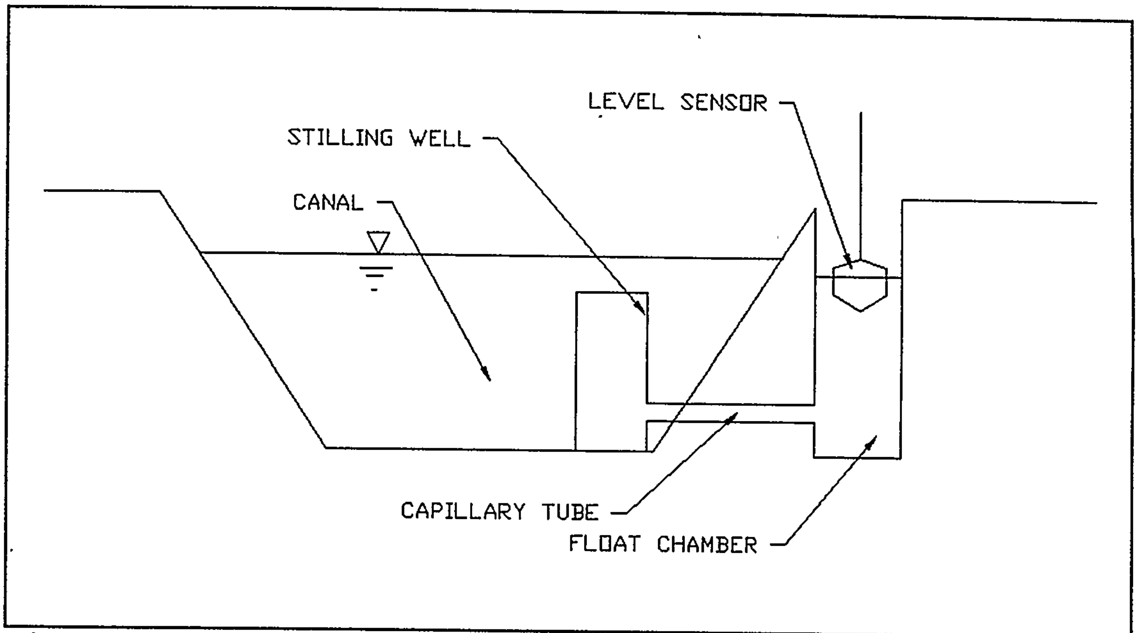


Figure 13 Hydraulic depth sensor damping (Buyalski 1979)

preset water level, there is no need to turn the reset action on and off. Indeed as previously stated, leaving the reset action on may enhance the overall operation of the controller.

3.3.5 Differential Control

Differential control controls the rate of correction. Differential control is expressed as:

$$C = K_d \frac{de}{dt}$$

Initially when a disturbance is sensed in the system the control correction is very large. As the controller reaches the setpoint the rate of change of error becomes small, thus reducing the rate of change of the control correction. This essentially produces a damping. This damping effect minimizes overshooting of the set point.

Similar to the integral control the differential control is usually used in conjunction with proportional control. This may be expressed as:

$$C=K_p e+K_d \frac{de}{dt}$$

This combination provides a fast initial response to changes in the system as well as a damping effect once the error becomes small. The constants K_p and K_d must be chosen carefully so that the differential portion of the control is dominant when small errors exist.

3.3.6 Combination Proportional + Integral + Differential

By combining all the above control methods a system with quick initial response to a disturbance, continuous adjustment around the setpoint and a damping of the rate of the controller near the set point occurs. The constant values of K_p, K_d and T_r however, will not be identical to those chosen for the separate control actions. Additionally these constants must be chosen so that the integral and differential controls dominate near the setpoint. Thus the value of K_p and T_r will typically be lower and K_d will be higher than that for the separate control actions.

3.3.7 Rate Control (C.A.R.D.D. Controller)

The Canal Automation for Rapid Demand Deliveries (CARDD) system was developed by Burt (1983). This system was tested on both short and long canal reaches using the USM, Unsteady flow computer program from the U.S.B.R.

The CARDD system uses measurements from multiple sensor locations within a reach to control the gate movements. The levels recorded from each sensor are analyzed using a linear regression algorithm. The water elevation as calculated by this algorithm is used to calculate the rate of change of water surface. Depending on the rate of change of water surface and the elevation of the actual water surface the controller either makes no movement, very slow, slow, moderate, fast moderately fast or very fast movements. This type of controller action is essentially that of rate control.

Underwood McClellan Associates (UMA) has adopted a modified version of this controller for use in southern Alberta. Installations of this controller have been made on the Saint Mary's River Irrigation District (SMRID) canals. Details of the modifications to this controller were unavailable at the time of this writing.

3.4 SUMMARY

All of the automatic controllers discussed are closed loop systems. The actions of the controllers are based on the measured upstream, downstream or a composite of water levels. The actions of the controllers differ from a purely On-Off nature to continuously adjustable. The water level measurements used to control the actions of the controller may be either passive (floats connected to gate), active (water level actually measured in a single location) or composite (many water levels measured resulting in a single water level number). All of the controllers studied, with the exception of the classical automatic controls, have been used on actual irrigation or drainage systems.

Of interest in evaluating automatic controllers is the quality and range of control. The quality of control refers to the ability of an automatic structure to maintain a preset water level or flow rate. The range of control refers to the ability to maintain a specific quality over a range of differing flow rates and water levels. It should be noted that the range of control is not only a function of the automatic controller but also of the hydraulic characteristics of the structure. All of the automatic controllers studied gave either in qualitative or quantitative terms an indication of the quality of control. None of the studied controllers gave any indication as to the range of control, other than the particular projects studied.

In order to select and justify (operationally or economically) an automatic controller the quality and range of control must be evaluated. While, as always, controller characteristics may be gleaned from existing projects and applied to future projects, a definitive basis for selection of one automatic control structure over another based on quality and range of control is nonexistent.

With the recent advancement of computer systems and irrigation conveyance system simulations it has become possible to simulate the actions of automatic controllers. Indeed, as with the EL-FLO controller this has already been done. No known initiative to date, however, has endeavoured to use computer simulations for the comparison, evaluation and justification of automatic controllers at specific sites.

4.0 METHOD OF AUTOMATIC CONTROLLER DEMONSTRATION

The automatically controlled structures which are to be compared all attempt to maintain the upstream water depth at a specified level. The gate responds, based on the automatic controller algorithm, to water levels which differ from that specified. This gate response is done in an attempt to control the upstream water level. It should be noted that although the gate position is modified in response to the upstream water level, no attempt should be made to control the gate. Instead, the gate is being moved to control the upstream water level.

In order to simulate the actions of automatic controllers a fully dynamic open channel conveyance system simulation must be used. This is due to the fact that the upstream water level is being controlled. To evaluate how well the upstream water level is being controlled, and thus the response of the different automatic controllers, all hydraulic phenomonen which can occur up and downstream of the controller must be simulated. For this reason the Irrigation Conveyance System Simulation (ICSS 2) computer model was chosen.

The ICSS 2 computer simulation model is a fully dynamic open channel flow simulation. This model simulates the flow of water within an open channel conveyance system and the effects which control structures have on that flow. These effects include storage upstream of a checking or flow limiting structure and flow surges due to rapid changes in the structures position. Additionally, hydraulic structures and automatic controller logic can also be easily added, modified and disabled using the ICSS 2 model.

4.1 IRRIGATION CONVEYANCE SYSTEM HISTORY

The first version of the Irrigation Conveyance System Simulation (ICSS) was developed by Dr. David Manz beginning in 1982. The original motivation for the development of this model was to give management, designers and operators of canal systems the opportunity to operate and evaluate the performance of their canal systems using computer simulations. In order to accomplish this goal hydraulic structures were programmed to operate similarly to the actual system. As well, the structures are easily inserted into the framework model. The latest innovation to the model has been the development of automatically controlled structures.

The original ICSS model was developed in BASIC using a micro computer. It was soon found that these micro computers were inadequate for solving the St. Venant equations using the four point implicit method. The ICSS model thus evolved into the world of mainframe computers. Rewritten in FORTRAN, the ICSS model now runs on the CYBER 860 computer.

4.2 IRRIGATION CONVEYANCE SYSTEM SENSITIVITY ANALYSIS

Manz (1985) examines the sensitivity of the model on three dependent parameters. These parameters are the time increment, the distance increment and the finite difference weighting parameter.

Increasing the time increment had the effect of shifting the hydrograph to the right as shown in Figure 14. This shift could become significant for larger time increments greater than 0.05 hrs and the simulation would take far to much computer time for time increments less than 0.05 hours. Thus a time increment of 0.05 hours was chosen for our simulations of automatic controllers.

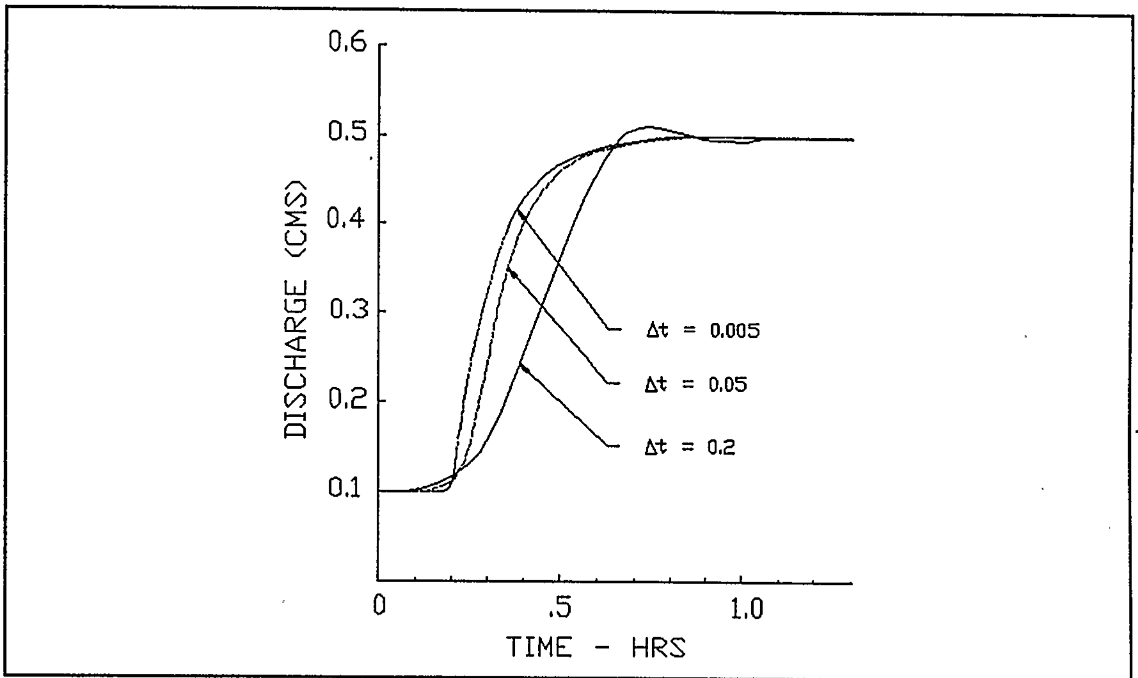


Figure 14 Variation in outlet hydrographs in response to a positive step change in the inlet of the canal. (MANZ 1985)

The distance increment chosen affects the accuracy of the solution and the stability of the model. Figure 15 shows the hydrographs using three different distance increments. The largest distance increment exhibits signs of instability. This instability is due to the inaccuracy of the solution during the simulation. The model used to test the controllers was configured such that its operation would be very stable and accurate. For these experiments the distance increment was set to approximately 16 meters.

If the finite difference weighting factor is 0.5 then the numerical procedures in the flow routing subroutine of the ICSS 2 model is fully centered and theoretically stable. Manz (1985) showed that in reality if the finite difference weighting factor is greater than 0.5 the model would then become stable. This is shown in Figure 16. A finite difference weighting factor of 0.55 was used for these numerical experiments.

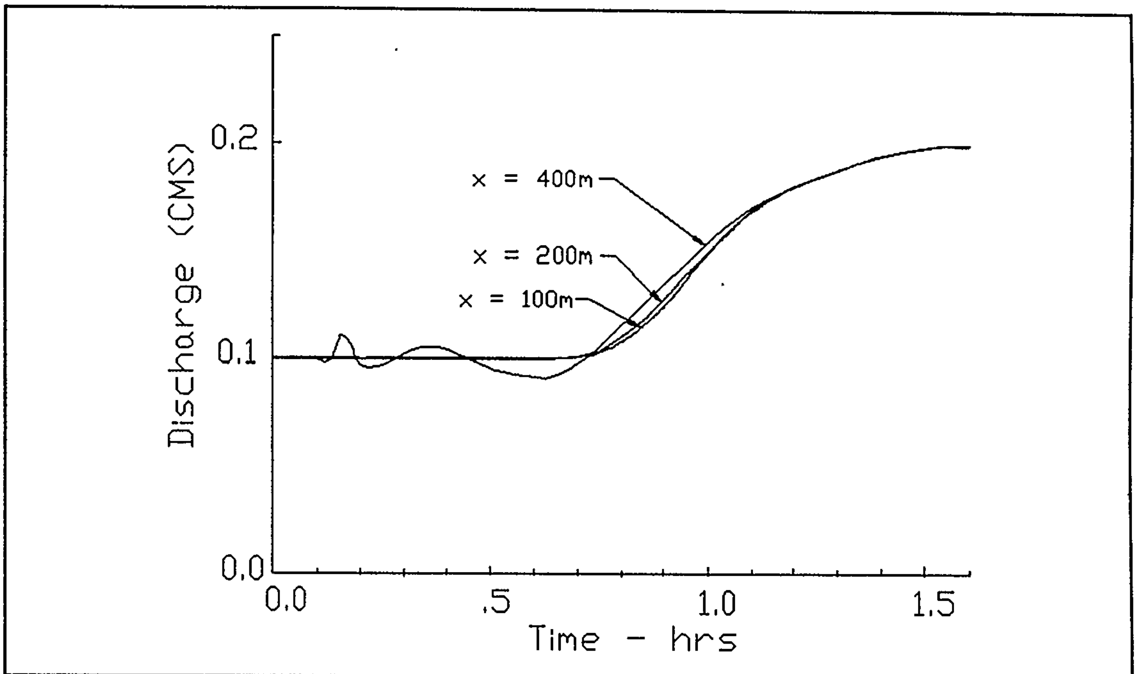


Figure 15 Variation of outlet hydrographs from canal in response to a positive step change in the inlet of canal. (MANZ 1985)

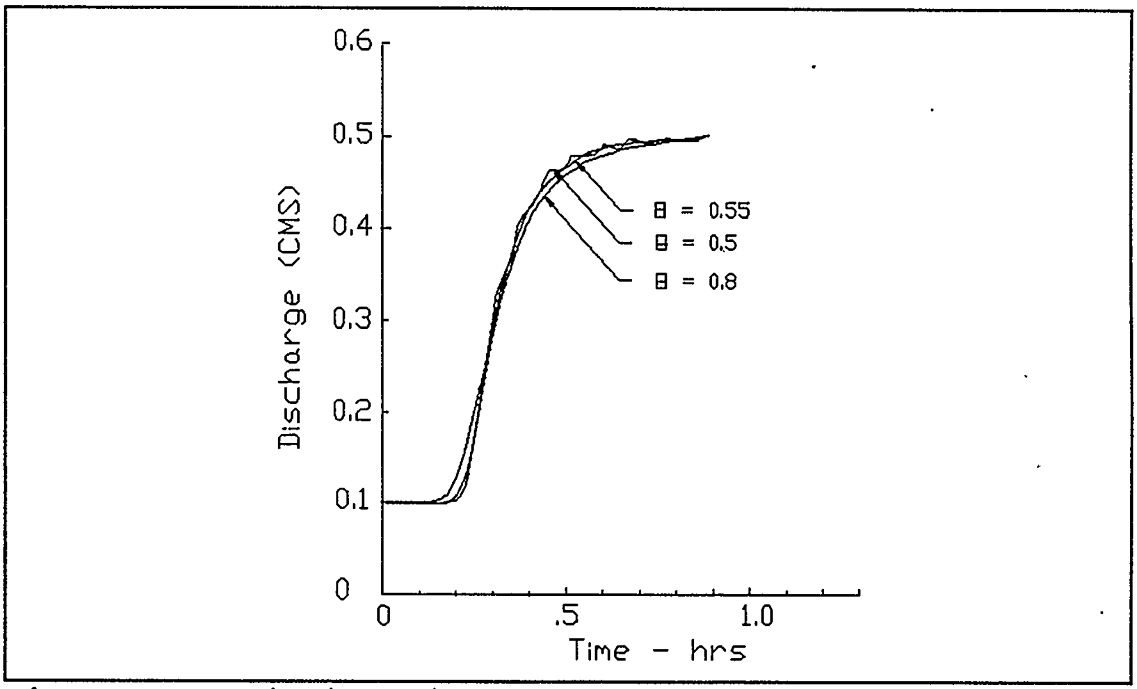


Figure 16 Variations in outlet hydrographs from canal in response to a positive step change in inlet hydrograph. (MANZ 1987)

4.3 Automatic Controller Algorithm Sensitivity.

The automatic controller algorithms are only sensitive to the time increment. The time increment dictates the minimum length of time that a controller must operate before another water level reading, and subsequent controller operation correction can occur.

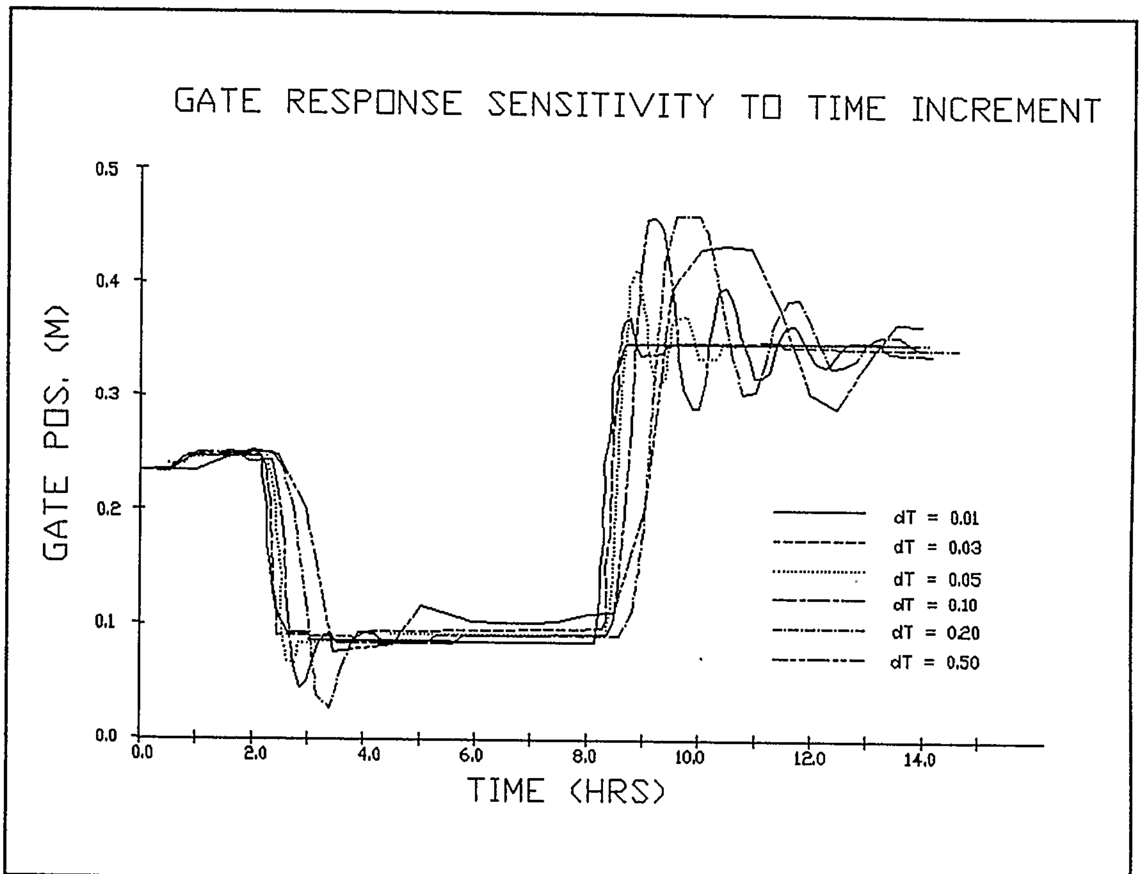


Figure 17. Variations in gate response due to a disturbance at the inlet canal for varying time increments.

Figures 17 and 18 show the effects of different time increments on the operation of the gate and the upstream water level response.

As expected the water level hydrograph shifts to the right as time increment is increased. This shift is partially due to the shift encountered in the time increment discussion of section 4.2. Some of this shift to the right may be attributed to the fact that the gate may not be operated at any time which is less than or not a multiple of the time increment.

As the time increment increases it is also noted that the water level and gate responses become peakier. This increase in peakedness may be explained in terms of the time increment in that once a particular gate operation is invoked this operation is obliged to persist until the next time increment. The longer the time increment, the longer the gate operation persists without being updated. Thus the gate may drastically overshoot or undershoot the desired position.

The purpose of this thesis is to compare the operation of different automatic controllers. As long as the comparison takes place on an equal basis (i.e. the time increment is the same in all experiments) the relative response of the controllers can be ascertained. We must, however, use a time increment which is reasonable for our experiments. The time increment (0.05 hrs) as chosen in section 4.2 is still appropriate when viewed within the context of automatic gate operations.

Changes in the flow and depth of canal systems usually take place in terms of hours. The sampling time increment is 0.05 hrs (3 minutes) which translates to 20 samples every hour. It is felt that this time increment is appropriate for two

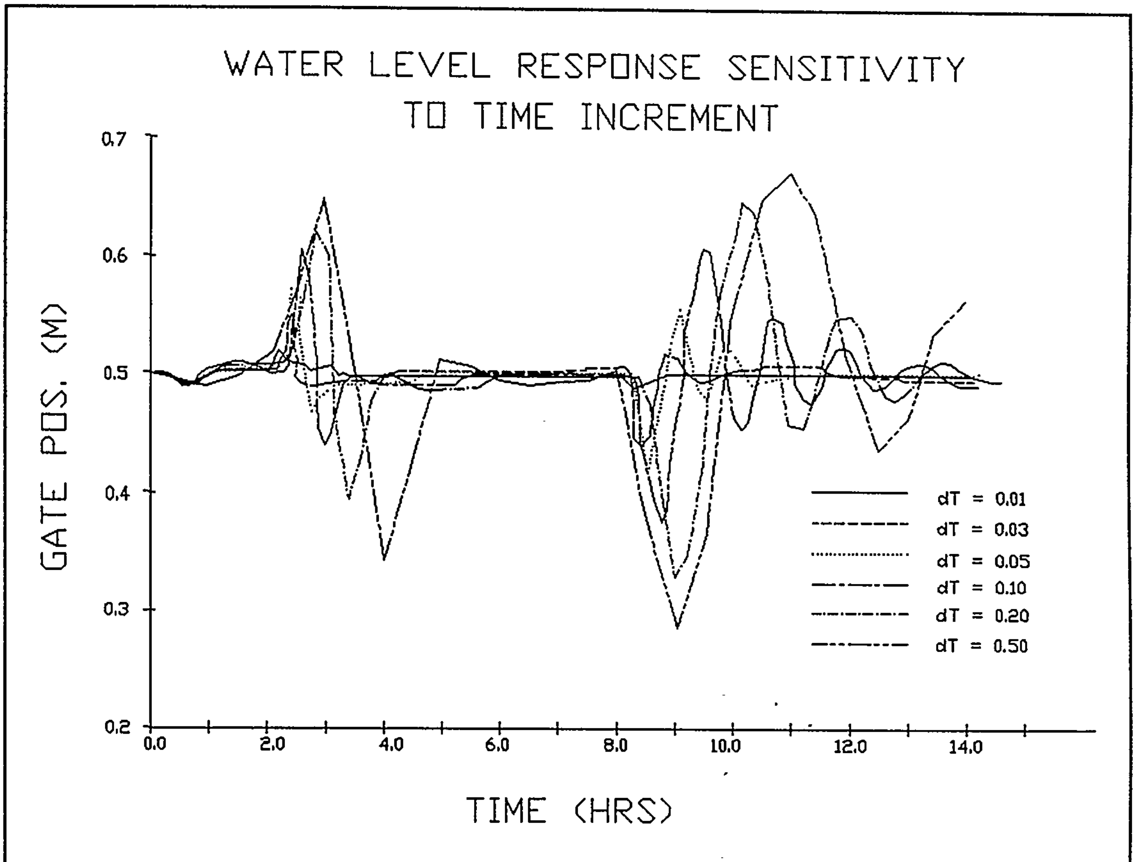


Figure 18 Variation in water level response due to gate adjustments and a disturbance at the inlet for varying time increments.

reasons. These are:

1. Real time sampling requires the collection of many water level readings. These readings are averaged over a specified time period. Sampling intervals of 1 to 5 minutes are not uncommon.

2. Mechanical considerations dictate that the gate control motors not stop and start too frequently. This stopping and starting shortens the life of the motor considerably. The generally accepted number of starts and stops of a motor is 10 per hour. The sampling rate we are using (20

per hour) is twice that; allowing 50% more operations than would be considered acceptable.

5.0 DESCRIPTION OF EVALUATED AUTOMATIC CONTROLLERS

The controllers which are to be compared are the Littleman, EL-FLO and Proportional, Integral and Differential (PID) controller. The algorithms used to simulate these controller types are described below. All controllers are simulated using the overshot pivoting weir as a means of controlling the water level.

5.1 THE OVERSHOT PIVOTING WEIR

The overshot pivoting weir is shown in Figure 19. This type of weir has been extensively used in irrigation projects in Southern Alberta. This structure consists of a winch assembly connected to the top end of the overshot pivoting weir. The bottom of the overshot pivoting weir is connected to a pivot at the bottom of the control structure. The winch raises and lowers the weir, like a draw bridge, in order to control the upstream water depth. In the fully upright position the weir behaves hydraulically like a sharp crested weir. In the downward position the hydraulic characteristics of the weir resemble that of a broad crested weir. It is assumed, for these simulations, that the winch assembly consists of an electric motor which may be controlled by the respective controllers. The maximum speed of the electric motor - winch assembly is simulated as part of the automatic controller operation. The maximum speed of the controller's gate cable is set at 0.5 metres per minute. (See Fig 19). Due to the nature of the gate, the height of the weir crest from the canal bottom could not be used as a rate control. The use of the weir crest as a rate control would require a variable speed electric motor-winch assembly.

The winch assembly unit can be controlled in one of two ways. The first mode of control is used in conjunction with the

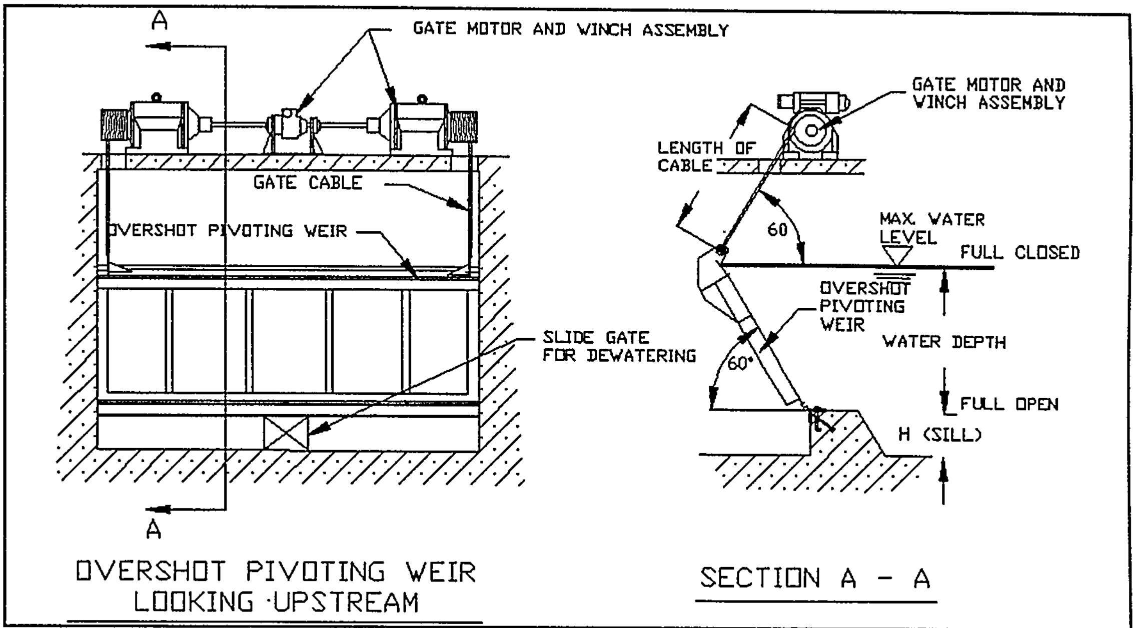


Figure 19. Overshot Pivoting Weir

Littleman controller. This control mode accepts as input an instruction to move the gate up (1), down (-1) or not to move the gate at all (0). When the gate is engaged with a "move gate up or down command" the gate will be adjusted at a rate as dictated by the maximum rate of wire travel. The algorithm for this mode of control is presented in Figure 20. The length of the cable in (1) Figure 20, is calculated taking into account the maximum rate of cable travel and the up-down timer settings.

The second mode of control can be used in conjunction with the EL-FLO and PID controllers. Both of these controllers send the change in the height of the weir crest required. a negative number indicates the raising of the weir crest. An adjustment of zero indicates that no movement of the weir crest is to take place.

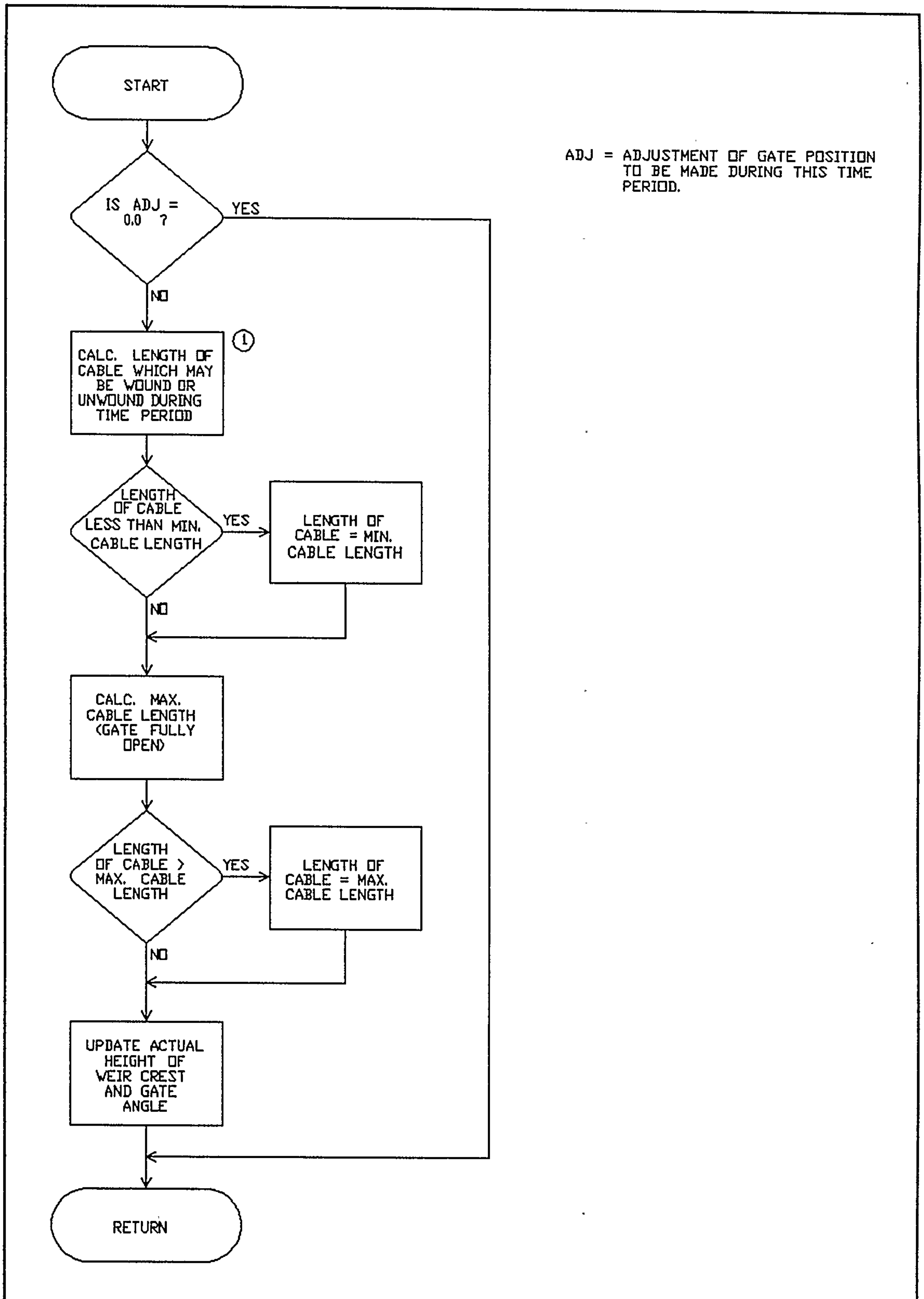


Figure 20 Littleman motor and winch algorithm

The maximum allowable adjustment in (1) Figure 21 of the weir crest height is calculated based on the maximum rate of cable travel. If the adjustment required is greater than the maximum allowable, the gate is only moved to the maximum allowable adjustment. If the adjustment required is less than the maximum allowable, the gate is moved the required amount. Figure 21 presents the algorithm for this mode of control.

5.2 LITTLEMAN CONTROLLER

The Littleman controller is simulated as described in section 3.3.2.3 The simulation of the Littleman controller includes the up and down timer switch as well as the anti-hunt device. All of these modifications may be individually selected so as to configure the Littleman controller to any variation previously described.

The timers may be individually set for on operating time in terms of percent. For example if a timers are set to 60%, the timer would be ON 60% of the time and OFF 40%. (ON 36 seconds and OFF 24 seconds every minute). Setting both timers to 100% has the effect of operating the Littleman control in its unmodified mode (i.e. no timers).

The Anti Hunt Device may be set either ON or OFF. If the Anti Hunt Device is set to ON, the operation of the drag clutch, micro switch assembly shown in Figure 9 is simulated.

The Littleman controller setpoint can be specified. The setpoint is the depth at which we are trying to control the water level. At this depth the gate should not be engaged in either an upward or downward motion. Small disturbances, however, in the water level may cause the gate to be activated. For this reason a deadband is specified. The deadband is a region around the setpoint in which the water

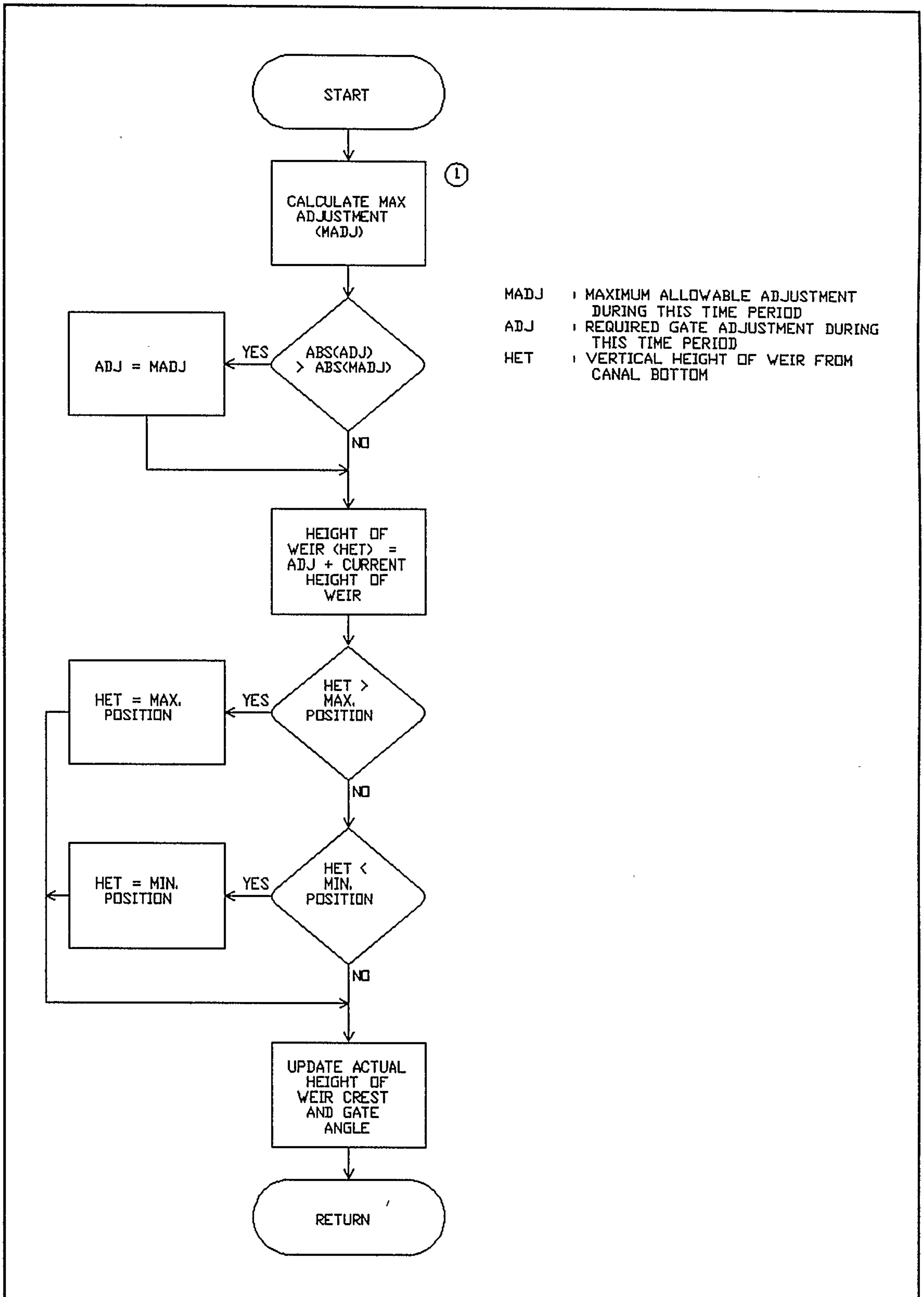


Figure 21 PID and EL-FLO motor and winch algorithm

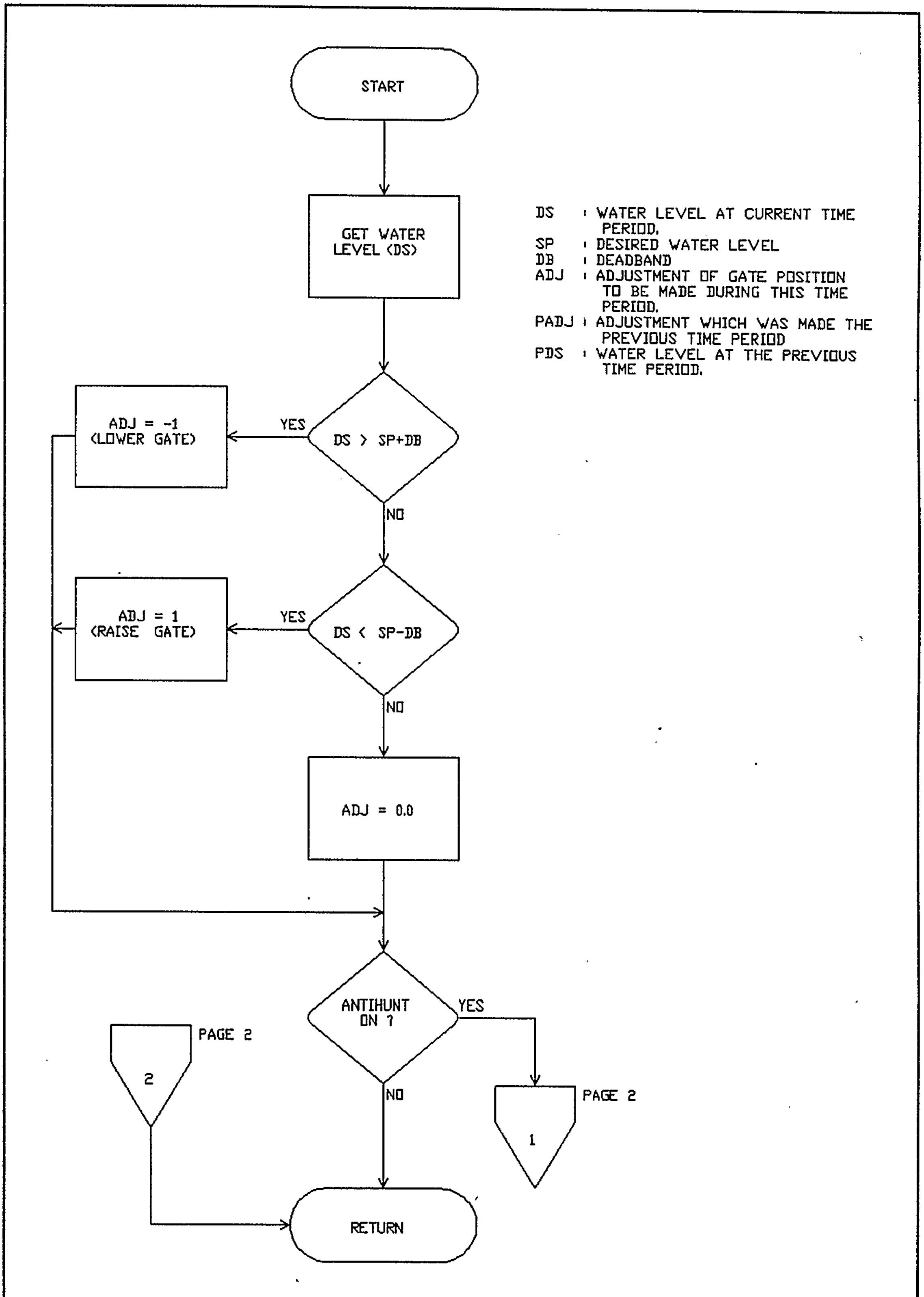


Figure 22A Littleman Controller Algorithm (Page 1)

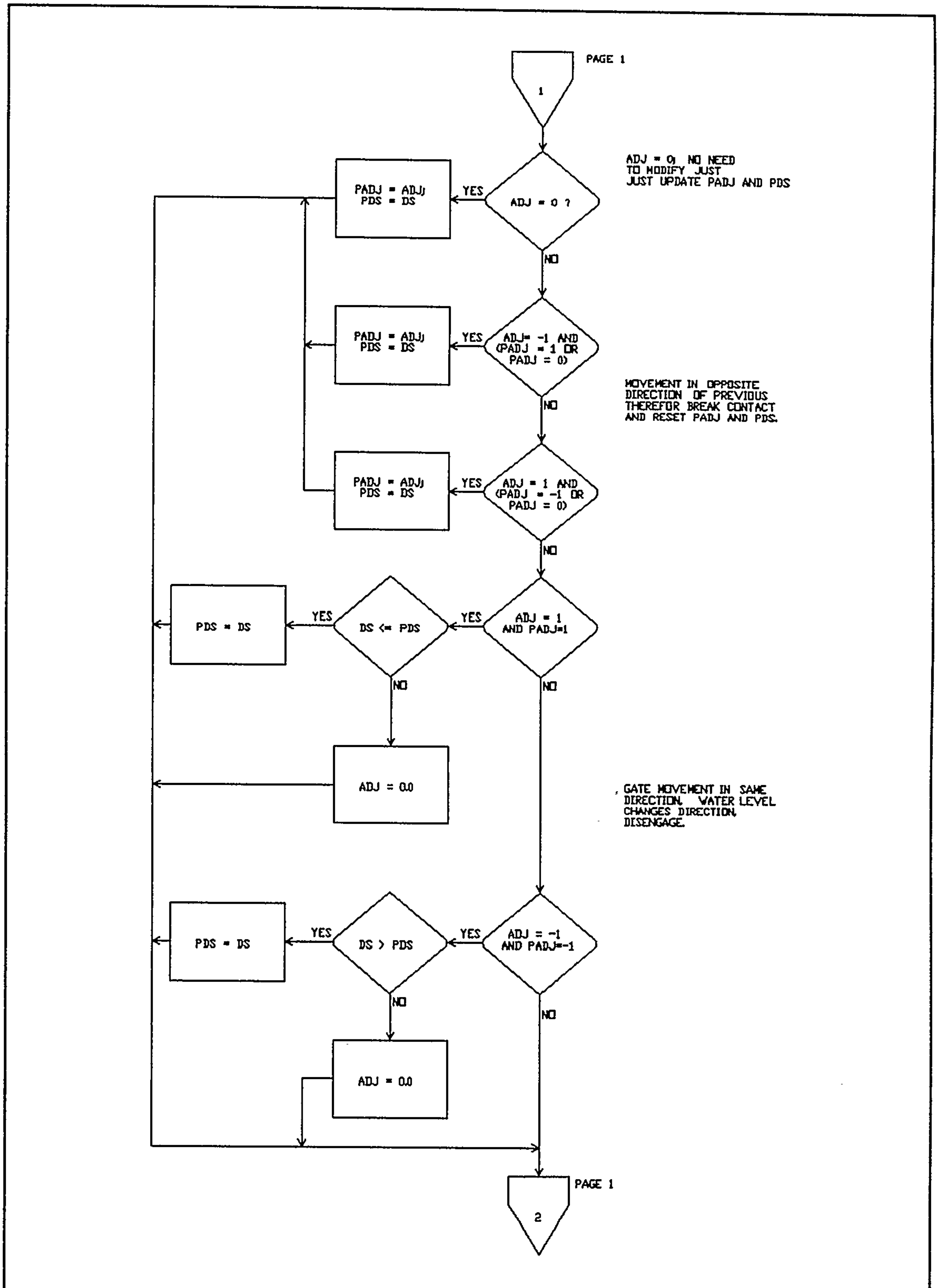


FIGURE 22B Littleman Controller Antihunt Device Algorithm (Page 2) level is allowed to fluctuate without engaging the gate. The deadband may be specified as a distance from the setpoint. For example if the setpoint is 0.500 metres and the deadband is 0.030 metres, the water level will be allowed to move from 0.470 to 0.530 without any movement of the gate occurring.

The algorithm used to simulate the behaviour of the Littleman controller is presented in Figure 22A and 22B.

5.3 EL-FLO CONTROLLER

The EL-FLO controller has been simulated as described in section 3.3.5.2, including the reset deadband and the gate deadband modifications. The reset and gate deadbands may be set individually. The gain factors K1 and K2 may also be set independently. If K2 is set to zero, then this effectively turns the reset portion of the controller off.

The algorithm used to simulate the behaviour of the El-Flo Controller is presented in Figure 23A and Figure 23B.

5.4 PROPORTIONAL, INTEGRAL AND DIFFERENTIAL (PID) CONTROLLER

The Proportional, Integral and Differential (PID) controller has been designed to have the ability to simulate Proportional control only (Section 3.3.4), Proportional + Reset (Integral) (Section 3.3.5.1) , Proportional + Differential (Section 3.3.6) and the full Proportional + Integral + Differential controller (Section 3.3.7). The gain constants are denoted K_p, K_i and K_d and are the Proportional, Integral and Differential gain constants respectively. The different modes of operations may be simulated by setting the respective gain constants to zero. (For example if one wishes to simulate a proportional controller only, the constants K_i and K_d are set to zero.) The reset time constant T_r is included in the controller. This constant is set to 1 in most cases. Adjustment of the reset time constant has a reciprocal effect to changing the integral constant K_i.

The algorithm used to simulate the PID controller is presented in Figure 24.

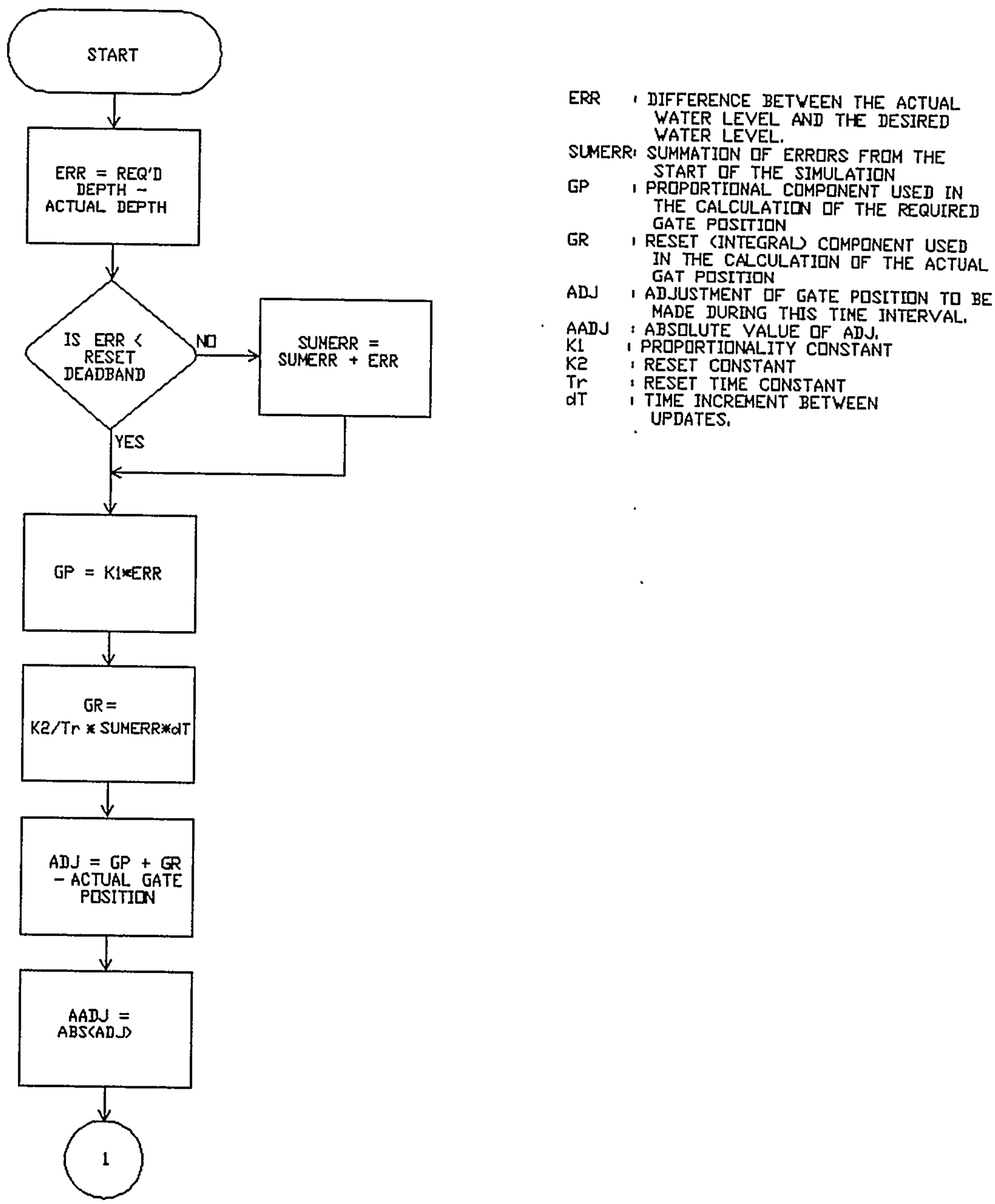


Figure 23A EL-FLO controller algorithm. (Page 1)

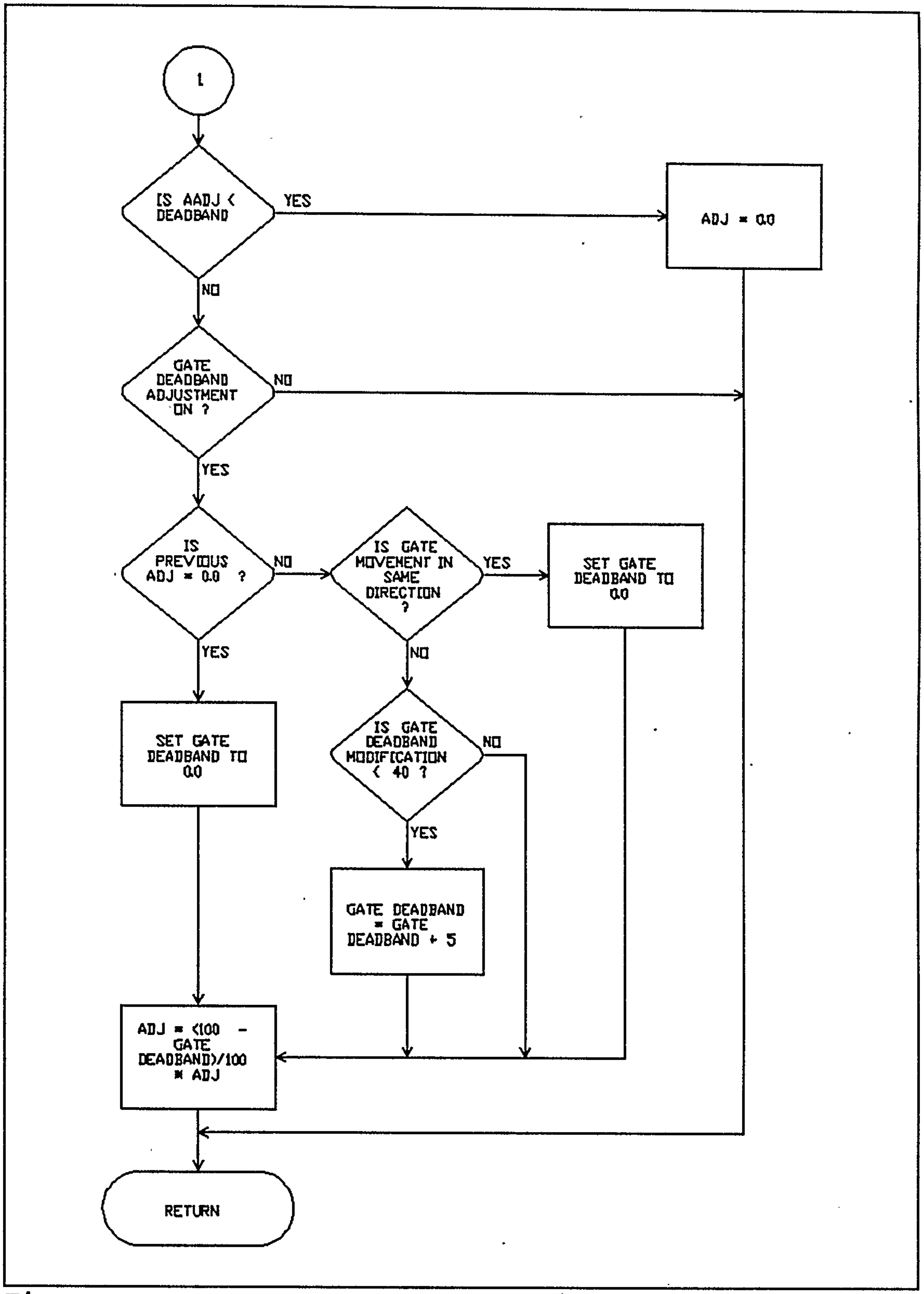


Figure 23B EL-FLO controller alogorithm (Page 2)

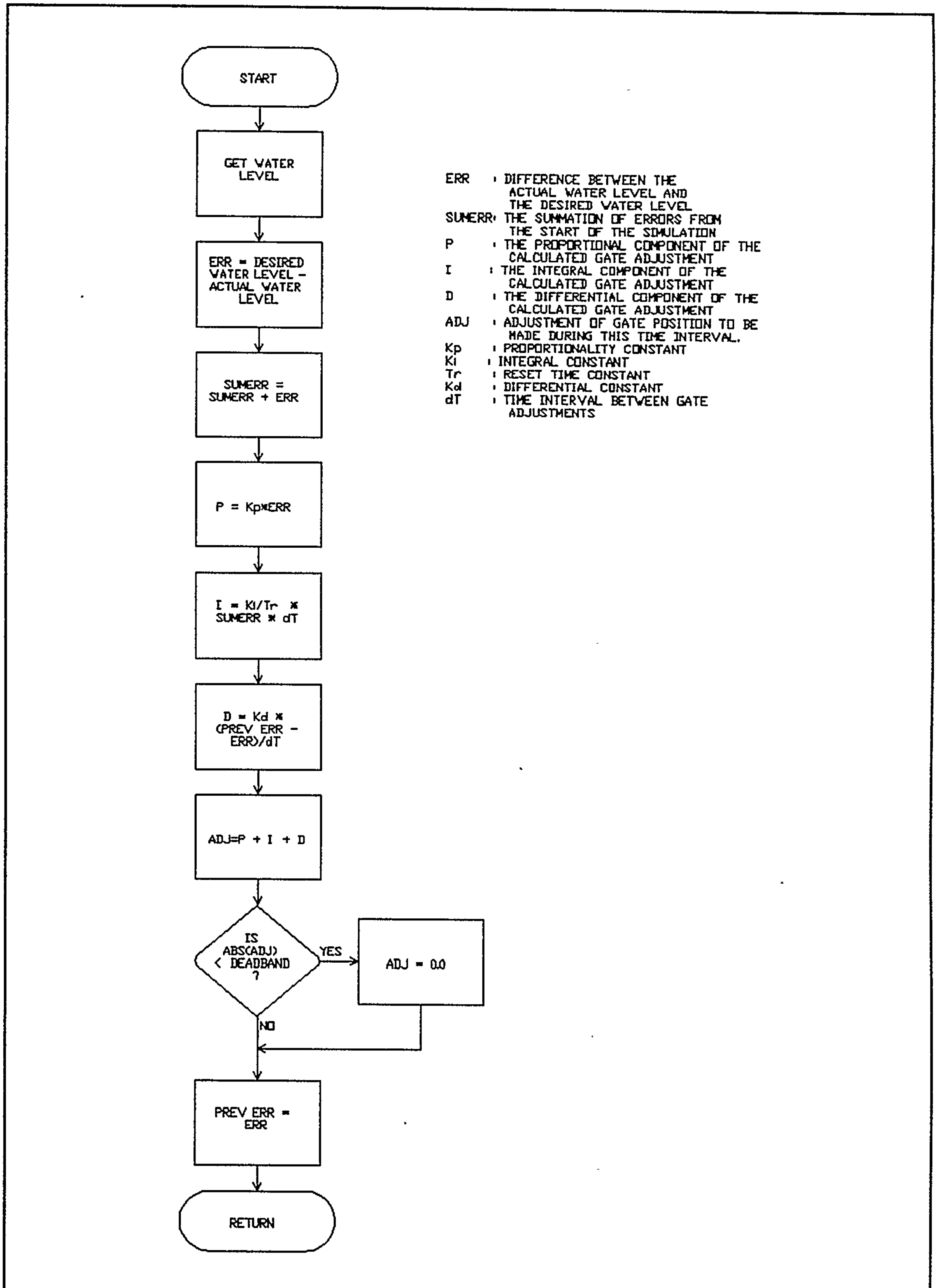


Figure 24 PID Controller Algorithm

6.0 METHOD OF ANALYSIS

All numerical experiments were carried out with the automatic controller using the same canal system characteristics. The flow into the canal is varied to test the reaction of the controller. The following sections describe the canal system, controller parameter settings and canal inlet variations used in this investigation.

6.1 TEST CANAL SYSTEM

The automatically controlled overshot pivoting weir was tested, in its different modes of operation, using a small canal as shown in Figure 25. The reach parameters used for the test canal are given in Table 1.

Table 1 Canal section 1 parameters

Description	Reach 1	Reach 2	Reach 3
Length	500 m	500 m	500 m
Canal Bottom Width	0.5 m	0.5 m	0.5 m
Side Slopes	3:1	3:1	3:1
Mannings 'n'	0.020	0.020	0.020
Slope	0.001	0.001	0.001
Seepage	NONE	NONE	NONE
U/S Canal Structure	RESERVOIR	N/A	N/A
D/S Canal Structure	CHECK-TURNOUT	OVERSHOT PIVOTING WEIR	CHECK - TURNOUT

All numerical experiments were run on this canal section except for the very last ones. The last numerical experiments were designed to demonstrate the effectiveness of the automatically controlled pivoting weir on the delivery through an upstream farm turnout. An additional short reach is added with a farm turnout as shown in Figure 26. The parameters

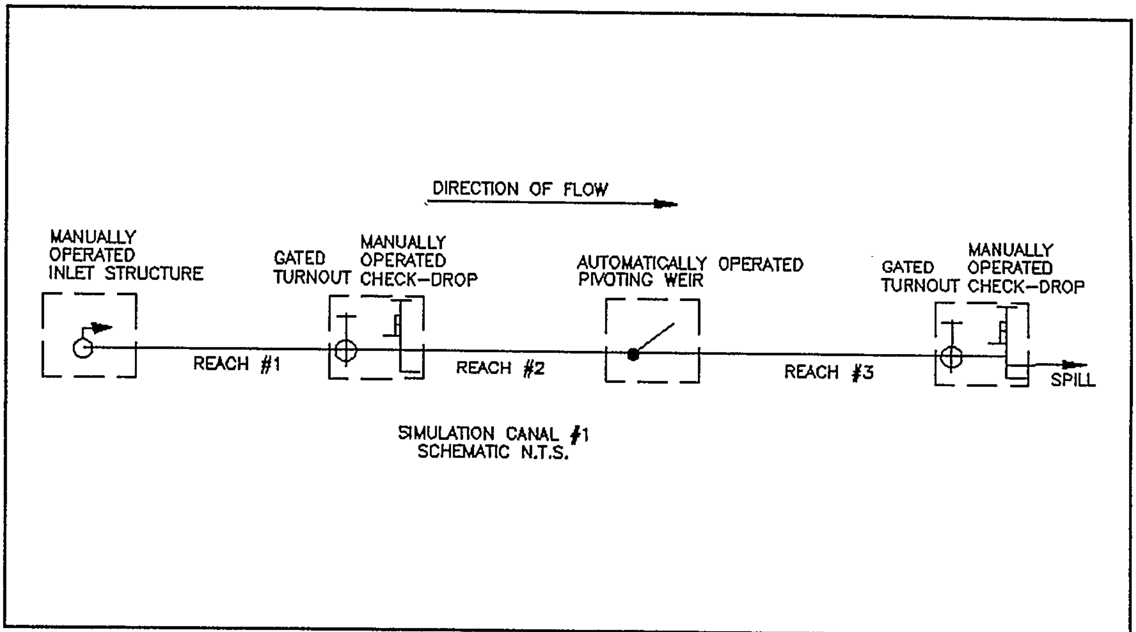


Figure 25 Test Canal Schematic Type 1

used for canal #2 are given in Table 2.

The canal chosen for these experiments is a small canal typical of distributary canals in southern Alberta. Typically these canal sizes are very sensitive to changes in control structures due to the relatively small amount of storage upstream of the structure. This small storage creates less of a damping effect for disturbances than larger amounts of storage would. This then essentially becomes an "acid" test for the controller in that the ability of the controller to quickly adjust and maintain the upstream water level may be rigorously evaluated.

6.2 CANAL INLET VARIATIONS

Numerical experiments were performed based on seven types of inlet variations. These inlet variation types are shown below:

Table 2 Canal Section #2 Parameters

DESCRIPTION	REACH 1	REACH 2	REACH 3	REACH 4
Length	500 m	490 m	10 m	500 m
Canal Bottom	0.5 m	0.5 m	0.5 m	0.5 m
Side Slopes	3:1	3:1	3:1	3:1
Mannings 'n'	0.020	0.020	0.020	0.020
Slope	0.001	0.001	0.001	0.001
Seepage	NONE	NONE	NONE	NONE
U/S Structure	RESERVOIR	N/A	N/A	N/A
D/S Structure	CHECK - TURNOUT	FARM TURNOUT	OVERSHOT PIVOTING WEIR	CHECK - TURNOUT

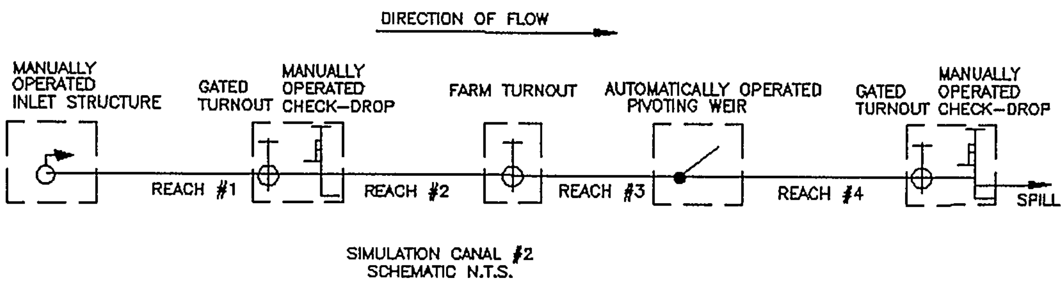


Figure 26 Test Canal Schematic Type 2

TYPE 1: USED EXCLUSIVELY WITH CANAL TYPE 1

SET INFLOW (U/S REACH 1) TO 0.2 m^3/S

RUN SIMULATION FOR 2 HOURS

INSTANTANEOUS INCREASE IN FLOW TO 0.4 m^3/S

RUN MODEL FOR 6 HOURS TO STABILIZE

INSTANTANEOUS DECREASE IN FLOW TO 0.1 m^3/S

RUN MODEL FOR 6 HOURS TO STABILIZE

TYPE 2: CANAL TYPE 2; SMALL INCREASE

SET INFLOW (U/S REACH 1) TO 0.3 m^3/S
RUN SIMULATION FOR 2 HOURS
INSTANTANEOUS INCREASE IN FLOW TO 0.35 m^3/S
RUN SIMULATION FOR 6 HOURS TO STABILIZE
INSTANTANEOUS DECREASE IN FLOW TO 0.30 m^3/S
RUN SIMULATION FOR 6 HOURS TO STABILIZE

TYPE 3: CANAL TYPE 2; SMALL DECREASE

SET INFLOW (U/S REACH 1) TO 0.3 m^3/S
RUN SIMULATION FOR 2 HOURS
INSTANTANEOUS DECREASE IN FLOW TO 0.25 m^3/S
RUN SIMULATION FOR 6 HOURS TO STABILIZE
INSTANTANEOUS INCREASE IN FLOW TO 0.30 m^3/S
RUN SIMULATION FOR 6 HOURS TO STABILIZE

TYPE 4: CANAL TYPE 2; SMALL INCREASE - SMALL DECREASE

SET INFLOW (U/S REACH 1) TO 0.3 m^3/S
RUN SIMULATION FOR 2 HOURS
INSTANTANEOUS INCREASE IN FLOW TO 0.35 m^3/S
RUN SIMULATION FOR 6 HOURS TO STABILIZE
INSTANTANEOUS DECREASE IN FLOW TO 0.25 m^3/S
RUN SIMULATION FOR 6 HOURS TO STABILIZE

TYPE 5: CANAL TYPE 2; LARGE INCREASE

SET INFLOW (U/S REACH 1) TO 0.3 m^3/S
RUN SIMULATION FOR 2 HOURS
INSTANTANEOUS INCREASE IN FLOW TO 0.50 m^3/S
RUN SIMULATION FOR 6 HOURS TO STABILIZE
INSTANTANEIOUS DECREASE IN FLOW TO 0.30 m^3/S
RUN SIMULATION FOR 6 HOURS TO STABILIZE

TYPE 6: CANAL TYPE 2; LARGE DECREASE

SET INFLOW (U/S REACH 1) TO 0.3 m^3/S
RUN SIMULATION FOR 2 HOURS
INSTANTANEOUS DECREASE IN FLOW TO 0.15 m^3/S
RUN SIMULATION FOR 6 HOURS TO STABILIZE
INSTANTANEOUS INCREASE IN FLOW TO 0.30 m^3/S
RUN SIMULATION FOR 6 HOURS TO STABILIZE

TYPE 7: CANAL TYPE 2; LARGE INCREASE; LARGE DECREASE

SET INFLOW (U/S REACH 1) TO 0.3 m^3/S
RUN SIMULATION FOR 2 HOURS
INSTANTANEOUS INCREASE IN FLOW TO 0.50 m^3/S
RUN SIMULATION FOR 6 HOURS TO STABILIZE
INSTANTANEOUS DECREASE IN FLOW TO 0.15 m^3/S
RUN SIMULATION FOR 6 HOURS TO STABILIZE

The Type 1 inlet variation is used exclusively for the evaluation of the overshot pivoting weir using canal system type 1 (3 reaches). Inlet variations type 2-7 are used to evaluate the performance of the overshot pivoting weir using canal type 2.

The range of operation of the automatically controlled overshot pivoting weir was tested in two ways. The first was by changing the controller parameters and evaluating the effects and the magnitude of the effects on the operation of the controller. The second way of testing the range of the controller was accomplished by changing the inflow rate keeping the controller parameters constant and evaluating the performance of the controller. Type 1 input was used to evaluate the range of controller operation using the first method. Input types 2-7 were used to evaluate the range of operation using the second method.

6.3 CONTROLLER PARAMETER SETTINGS

Using the Canal Inlet Variations as described above a number of numerical experiments were performed by varying the settings of each controller. Although only three controllers are modelled, five sets of numerical experiments are performed. This is due to the Proportional + Integral + Differential (PID) controller being treated as three different controllers. These three controllers are:

- Proportional
- Proportional + Integral (Reset)
- Proportional + Differential (Rate)

Controller settings for each of the automatic controllers are listed in Tables 3-7 below.

Table 3 Littleman Controller Parameters

Setpoint = 0.50 M
Deadband = 0.030 M
Rate of cable Travel = 0.5 M/min.

Controller Run #	Inlet Type #	Timer Up (%)	Timer Down(%)	Anti-Hunt Device
1	1	100	100	OFF
2	1	50	50	OFF
3	1	50	30	OFF
4	1	50	30	ON

A final set of numerical experiments were performed which are designed to evaluate the effectiveness of the PID controller subjected to various flow conditions. The effectiveness of the controller is measured in two ways; 1. using graphical and mathematical analysis as before, 2. evaluating the quality of the water delivery to a farm turnout upstream of the automatic PID controller. The difference in the effectiveness of automatic control was evaluated for two different situations.

One of high checking (0.65 m) and low checking (0.45 m). The parameters used for these experiments are listed in Table 8.

6.4 GRAPHICAL ANALYSIS

The gate position, upstream water depth and desired water level are plotted for every numerical experiment performed. This type of analysis provides visual indications about the performance of the automatic controller. Visual cues include the determination of smoothness of operation, evaluation of stability; including damping, controller response time, water level response to controllers actions. Comparing the controller graphs within controller types can give an indication of the optimal controller settings and range of operations. Comparison of the controller graphs across controller types can give an indication of the applicability of controller for use in a particular situation.

6.5 MATHEMATICAL ANALYSIS

A computer program was written which uses the numerical information used to plot the graphs to analyze, mathematically, the response of the automatic controller. The response of the automatic controller was evaluated using three criterion. These criterion are:

- Maximum water level overshoot from the desired level
- Maximum water level undershoot from the desired level
- Summation of the error from the desired level squared.

Table 4. EL-FLO Controller Parameters

Setpoint = 0.50 m
Deadband = 0.005 m
Rate of Cable Movement = 0.5 m/min.

Controller Run #	Inlet Type #	K_p	K_i
1	1	0.1	0.0
2	1	1.0	0.0
3	1	2.0	0.0
4	1	5.0	0.0
5	1	3.0	0.0
6	1	3.0	0.1
7	1	3.0	0.5
8	1	3.0	1.0
9	1	3.0	2.0

Table 5. Proportional Controller Parameters

Setpoint = 0.50 m
Rate of Cable Movement = 0.5 m/min.

Controller Run #	Inlet Type #	K_p	K_i	K_d	T_r	Deadband
1	1	0.10	0.00	0.00	1.0	0.005
2	1	0.50	0.00	0.00	1.0	0.005
3	1	1.00	0.00	0.00	1.0	0.005
4	1	2.00	0.00	0.00	1.0	0.005
5	1	5.00	0.00	0.00	1.0	0.005
6	1	0.10	0.00	0.00	1.0	0.010
7	1	0.50	0.00	0.00	1.0	0.010
8	1	1.00	0.00	0.00	1.0	0.010
9	1	2.00	0.00	0.00	1.0	0.010
10	1	5.00	0.00	0.00	1.0	0.010
11	1	0.10	0.00	0.00	1.0	0.025
12	1	0.50	0.00	0.00	1.0	0.025
13	1	1.00	0.00	0.00	1.0	0.025
14	1	2.00	0.00	0.00	1.0	0.025
15	1	5.00	0.00	0.00	1.0	0.025
16	1	1.50	0.00	0.00	1.0	0.010
17	1	3.00	0.00	0.00	1.0	0.010
18	1	4.00	0.00	0.00	1.0	0.010

Table 6. Proportional + Integral (Reset) Parameters

Setpoint = 0.50 m
Rate of Cable Movement = 0.5 m/min

Controller Run #	Inlet Type #	K_p	K_i	K_d	T_r	Deadband
1	1	0.10	0.10	0.00	1.0	0.005
2	1	0.50	0.50	0.00	1.0	0.005
3	1	1.00	1.00	0.00	1.0	0.005
4	1	2.00	2.00	0.00	1.0	0.005
5	1	5.00	5.00	0.00	1.0	0.005
6	1	0.10	0.10	0.00	1.0	0.010
7	1	0.50	0.50	0.00	1.0	0.010
8	1	1.00	1.00	0.00	1.0	0.010
9	1	2.00	2.00	0.00	1.0	0.010
10	1	5.00	5.00	0.00	1.0	0.010
11	1	0.10	0.10	0.00	1.0	0.025
12	1	0.50	0.50	0.00	1.0	0.025
13	1	1.00	1.00	0.00	1.0	0.025
14	1	2.00	2.00	0.00	1.0	0.025
15	1	5.00	5.00	0.00	1.0	0.025
16	1	1.50	1.50	0.00	1.0	0.010
17	1	3.00	3.00	0.00	1.0	0.010
18	1	4.00	4.00	0.00	1.0	0.010
19	1	2.00	2.00	0.00	0.5	0.005
20	1	2.00	2.00	0.00	1.0	0.005
21	1	2.00	2.00	0.00	2.0	0.005
22	1	2.00	2.00	0.00	0.5	0.010
23	1	2.00	2.00	0.00	1.0	0.010
24	1	2.00	2.00	0.00	2.0	0.010
25	1	2.00	2.00	0.00	0.5	0.025
26	1	2.00	2.00	0.00	1.0	0.025
27	1	2.00	2.00	0.00	2.0	0.025

Table 7. Proportional + Differential (Rate) Parameters

Setpoint = 0.50 m
Rate of Cable Movement = 0.50 m/min.

Controller Run #	Inlet Type #	K_p	K_i	K_d	T_r	Deadband
1	1	2.00	0.00	0.05	1.0	0.005
2	1	2.00	0.00	0.10	1.0	0.005
3	1	2.00	0.00	0.01	1.0	0.005
4	1	2.00	0.00	0.05	1.0	0.010
5	1	2.00	0.00	0.10	1.0	0.010
6	1	2.00	0.00	0.01	1.0	0.010
7	1	2.00	0.00	0.05	1.0	0.025
8	1	2.00	0.00	0.10	1.0	0.025
9	1	2.00	0.00	0.01	1.0	0.025
10	1	1.00	0.00	1.00	1.0	0.005
11	1	1.00	0.00	0.50	1.0	0.005
12	1	1.00	0.00	0.10	1.0	0.005
13	1	1.00	0.00	1.00	1.0	0.010
14	1	1.00	0.00	0.50	1.0	0.010
15	1	1.00	0.00	0.10	1.0	0.010
16	1	1.00	0.00	1.00	1.0	0.025
17	1	1.00	0.00	0.50	1.0	0.025
18	1	1.00	0.00	0.10	1.0	0.025

Table 8. Proportional + Integral controller parameters. Experiments on the effectiveness of controller on farm water delivery.

Rate of Cable Travel = 0.5 m/min.

Controller Run #	Inlet Type #	K_p	K_i	K_d	T_r	Set-point	Deadband
1	2	2.00	2.00	0.00	1.00	0.65	0.010
2	3	2.00	2.00	0.00	1.00	0.65	0.010
3	4	2.00	2.00	0.00	1.00	0.65	0.010
4	5	2.00	2.00	0.00	1.00	0.65	0.010
5	6	2.00	2.00	0.00	1.00	0.65	0.010
6	7	2.00	2.00	0.00	1.00	0.65	0.010
7	2	2.00	2.00	0.00	1.00	0.45	0.010
8	3	2.00	2.00	0.00	1.00	0.45	0.010
9	4	2.00	2.00	0.00	1.00	0.45	0.010
10	5	2.00	2.00	0.00	1.00	0.45	0.010
11	6	2.00	2.00	0.00	1.00	0.45	0.010
12	7	2.00	2.00	0.00	1.00	0.45	0.010

The maximum overshoot and undershoot were obtained simply by reporting the maximum and minimum values of water level for the entire simulation. The summation of errors squared (e^2) about the desired water level (setpoint) was calculated by subtracting each water level value from the setpoint and squaring the result. This number was then added to all of the other errors squared which had been calculated previously.

The maximum water level overshoot and undershoot evaluate the automatic controllers ability to respond and correct any disturbances which originate upstream. The summation of the error from the desired level squared evaluates the ability of the controller to respond and correct the upstream water level as well as the ability to maintain that water level.

Small values of the undershoot, overshoot and error squared terms, in itself, may not be an indication of good controller response. Other factors which are most easily obtained from graphical analysis such as oscillatory gate operation and smoothness of operation are also necessary to totally evaluate controller behaviour. In order for the mathematical evaluation to be meaningful the graphical analysis discussed in the previous section must be utilized.

7.0 PRESENTATION OF NUMERICAL EXPERIMENTS AND ANALYSIS

Numerical experiments were conducted as described above. The results of these experiments along with the analysis are presented in the following sections.

7.1 LITTLEMAN CONTROLLER

Figures 27 to 30 show gate movement as controlled by the Littleman controller, the upstream water level and the desired water level. When the ICSS model is first started, the water levels and gate openings are set for steady state flow. Recalling the type 1 inlet condition, our first major inlet flow variation does not occur until two hours into the simulation. These facts account for the stability of the controller exhibited in all runs from time 0 hours to just after the 2 hour mark. When the disturbance reaches the upstream sensor the gate becomes unstable, oscillating above and below the desired water elevation in runs 1 2 and 3. At time 8 hours the inlet flow is reduced. Soon afterwards the disturbance reaches the upstream sensor and the gate movement still oscillates above and below the desired water elevation, but the length of the oscillations is longer for runs 1 2 and 3. Between 8 hours and the end of the simulation the gate movement graph all have flat tops. This indicates that the maximum height of the gate has been reached and no more corrections may take place.

Run 1 has the up and down timers both set to 100% (0.5 m/min). The speed of the motor is decreased, in both the up and down directions in run 2 to 50% (0.25 m/min). This decrease in speed results in an increase in the length of the oscillations. A further decrease in the motor speed to 30% (0.15 m/min) in the down direction only also has the effect of

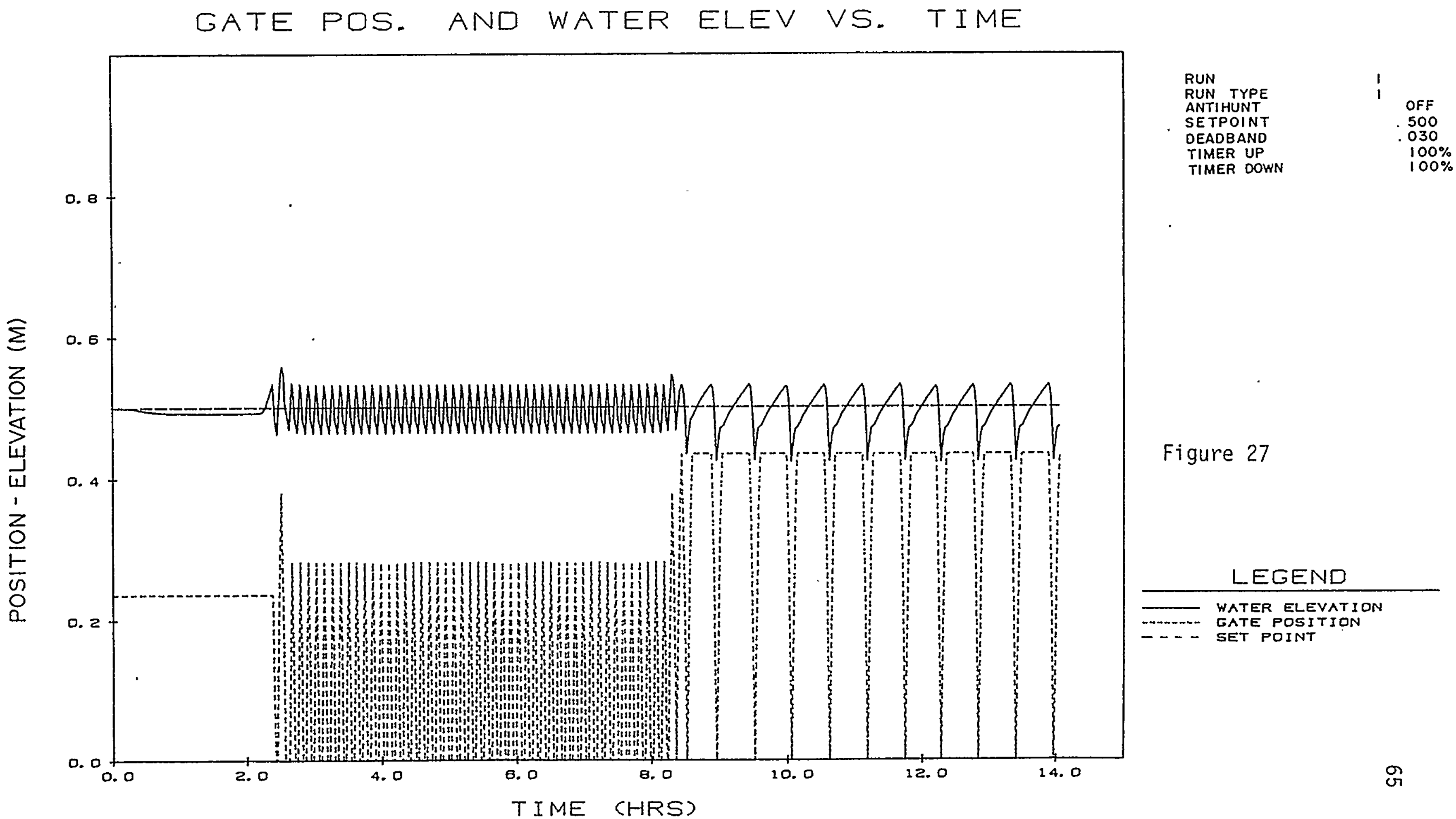

GATE POS. AND WATER ELEV VS. TIME
POSITION - ELEVATION (M)
TIME (HRS)
0.0
0.2
0.4
0.6
0.8
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
RUN 1
RUN TYPE 1
ANTIHUNT OFF
SETPOINT .500
DEADBAND .030
TIMER UP 100%
TIMER DOWN 100%
LEGEND
WATER ELEVATION
GATE POSITION
SET POINT

Figure 27

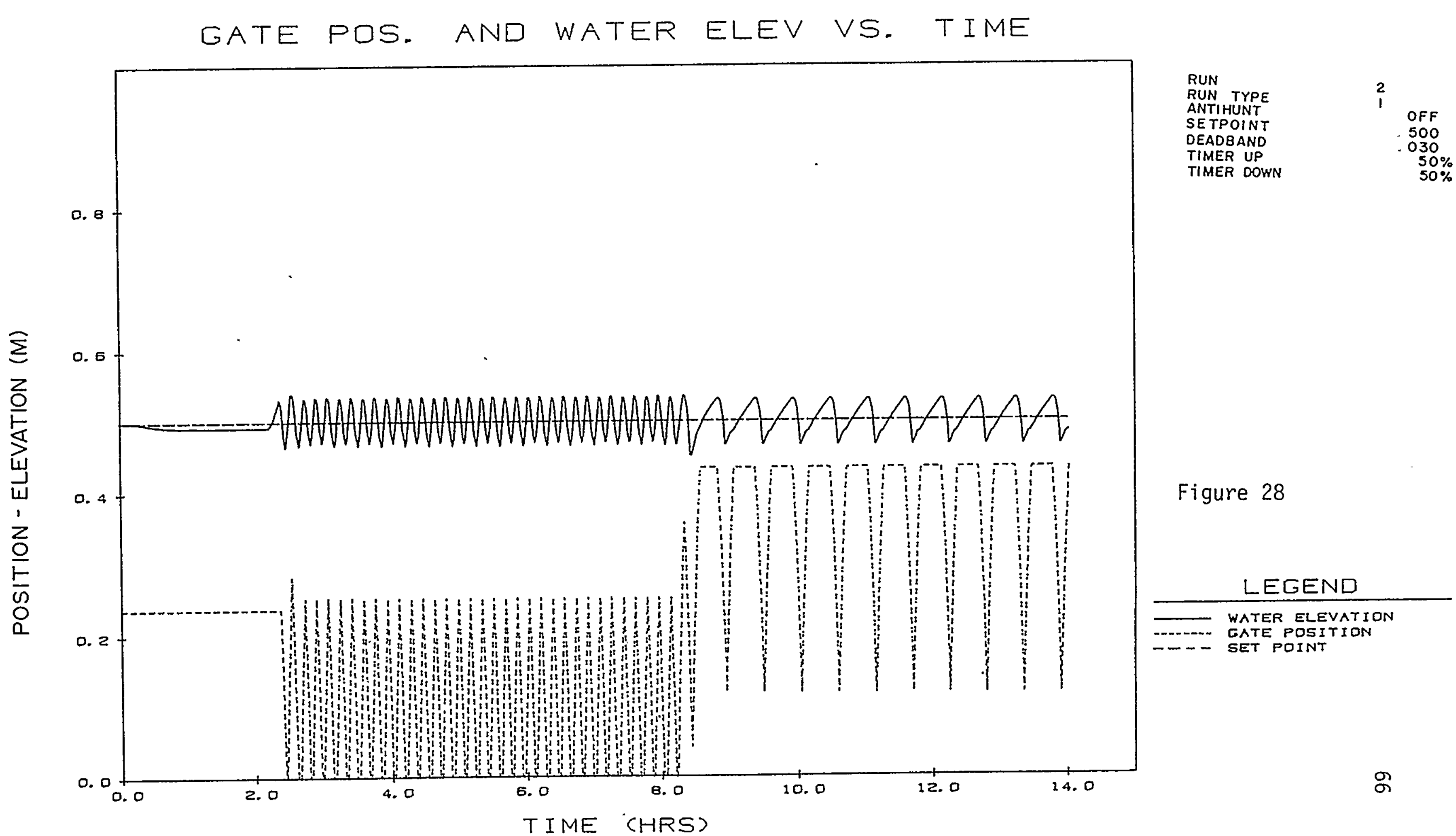

GATE POS. AND WATER ELEV VS. TIME
RUN 2
RUN TYPE 1
ANTIHUNT OFF
SETPOINT .500
DEADBAND .030
TIMER UP 50%
TIMER DOWN 50%
0.8
0.6
0.4
0.2
0.0
POSITION - ELEVATION (M)
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
TIME (HRS)
LEGEND
WATER ELEVATION
GATE POSITION
SET POINT

Figure 28

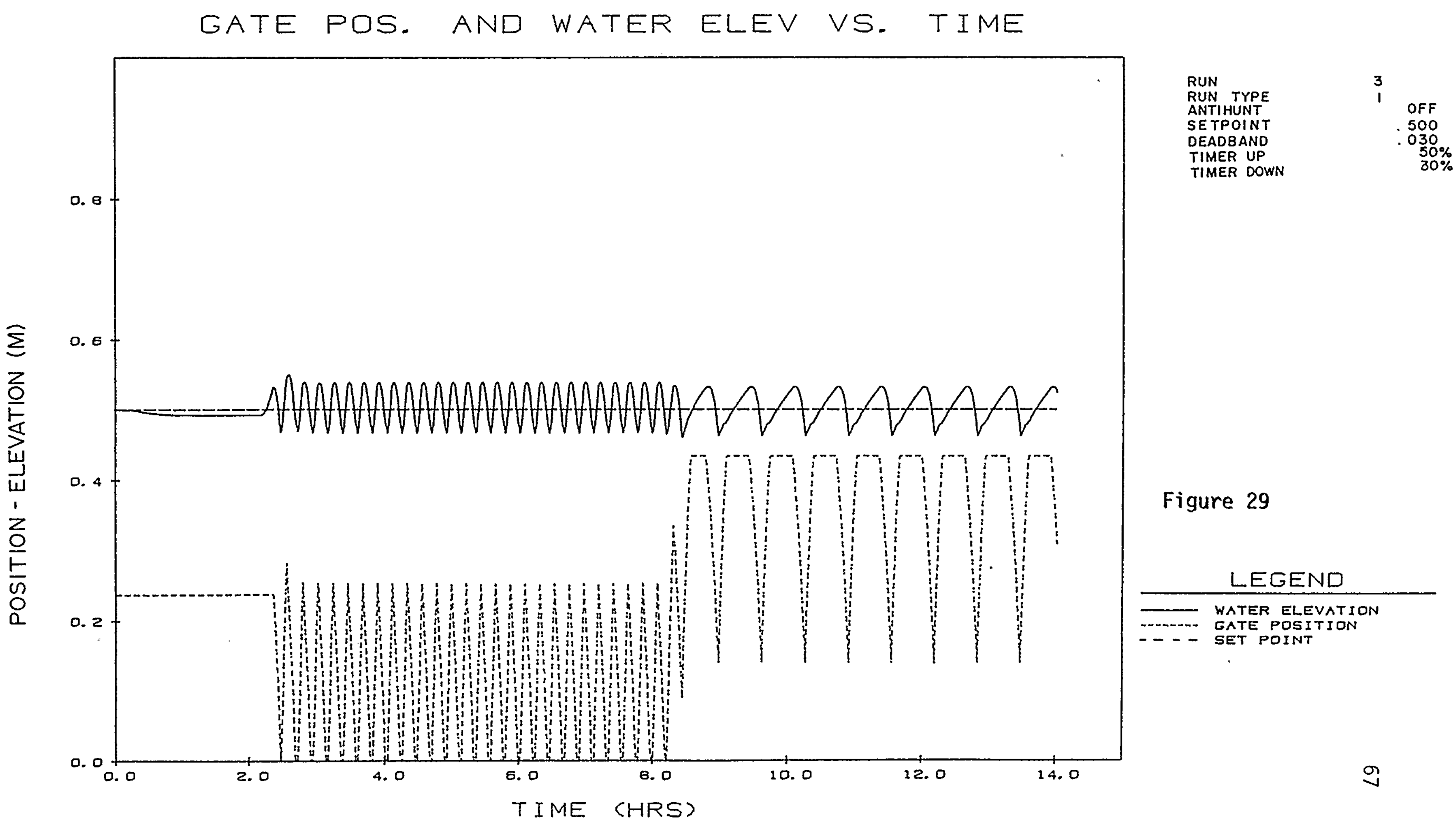

GATE POS. AND WATER ELEV VS. TIME
POSITION - ELEVATION (M)
0.0
0.2
0.4
0.6
0.8
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
TIME (HRS)
RUN 3
RUN TYPE 1
ANTIHUNT OFF
SETPOINT .500
DEADBAND .030
TIMER UP 50%
TIMER DOWN 30%
LEGEND
WATER ELEVATION
GATE POSITION
SET POINT

Figure 29

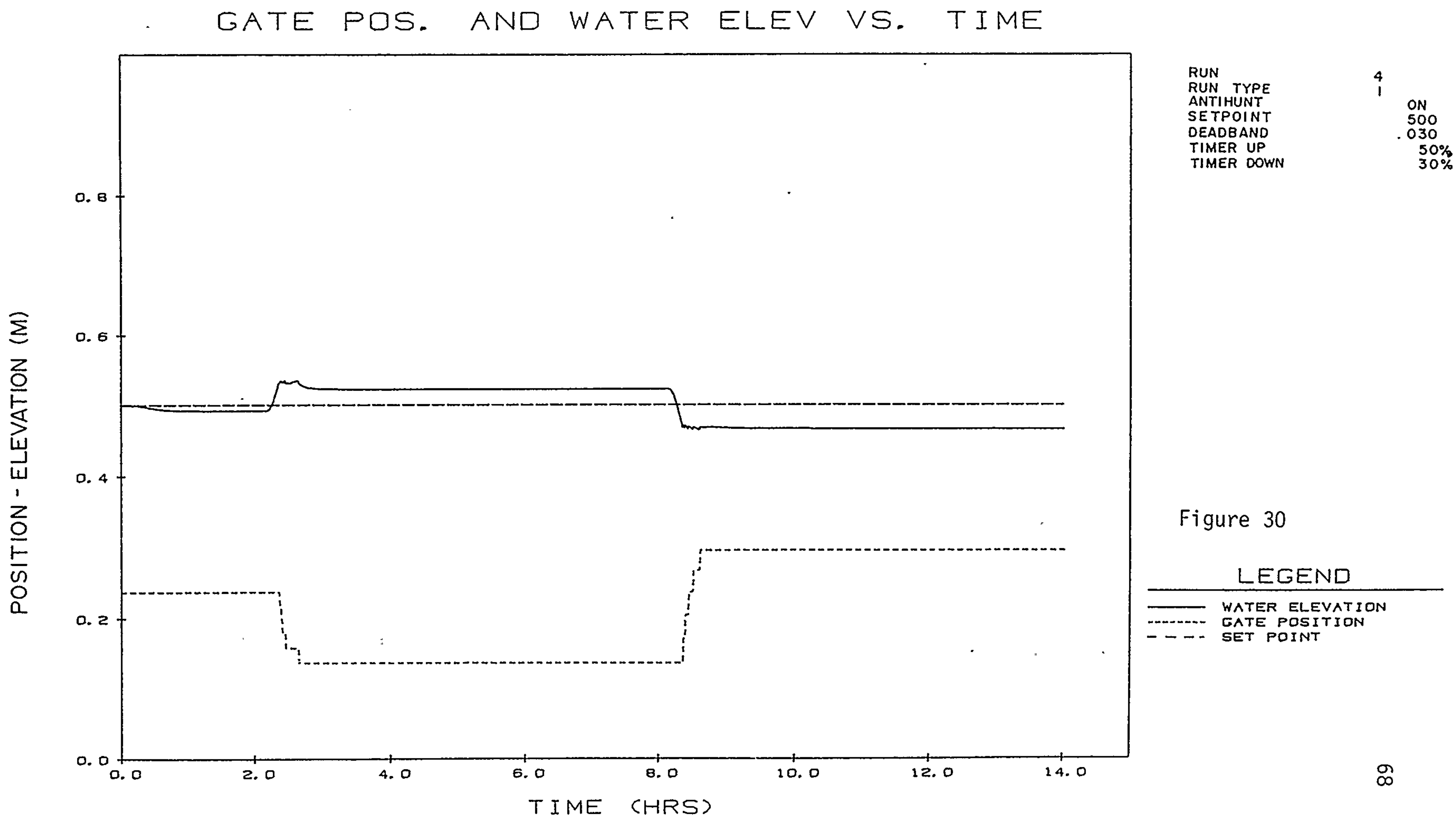

GATE POS. AND WATER ELEV VS. TIME
POSITION - ELEVATION (M)
0.0
0.2
0.4
0.6
0.8
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
TIME (HRS)
RUN 4
RUN TYPE 1
ANTIHUNT ON
SETPOINT 500
DEADBAND .030
TIMER UP 50%
TIMER DOWN 30%
LEGEND
WATER ELEVATION
GATE POSITION
SET POINT

Figure 30

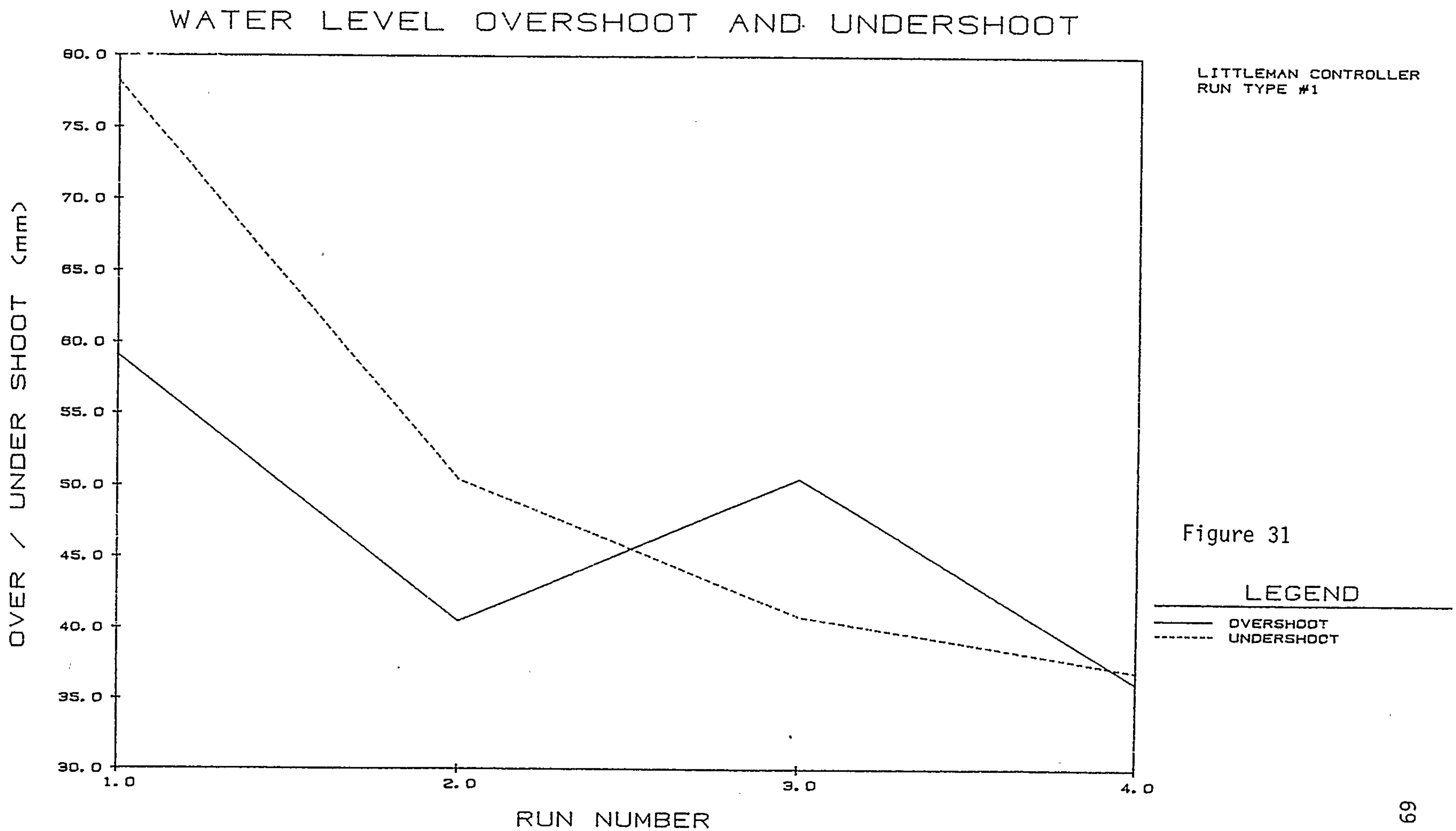

WATER LEVEL OVERSHOOT AND UNDERSHOOT
LITTLEMAN CONTROLLER
RUN TYPE #1
OVER / UNDER SHOOT (mm)
80.0
75.0
70.0
65.0
60.0
55.0
50.0
45.0
40.0
35.0
30.0
1.0
2.0
3.0
4.0
RUN NUMBER
LEGEND
OVERSHOOT
UNDERSHOOT

Figure 31

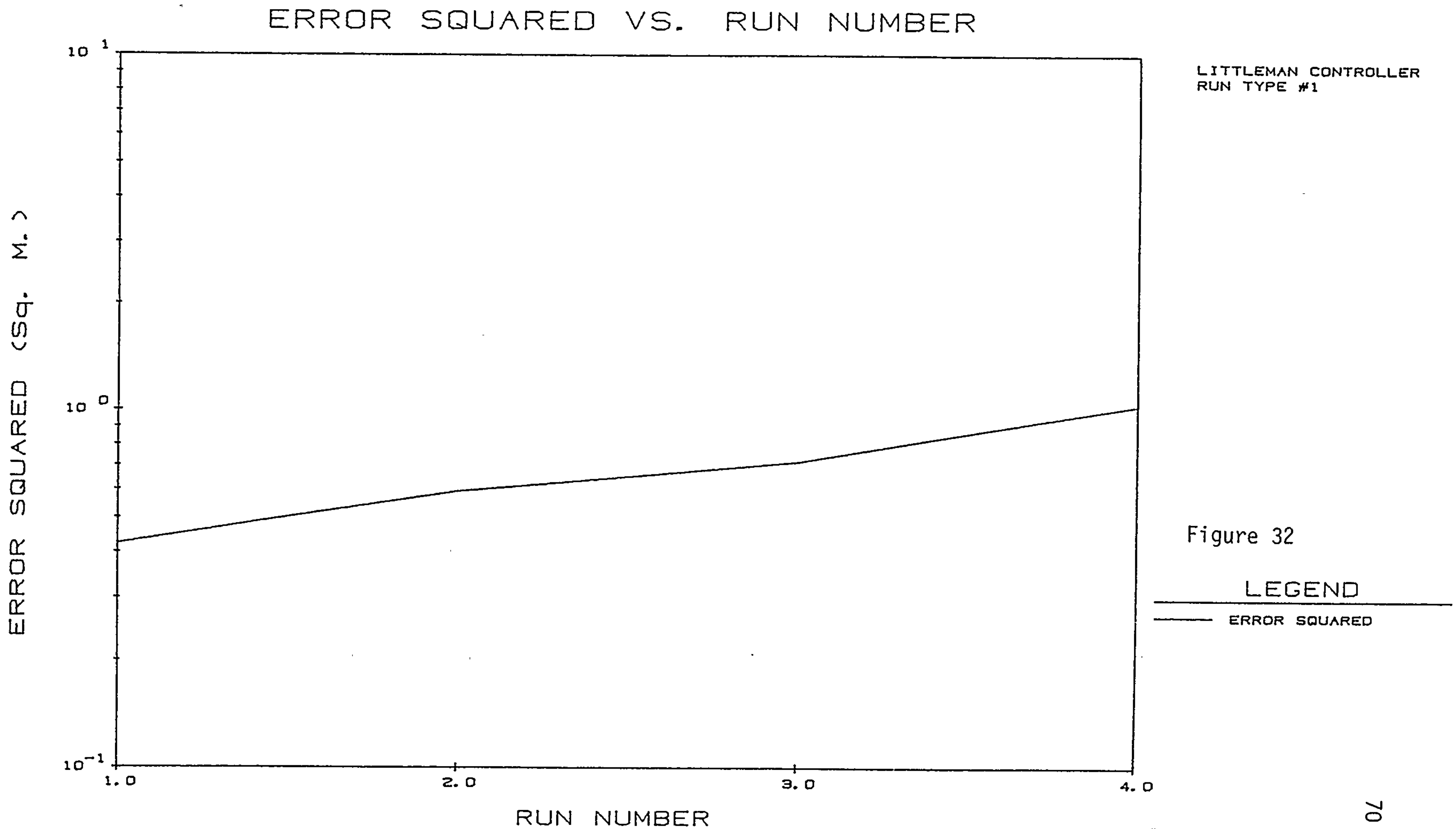

ERROR SQUARED VS. RUN NUMBER
LITTLEMAN CONTROLLER
RUN TYPE #1
ERROR SQUARED (Sq. M.)
10 1
10 0
10−1
1.0
2.0
3.0
4.0
RUN NUMBER
LEGEND
ERROR SQUARED

Figure 32

increasing the length of oscillations. The amplitude of the oscillations also decrease as the speed of the motor decreases.

By adding the Anti Hunt device operation of the Littleman controller becomes stable as shown in run 4 (Figure 30). The gate corrects the water level until it is within the deadband. Once inside the deadband, however, no additional correction takes place. Thus if the flow is increased (2-8 hours) the depth of the water will become stable above the desired water level. If the flow is decreased (8-14 hours) the depth of the water will become stable below the desired water level.

Table 9 shows the results of the mathematical analysis performed on the experimental data. Figures 31 and 32 show these same results in graphical form. As can be seen from examing the data the overshoot and undershoot generally decrease as the motor speed is decreased. The one exception to this is from Run 2 to Run 3. The maximum value of the overshoot increases. This is thought to be due to the decrease in the down motor speed.

Table 9. Littleman Controller; Values of Overshoot, Undershoot and Sum of e^2 terms for different parameter settings.

Timers UP(%)	Timers DOWN(%)	Anti Hunt	Over Shoot(mm)	Under Shoot(mm)	Sum of e^2 $(mm)^2$	Run #
100	100	OFF	59.10	78.20	0.4233	1
50	50	OFF	40.50	50.40	0.5922	2
50	30	OFF	50.50	40.80	0.7174	3
50	30	ON	36.10	36.90	1.0330	4

The e^2 term steadily increases as motor speed decreases. In this instance the e^2 term is not a good indicator of the performance of the controller. The reason for the increase is that as the length of the oscillations increase the time spent further away from the desired water elevation increases, until; during steady operation of the controller (Run 4) the water level never passes the desired water level elevation until a new disturbance enters the system.

7.2 EL-FLO CONTROLLER

The response of the EL-FLO controller to a type 1 inlet flow variation are shown in Figures 33 to 41. The first 5 experiments in this series were designed to test the proportional part of the controller only (K_i = 0.0). Recall from section 2.3.9 that we are attempting to calculate an absolute gate position. It is therefore reasonable to expect that an increased value of K_p will increase the actual gate height. Examining the graphs for Run 1 through 5 (Figures 33 - 37) we can see that this expectation is true. As the value of K_p increases the gate movements also increase, thus decreasing the range in which the water level will deviate. It must be noted, however, that the value of K_p cannot be increased indefinitely. Large values of K_p cause the gate to go to the maximum height rendering it incapable of controlling the upstream water level. This response can be seen in Figure 36.

Table 10 summarizes the values of maximum overshoot, undershoot and the summation of e^2 terms for each experiment. As the value of K_p increases the water level undershoot decreases in runs 1 2 and 3 with overshoot values of zero. Run 4 shows a large value of overshoot and e^2 values.

Table 10. EL-FLO + Reset Controller; Maximum Overshoot, Undershoot and Summation of e^2 terms for different parameter settings.

K_p	K_i	Overshoot (mm)	Undershoot (mm)	Sum of e_2 $(mm)^2$	Run #
0.1	0.0	0.0	283.9	27.2410	1
1.0	0.0	0.0	160.9	17.4967	2
2.0	0.0	0.0	108.3	8.0407	3
5.0	0.0	387.9	0.0	112.6772	4
3.0	0.0	0.0	82.0	4.6161	5
3.0	0.1	0.0	74.1	3.4525	6
3.0	0.5	0.0	57.2	1.4652	7
3.0	1.0	0.3	49.4	0.7764	8
3.0	2.0	11.9	44.9	0.3986	9

Figure 37 shows the operation of the EL-FLO controller using a value of K_p = 3.0. The response of this controller gives results which are closer to the desired water depth (setpoint) than any of the previous runs. The EL-FLO controller was configured using a value of 3.0 for K_p and varying the value of K_i to evaluate the response of the Reset function of the controller. Figures 38-41 are graphs of the response of the EL-FLO controller for different values of K_i. The most notable difference between the EL-FLO controller with the Reset function and those without is the ability of the controller to converge towards the desired water level, (setpoint). Examining Figures 38-41 it can be seen that as the values of K_i increase the rate at which the water level converges towards the desired water level increases.

The values of overshoot in Table 10, decrease in value. All values of undershoot are less than the value of undershoot for run 5 where K_i is 0.0. Runs 5, 6 and 7 have values of zero for the overshoot. Run numbers 8 and 9 have non-zero values of overshoot. These observations indicate that the Reset component of the EL-FLO controller has an effect on the overall operation of the controller and does not serve merely as a reset function for convergence towards the desired water

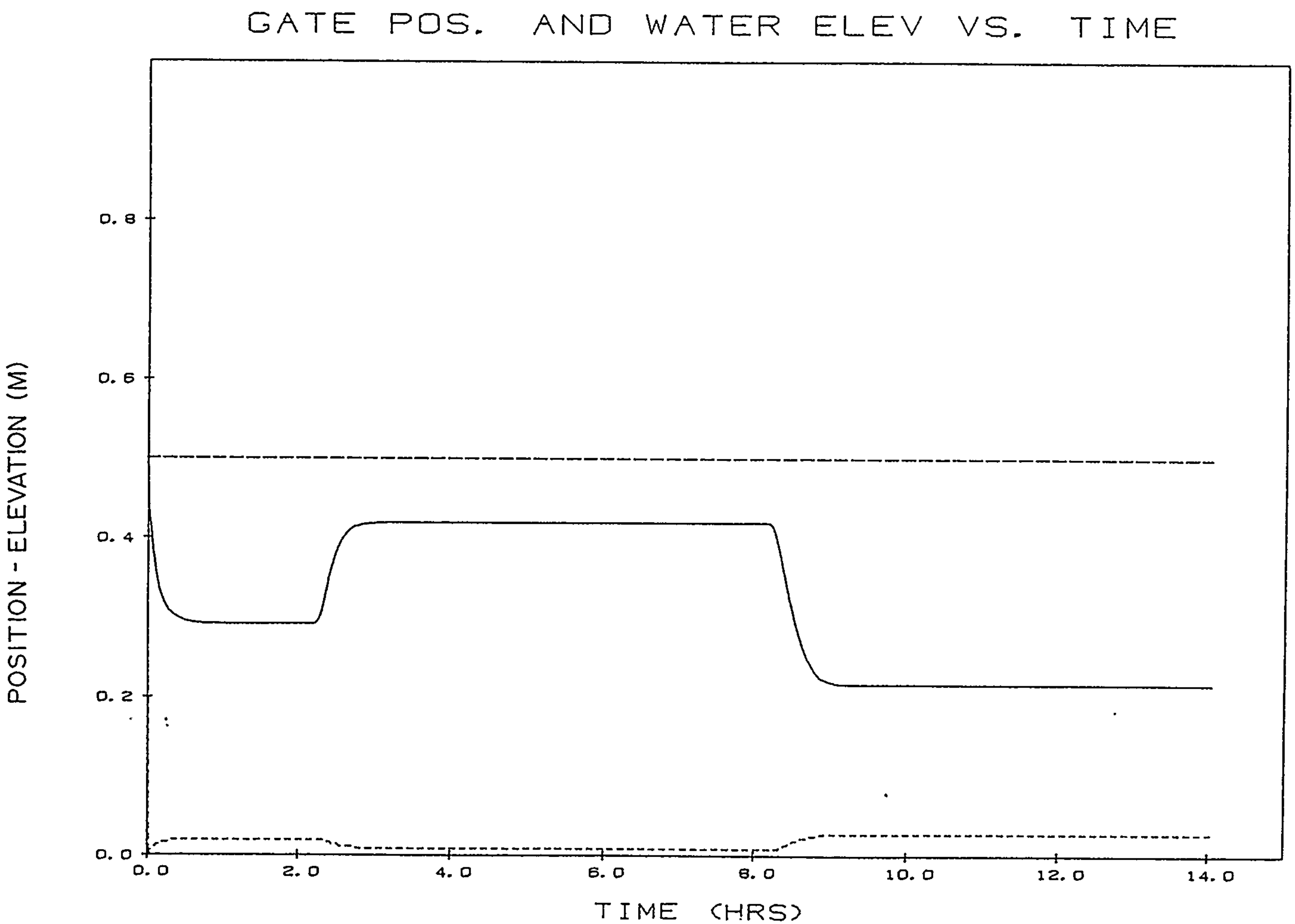

GATE POS. AND WATER ELEV VS. TIME
POSITION - ELEVATION (M)
0.0
0.2
0.4
0.6
0.8
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
TIME (HRS)
RUN 1
RUN TYPE 1
K -.100
SETPOINT .500
DEADBAND .005
Kc .000
Tr 1.000
Kd .000
LEGEND
WATER ELEVATION
GATE POSITION
SET POINT

Figure 33

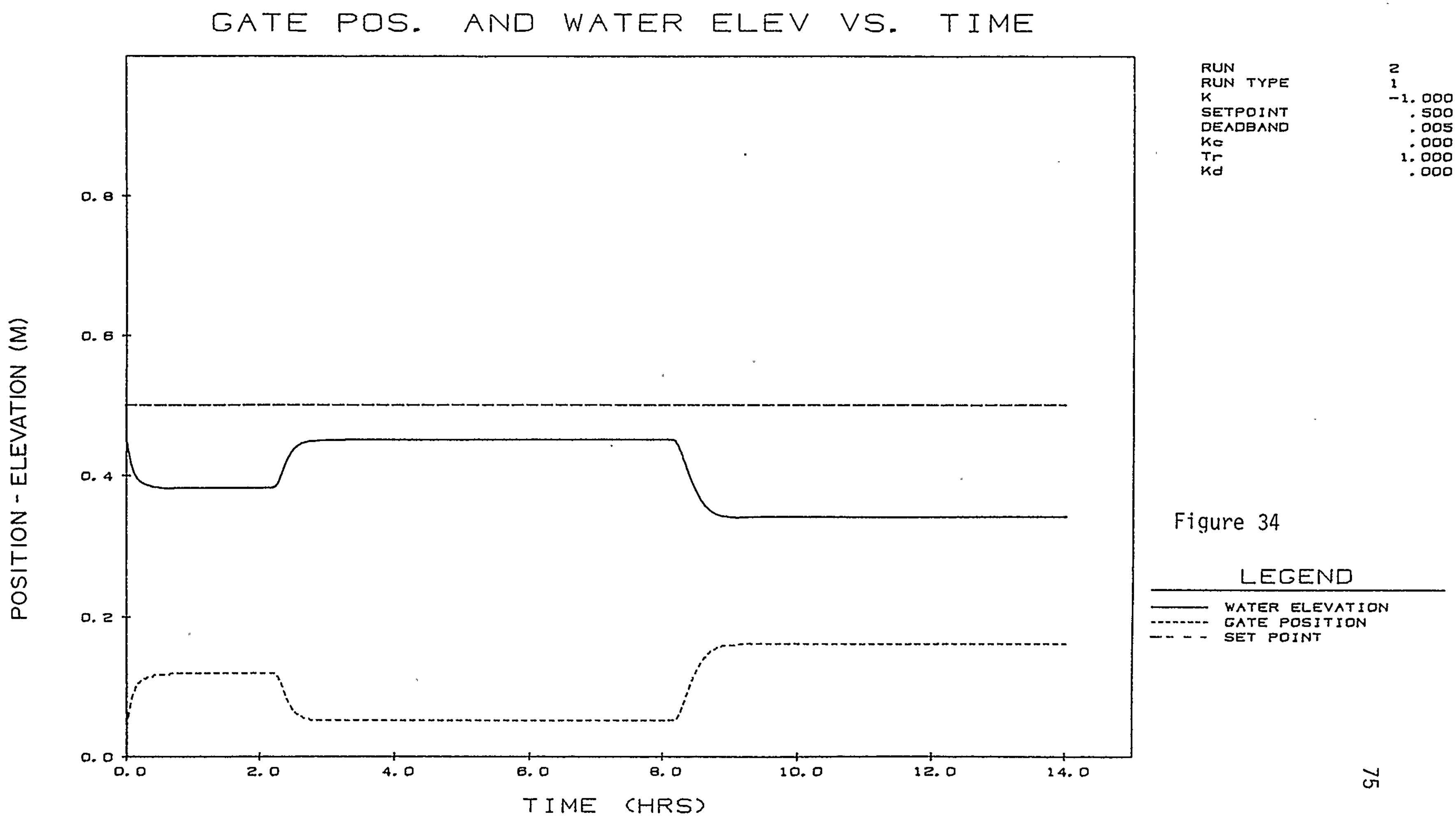
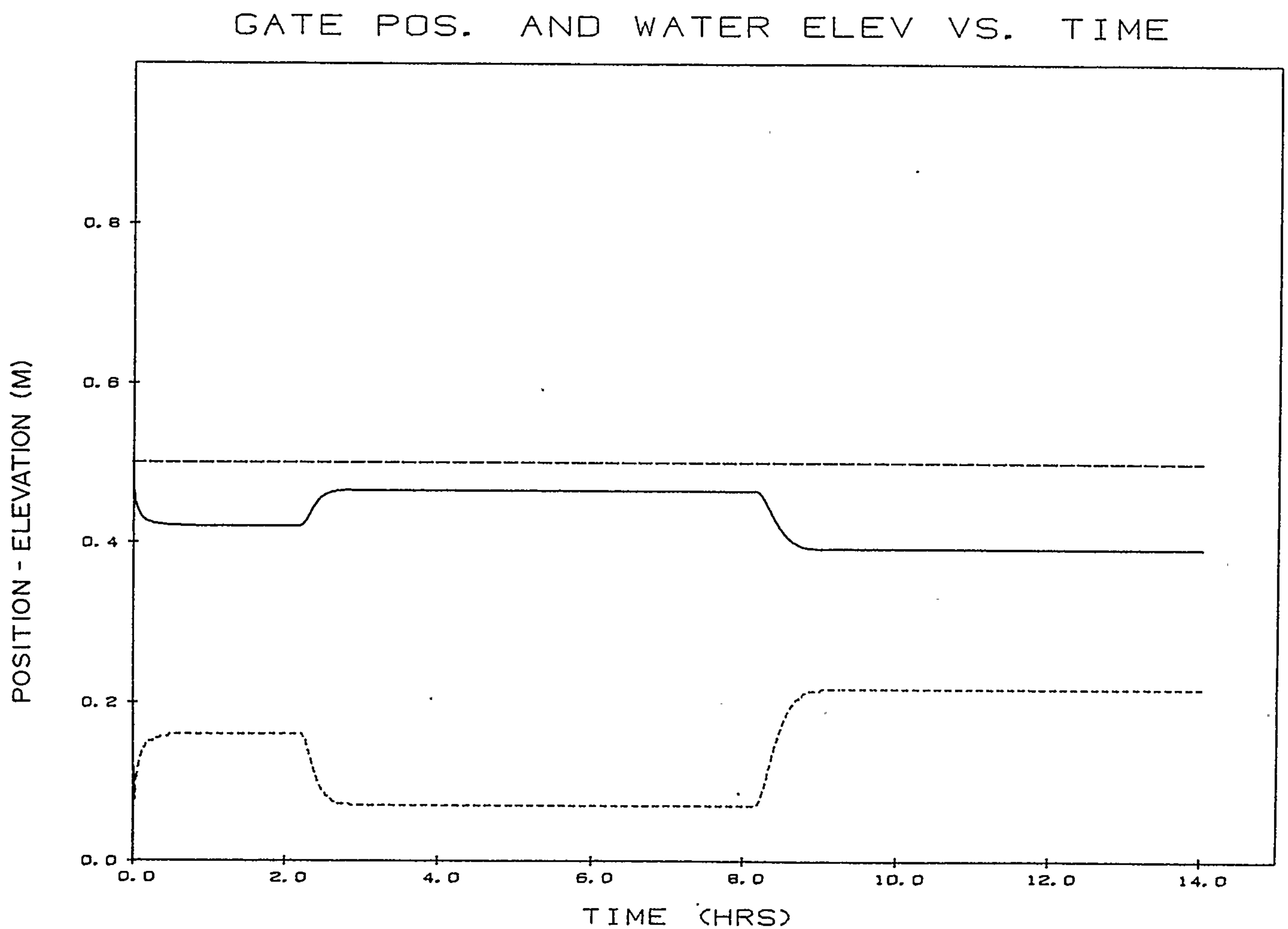

GATE POS. AND WATER ELEV VS. TIME
POSITION - ELEVATION (M)
0.0
0.2
0.4
0.6
0.8
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
TIME (HRS)
RUN 2
RUN TYPE 1
K -1.000
SETPOINT .500
DEADBAND .005
Kc .000
Tr 1.000
Kd .000
LEGEND
WATER ELEVATION
GATE POSITION
SET POINT

Figure 34



RUN	3
RUN TYPE	1
K	-2.000
SETPOINT	.500
DEADBAND	.005
Kc	.000
Tr	1.000
Kd	.000

Figure 35

LEGEND

WATER ELEVATION
GATE POSITION
SET POINT

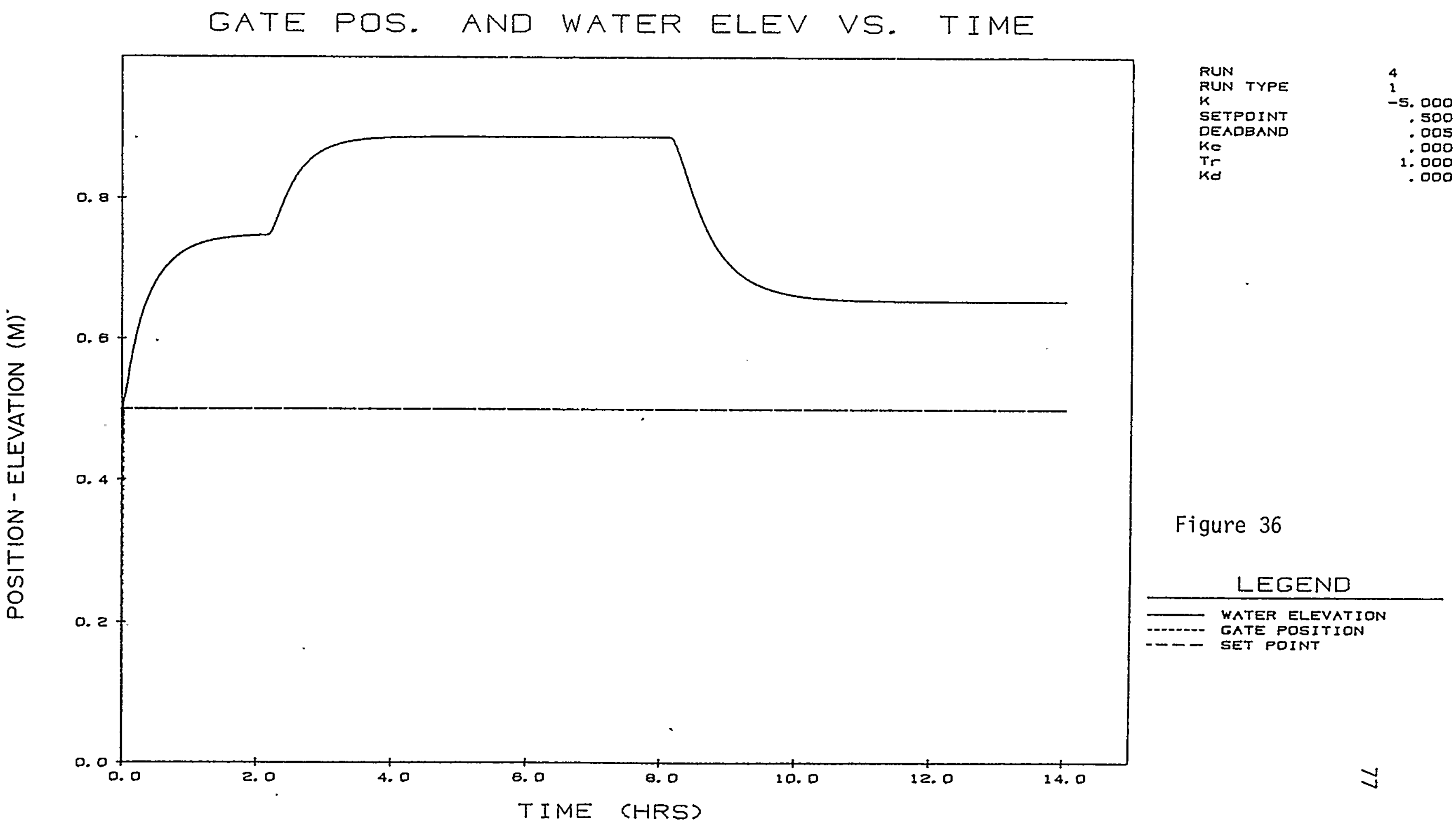

GATE POS. AND WATER ELEV VS. TIME
POSITION - ELEVATION (M)
TIME (HRS)
0.0
0.2
0.4
0.6
0.8
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
RUN 4
RUN TYPE 1
K -5.000
SETPOINT .500
DEADBAND .005
Kc .000
Tr 1.000
Kd .000
LEGEND
WATER ELEVATION
GATE POSITION
SET POINT

Figure 36

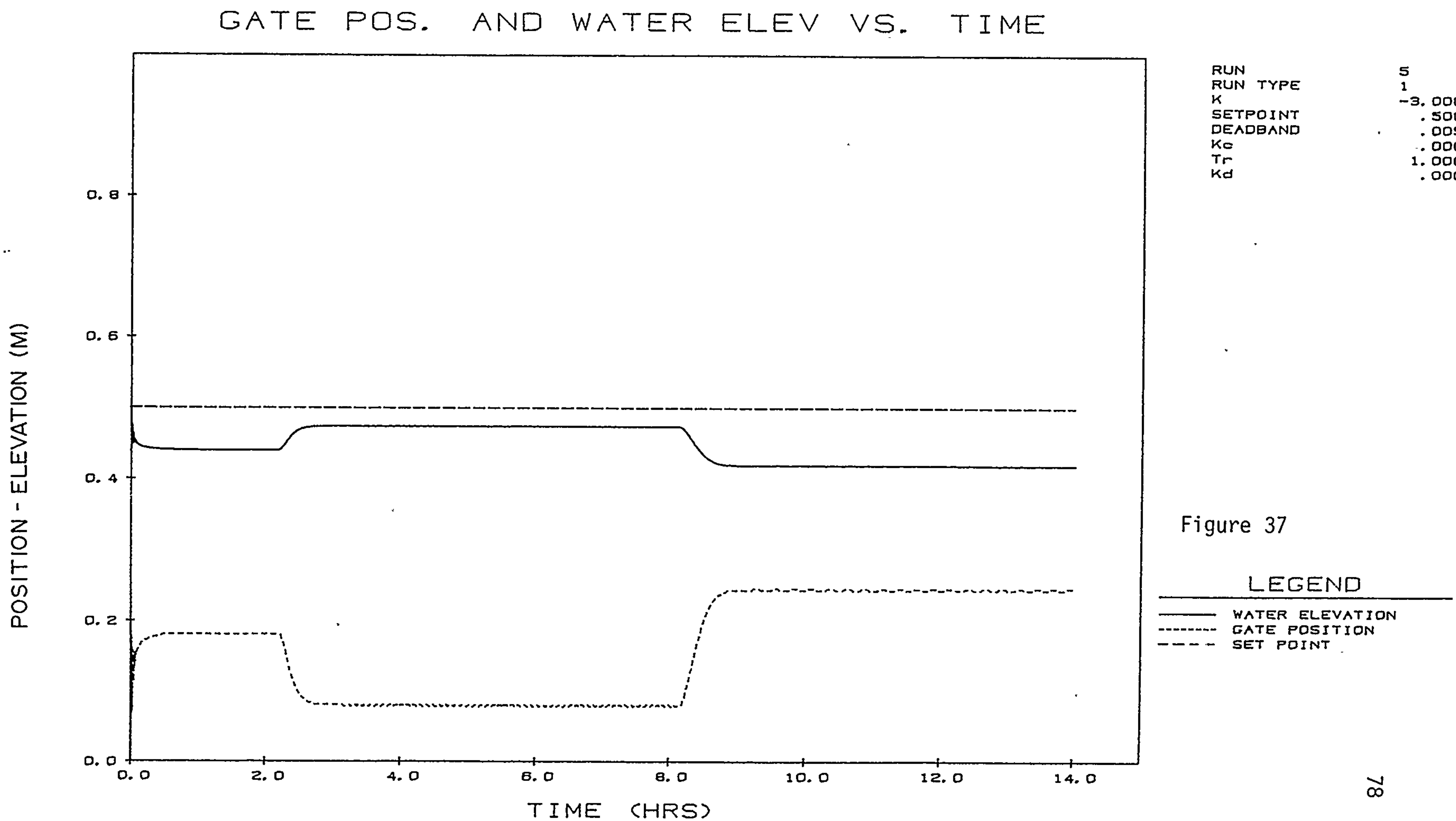

GATE POS. AND WATER ELEV VS. TIME
POSITION - ELEVATION (M)
0.0
0.2
0.4
0.6
0.8
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
TIME (HRS)
RUN 5
RUN TYPE 1
K -3.000
SETPOINT .500
DEADBAND .005
Kc .000
Tr 1.000
Kd .000
LEGEND
WATER ELEVATION
GATE POSITION
SET POINT

Figure 37

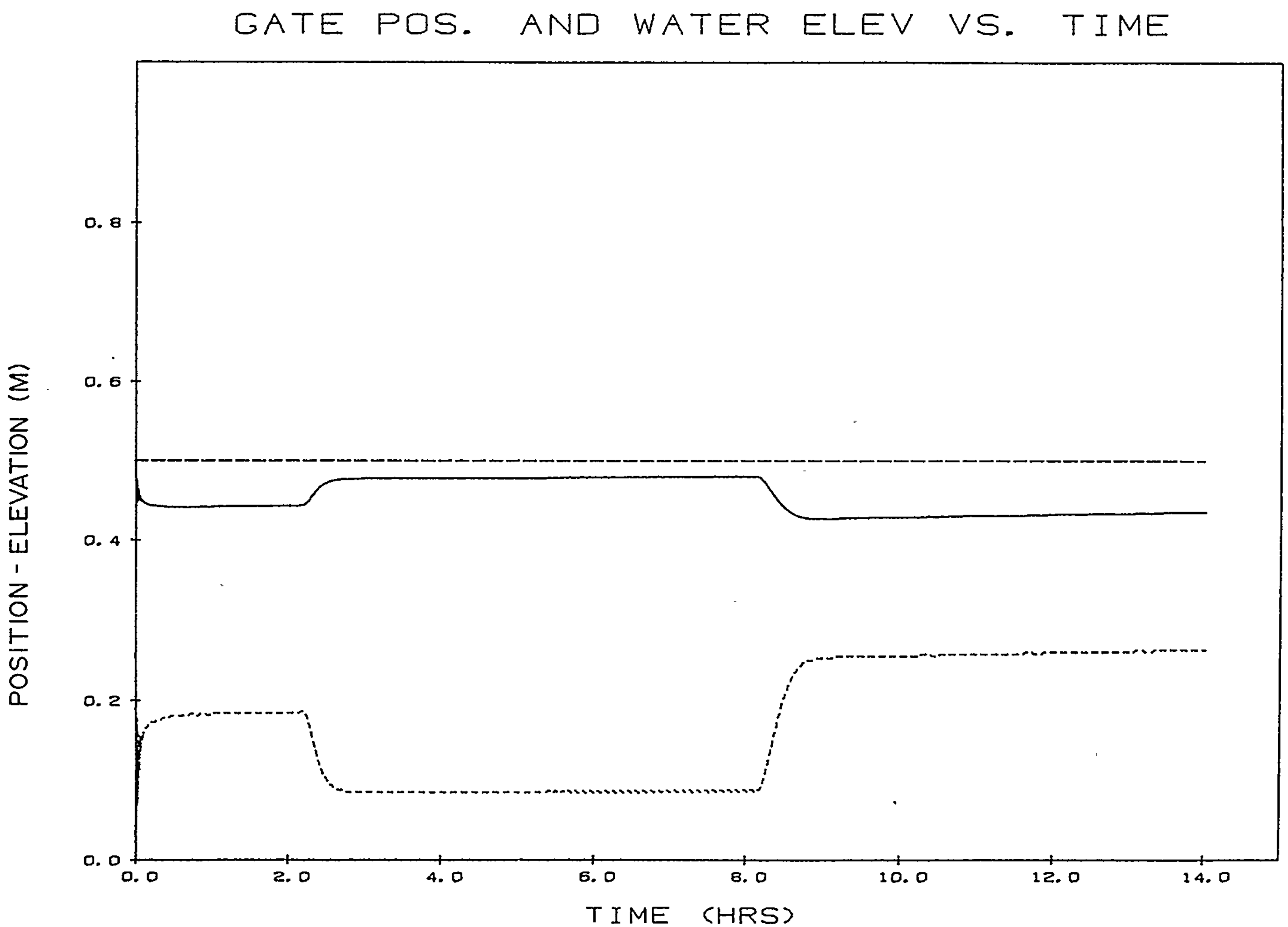

GATE POS. AND WATER ELEV VS. TIME
POSITION - ELEVATION (M)
0.0
0.2
0.4
0.6
0.8
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
TIME (HRS)
RUN 6
RUN TYPE 1
K -3.000
SETPOINT .500
DEADBAND .005
Ko -.100
Tr 1.000
Kd .000
LEGEND
WATER ELEVATION
GATE POSITION
SET POINT

Figure 38

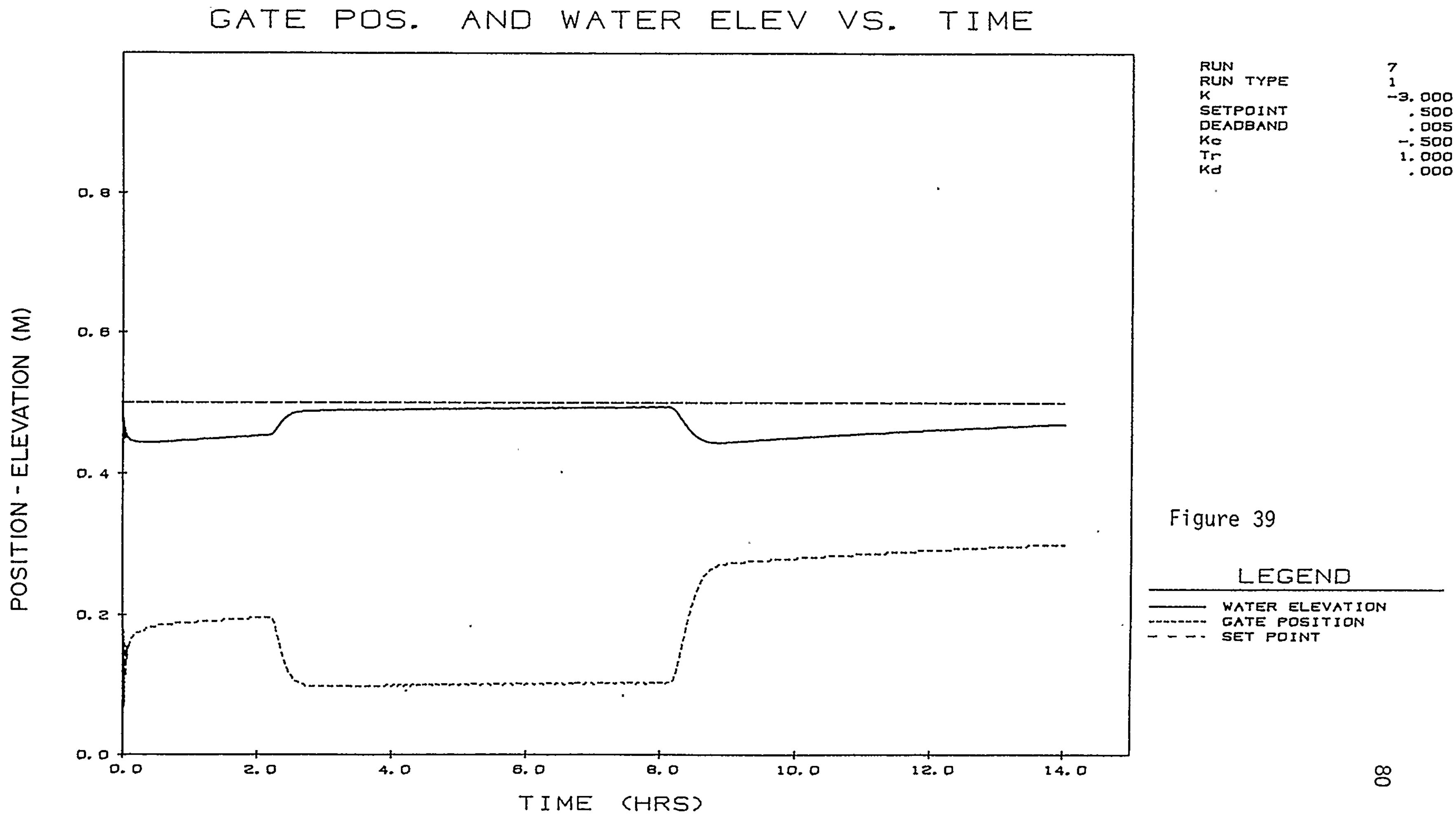

GATE POS. AND WATER ELEV VS. TIME
POSITION - ELEVATION (M)
0.0
0.2
0.4
0.6
0.8
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
TIME (HRS)
RUN 7
RUN TYPE 1
K -3.000
SETPOINT .500
DEADBAND .005
Kc -.500
Tr 1.000
Kd .000
LEGEND
WATER ELEVATION
GATE POSITION
SET POINT

Figure 39

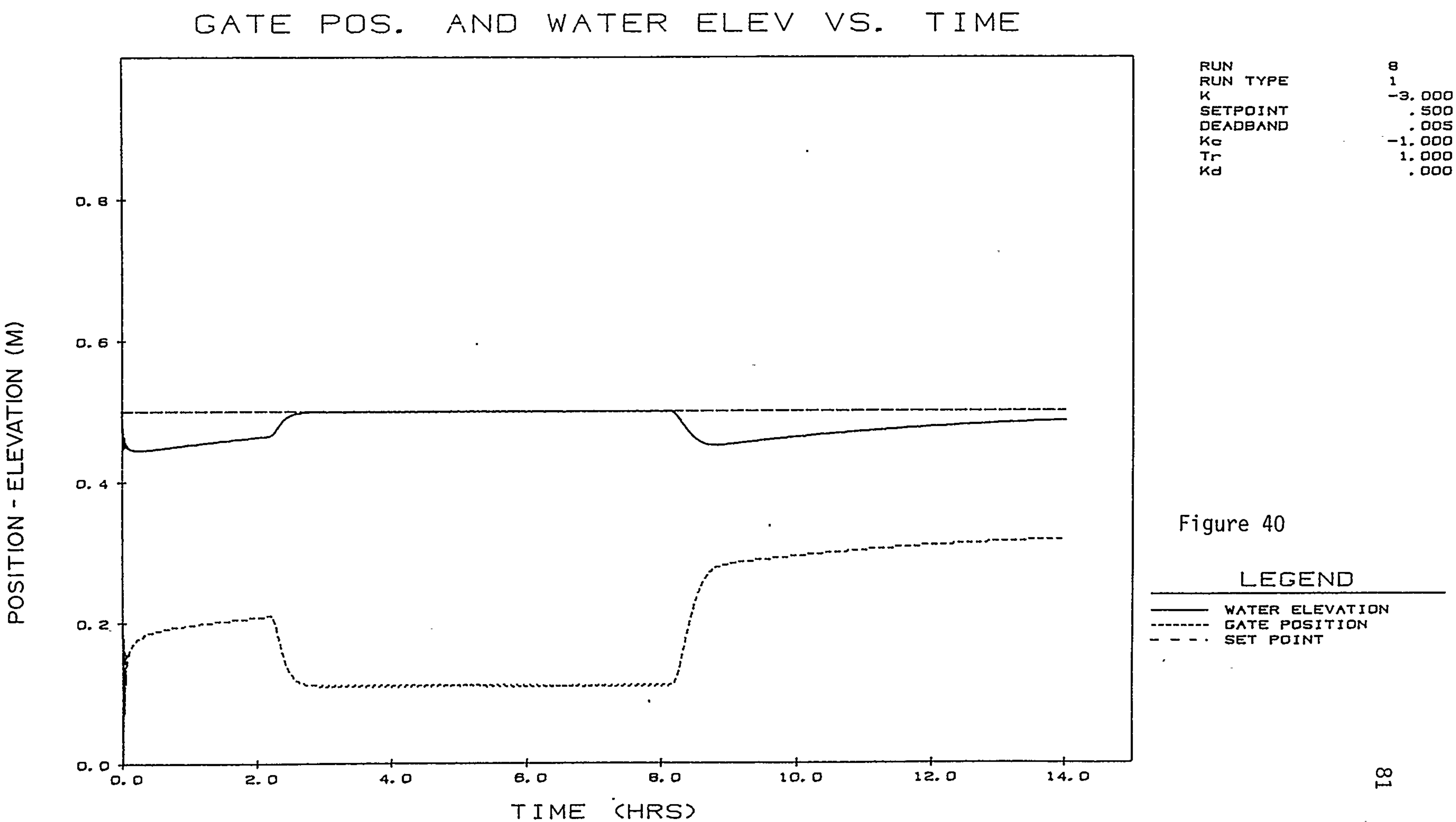

GATE POS. AND WATER ELEV VS. TIME
RUN 8
RUN TYPE 1
K -3.000
SETPOINT .500
DEADBAND .005
Kc -1.000
Tr 1.000
Kd .000
POSITION - ELEVATION (M)
0.0
0.2
0.4
0.6
0.8
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
TIME (HRS)
LEGEND
WATER ELEVATION
GATE POSITION
SET POINT

Figure 40

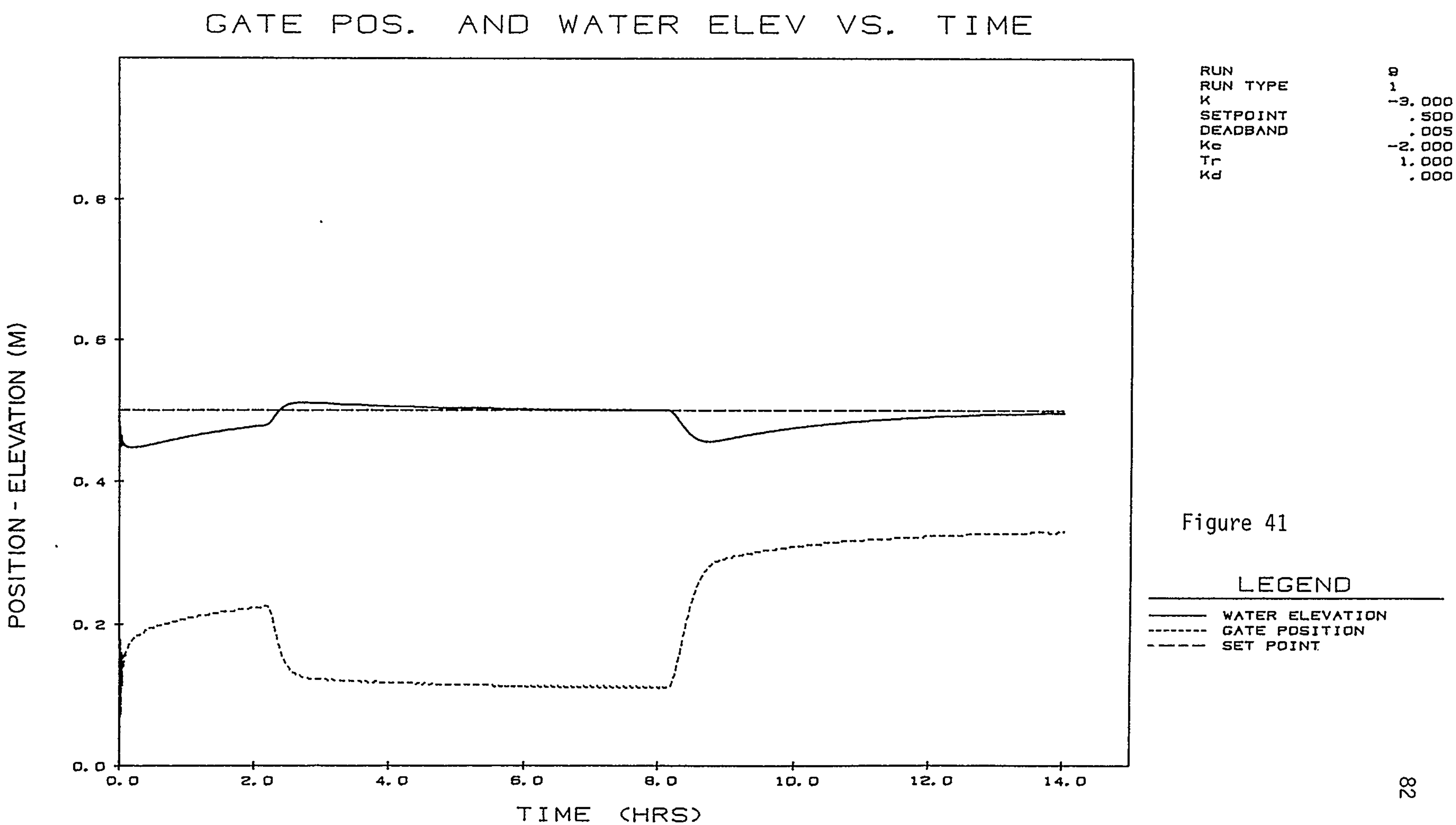

GATE POS. AND WATER ELEV VS. TIME
RUN 8
RUN TYPE 1
K -3.000
SETPOINT .500
DEADBAND .005
Kc -2.000
Tr 1.000
Kd .000
0.0
0.2
0.4
0.6
0.8
POSITION - ELEVATION (M)
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
TIME (HRS)
LEGEND
WATER ELEVATION
GATE POSITION
SET POINT

Figure 41

level. Table 10 also shows the values of the sum of e^2 terms which decrease as K_i increases. This decrease in the e^2 term is related to the rate at which the error is being reduced by the Reset function.

7.3 PROPORTIONAL CONTROLLER

The proportional controller experiments are presented in Figures 42-59. Unlike the EL-FLO controller the Proportional Controller attempts to calculate a change in gate position rather than an absolute gate position. In most cases the controller corrects for the disturbance within a couple of hours. The rate at which the controller will correct is dependent on the value of K_p. As can be seen by reviewing run number 1 through 5 (Figures 42-46) the initial reaction time becomes very quick. However, as the reaction time becomes quicker, the tendency to over react becomes greater. This is evidenced by the fact that run 1 takes 1/2 a cycle to become stable, run 2 takes 1 1/2 cycles and run 3 takes 2 cycles between 8 and 10 hours simulation time. As K_p becomes very large the controller has a tendency to become unstable [Undamped oscillations Section 3.3.6] (Figure 46). Cycling of the gate is seen between 2.0 and 8.0 hours. This cycling behaviour becomes even more pronounced as the deadband increases. Run 10 (Figure 51) exhibits unstable behaviour between 2 and 14 hours. Run 15 (Figure 56) exhibits this unstable behaviour between times 0 to 2 hours and 8 to 14 hours. Run 18 (Figure 59) is unstable between 0 and 8 hours.

Table 11 is a summary of the maximum overshoot, undershoot and the summation of e^2 over the duration of the simulation. Reviewing the first five runs in Table 11 we see that the overshoot, undershoot and e^2 terms all decrease as K_p increases. These values are plotted in Figures 60-62. We can see from these Figures that the reduction in the overshoot and

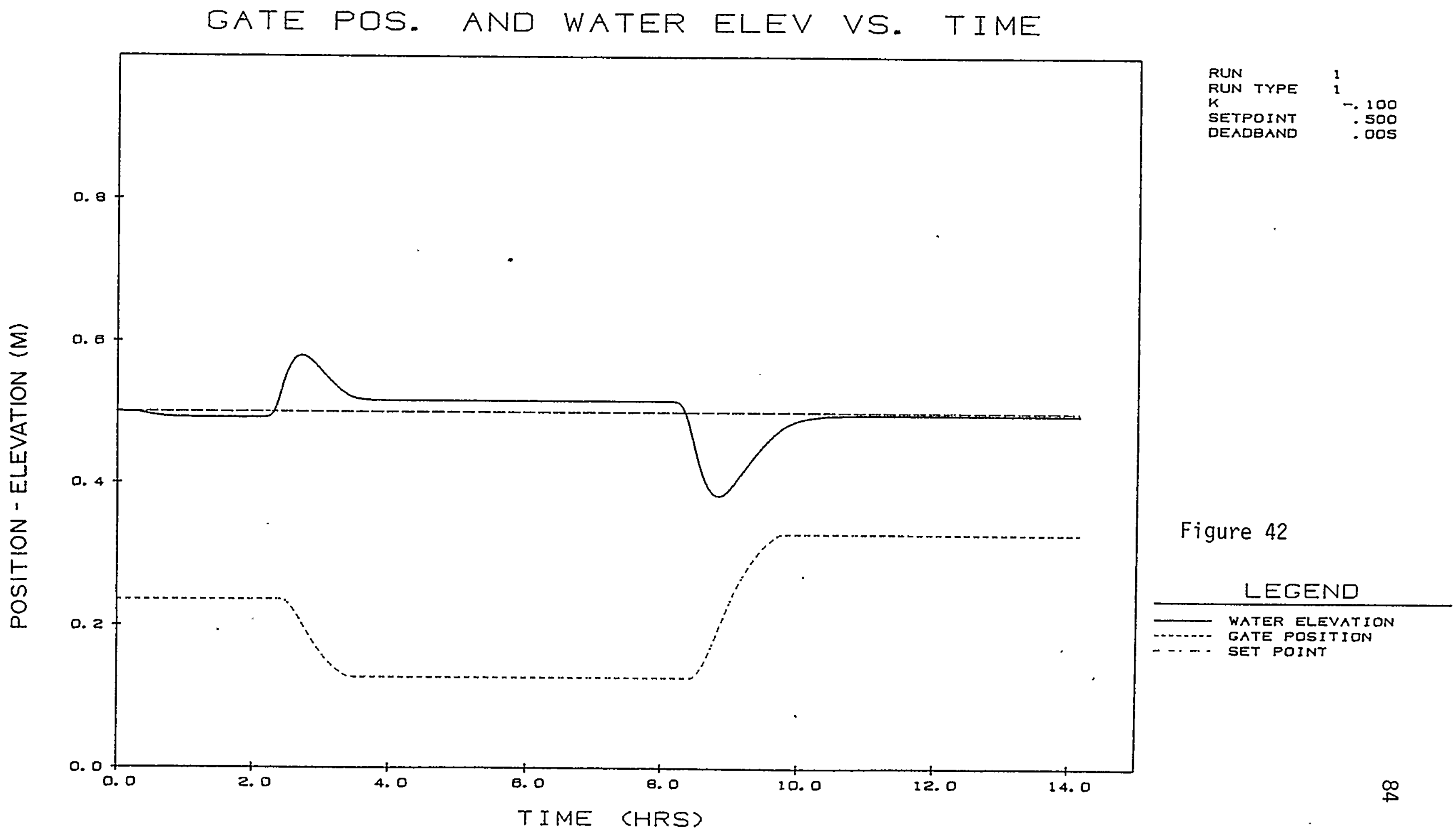

GATE POS. AND WATER ELEV VS. TIME
RUN 1
RUN TYPE 1
K -.100
SETPOINT .500
DEADBAND .005
POSITION - ELEVATION (M)
0.0
0.2
0.4
0.6
0.8
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
TIME (HRS)
LEGEND
WATER ELEVATION
GATE POSITION
SET POINT

Figure 42

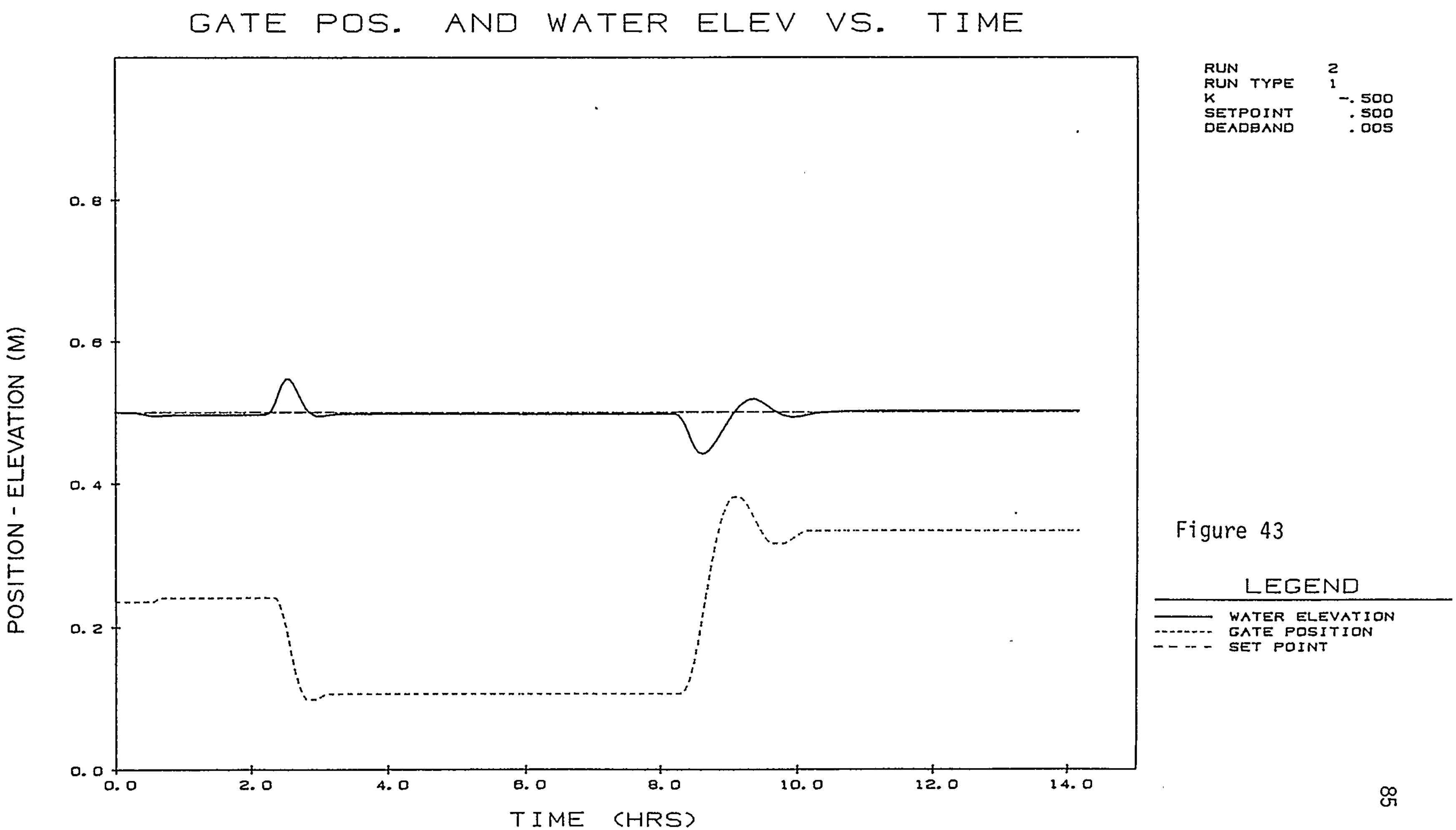
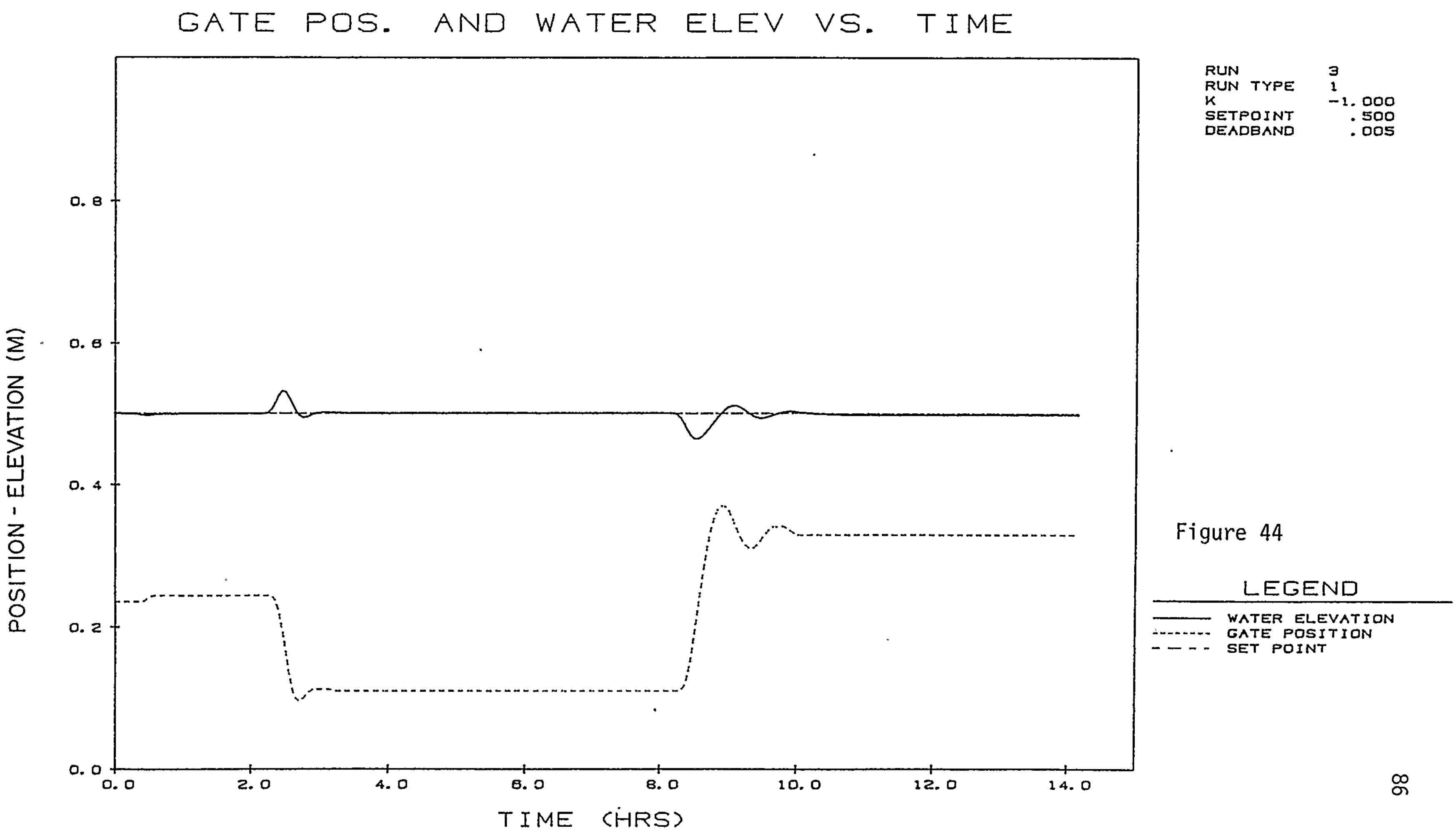
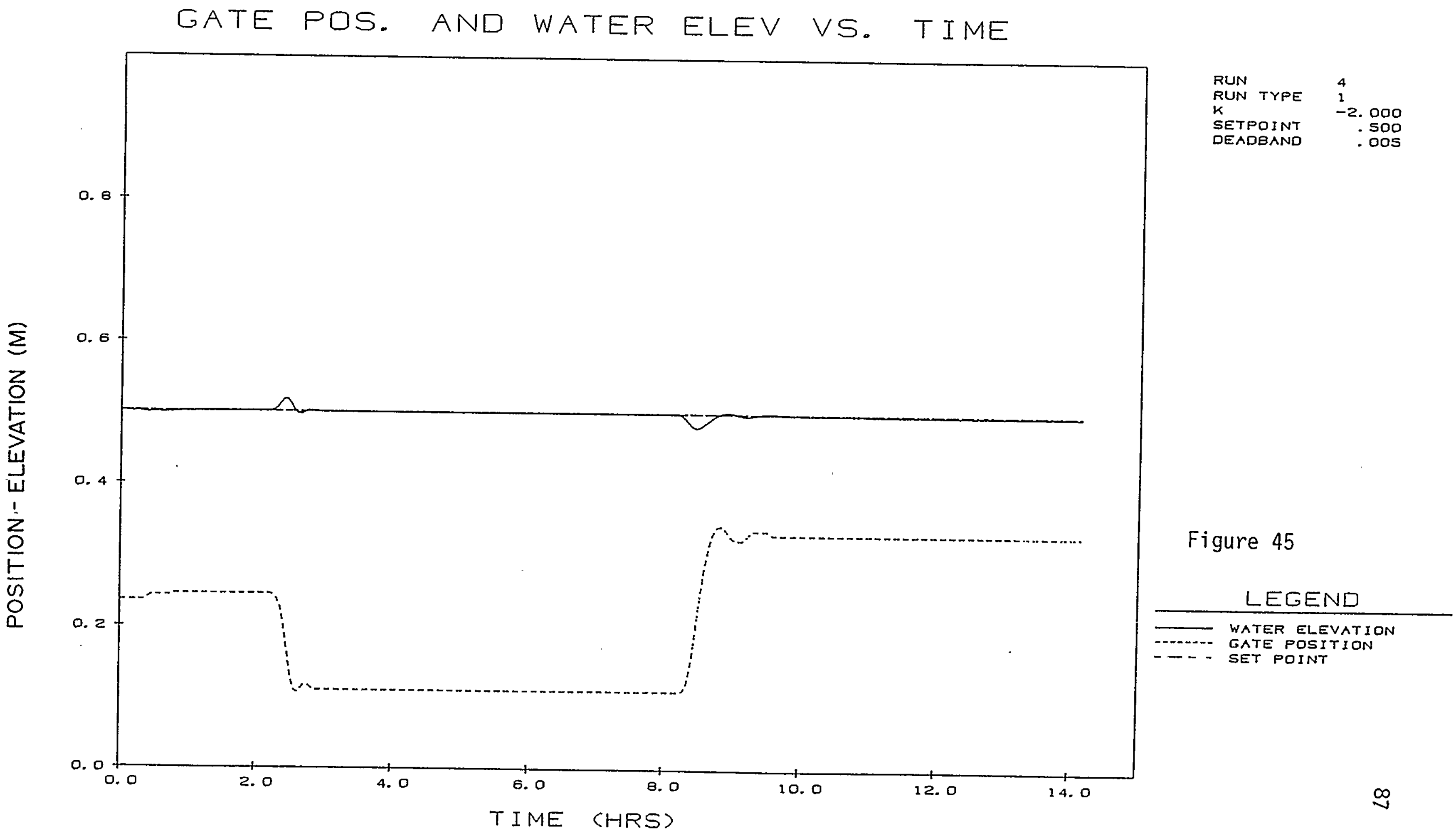

GATE POS. AND WATER ELEV VS. TIME
RUN 2
RUN TYPE 1
K -.500
SETPOINT .500
DEADBAND .005
POSITION - ELEVATION (M)
0.0
0.2
0.4
0.6
0.8
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
TIME (HRS)
LEGEND
WATER ELEVATION
GATE POSITION
SET POINT

Figure 43



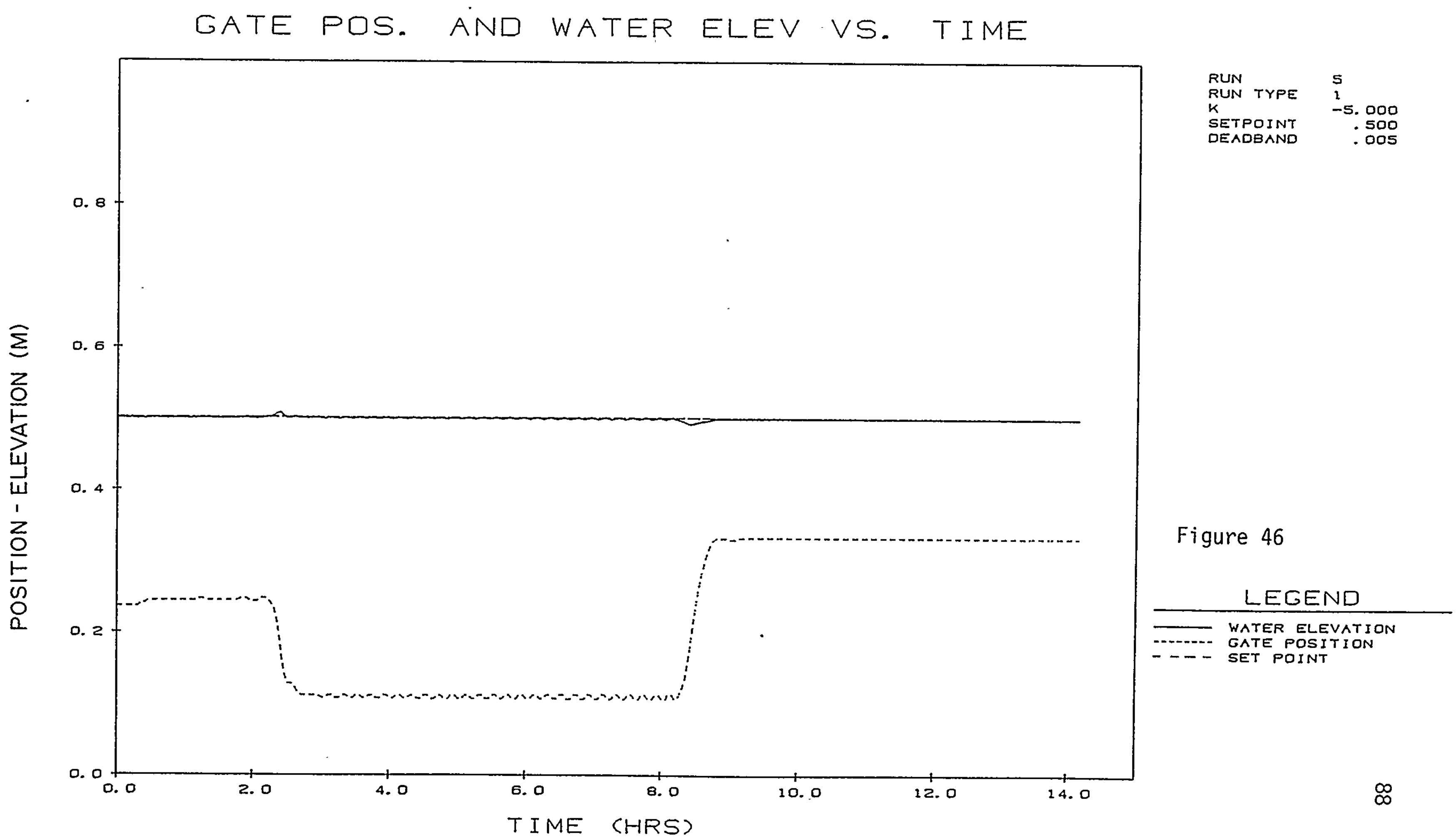
GATE POS. AND WATER ELEV VS. TIME
RUN 3
RUN TYPE 1
K -1.000
SETPOINT .500
DEADBAND .005
POSITION - ELEVATION (M)
0.0
0.2
0.4
0.6
0.8
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
TIME (HRS)
LEGEND
WATER ELEVATION
GATE POSITION
SET POINT

Figure 44



GATE POS. AND WATER ELEV VS. TIME
RUN 4
RUN TYPE 1
K -2.000
SETPOINT .500
DEADBAND .005
POSITION - ELEVATION (M)
0.0
0.2
0.4
0.6
0.8
0.0 2.0 4.0 6.0 8.0 10.0 12.0 14.0
TIME (HRS)
LEGEND
WATER ELEVATION
GATE POSITION
SET POINT

Figure 45



GATE POS. AND WATER ELEV VS. TIME
RUN S
RUN TYPE 1
K -5.000
SETPOINT .500
DEADBAND .005
POSITION - ELEVATION (M)
0.0
0.2
0.4
0.6
0.8
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
TIME (HRS)
LEGEND
WATER ELEVATION
GATE POSITION
SET POINT

Figure 46

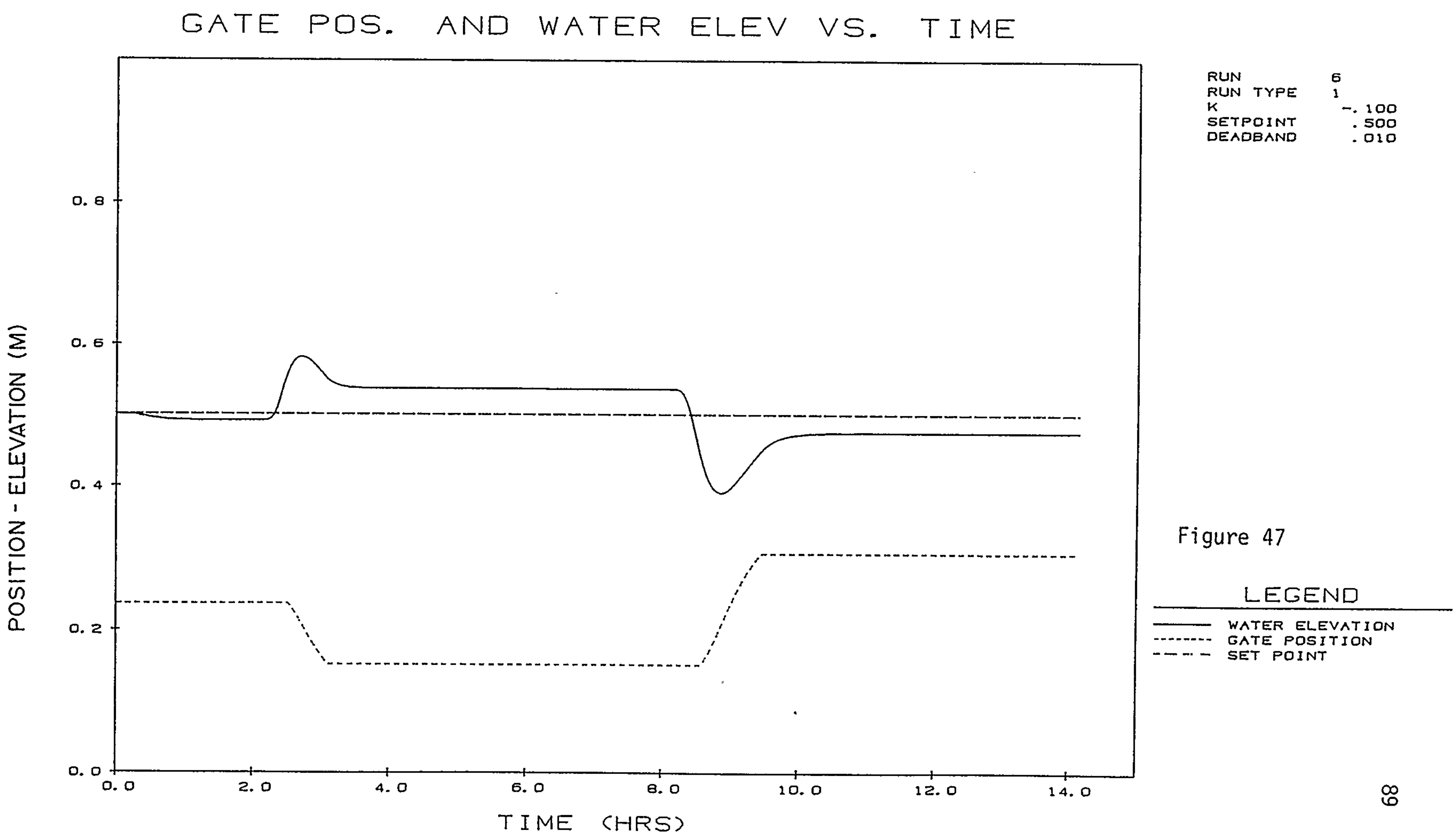

GATE POS. AND WATER ELEV VS. TIME
RUN 6
RUN TYPE 1
K -.100
SETPOINT .500
DEADBAND .010
POSITION - ELEVATION (M)
0.0
0.2
0.4
0.6
0.8
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
TIME (HRS)
LEGEND
WATER ELEVATION
GATE POSITION
SET POINT

Figure 47

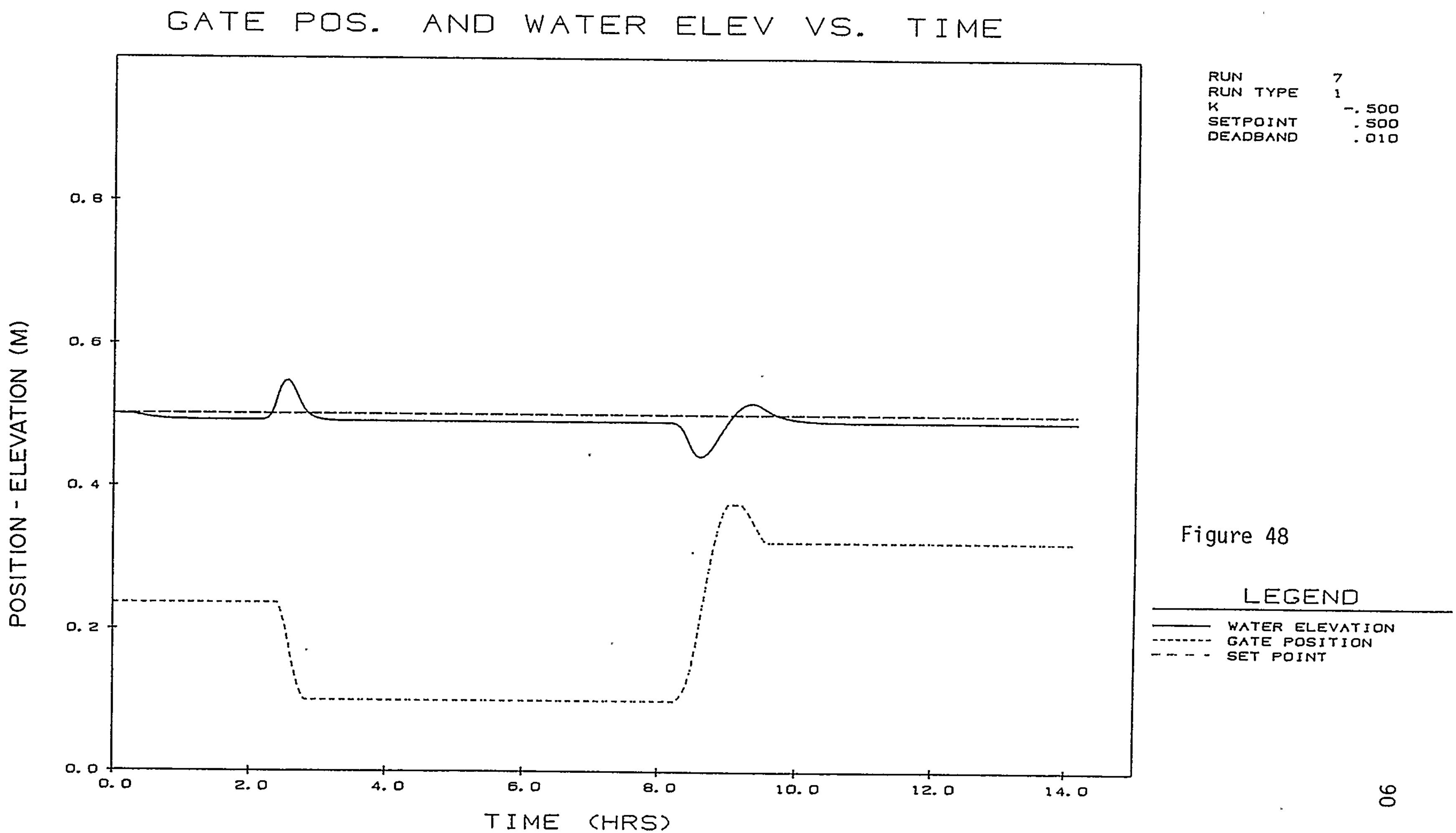
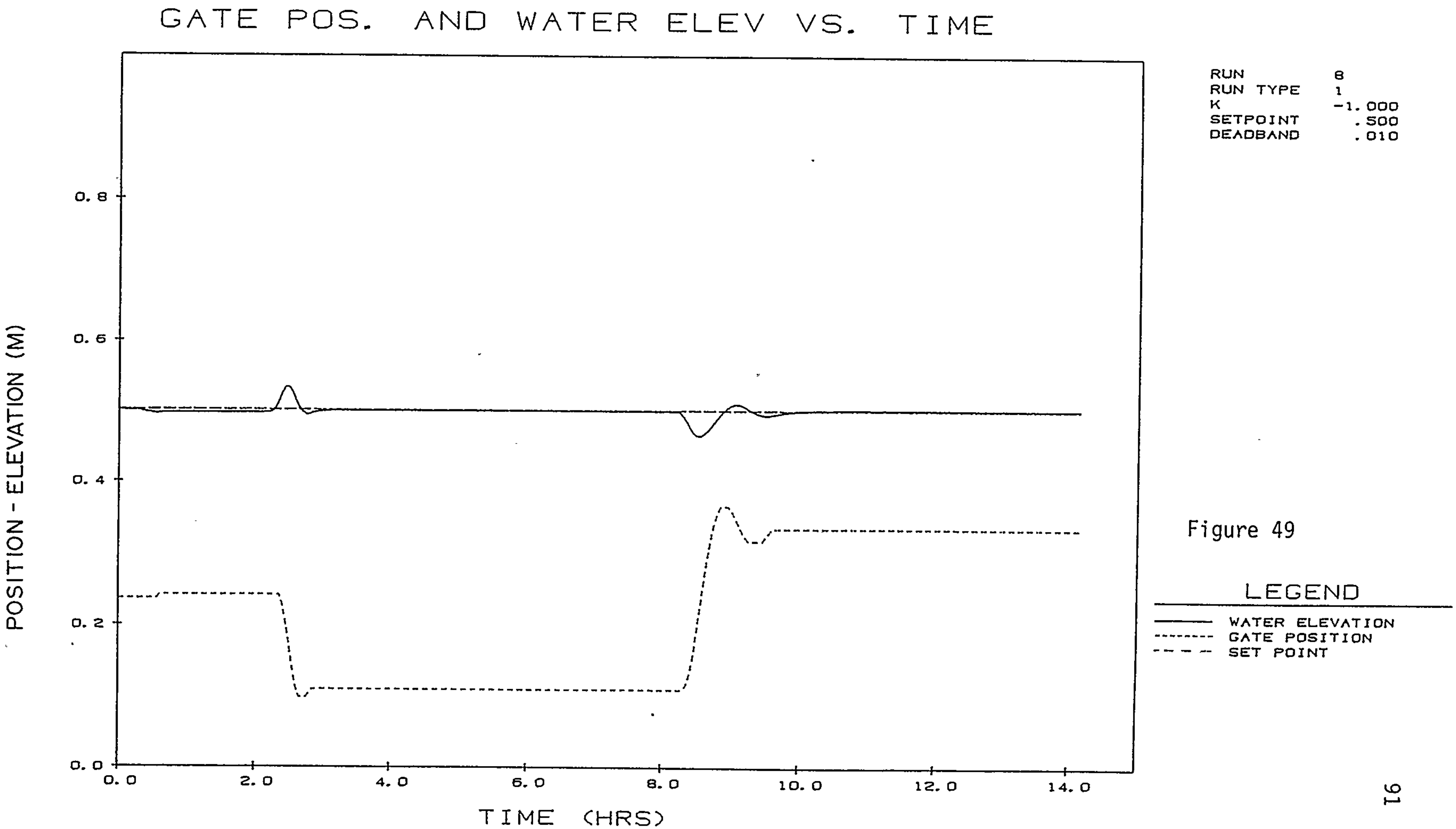

GATE POS. AND WATER ELEV VS. TIME
RUN 7
RUN TYPE 1
K -.500
SETPOINT .500
DEADBAND .010
POSITION - ELEVATION (M)
0.0
0.2
0.4
0.6
0.8
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
TIME (HRS)
LEGEND
WATER ELEVATION
GATE POSITION
SET POINT

Figure 48



GATE POS. AND WATER ELEV VS. TIME
RUN 8
RUN TYPE 1
K -1.000
SETPOINT .500
DEADBAND .010
POSITION - ELEVATION (M)
0.0
0.2
0.4
0.6
0.8
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
TIME (HRS)
LEGEND
WATER ELEVATION
GATE POSITION
SET POINT

Figure 49

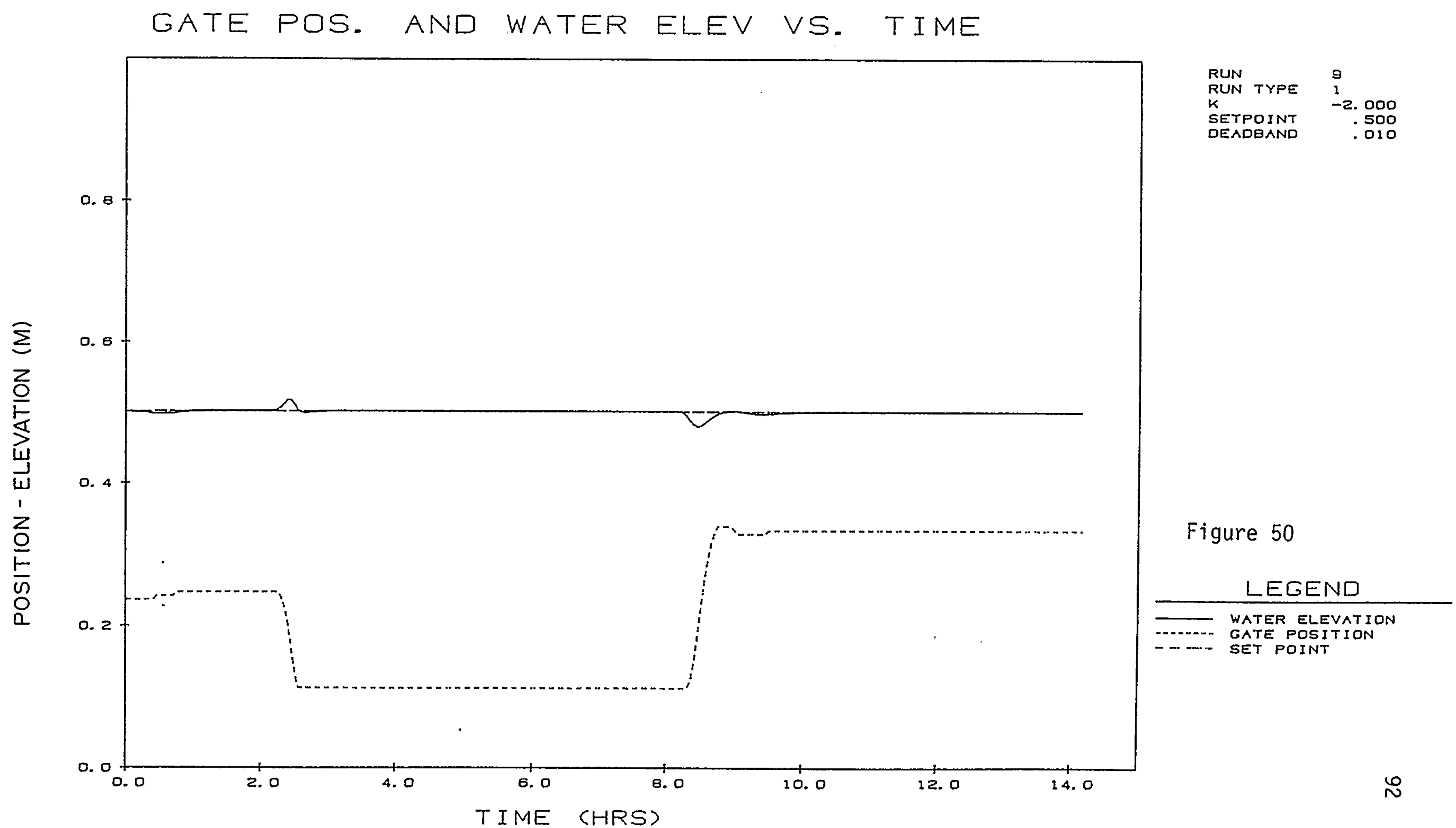

GATE POS. AND WATER ELEV VS. TIME
RUN 9
RUN TYPE 1
K -2.000
SETPOINT .500
DEADBAND .010
POSITION - ELEVATION (M)
0.0
0.2
0.4
0.6
0.8
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
TIME (HRS)
LEGEND
WATER ELEVATION
GATE POSITION
SET POINT

Figure 50

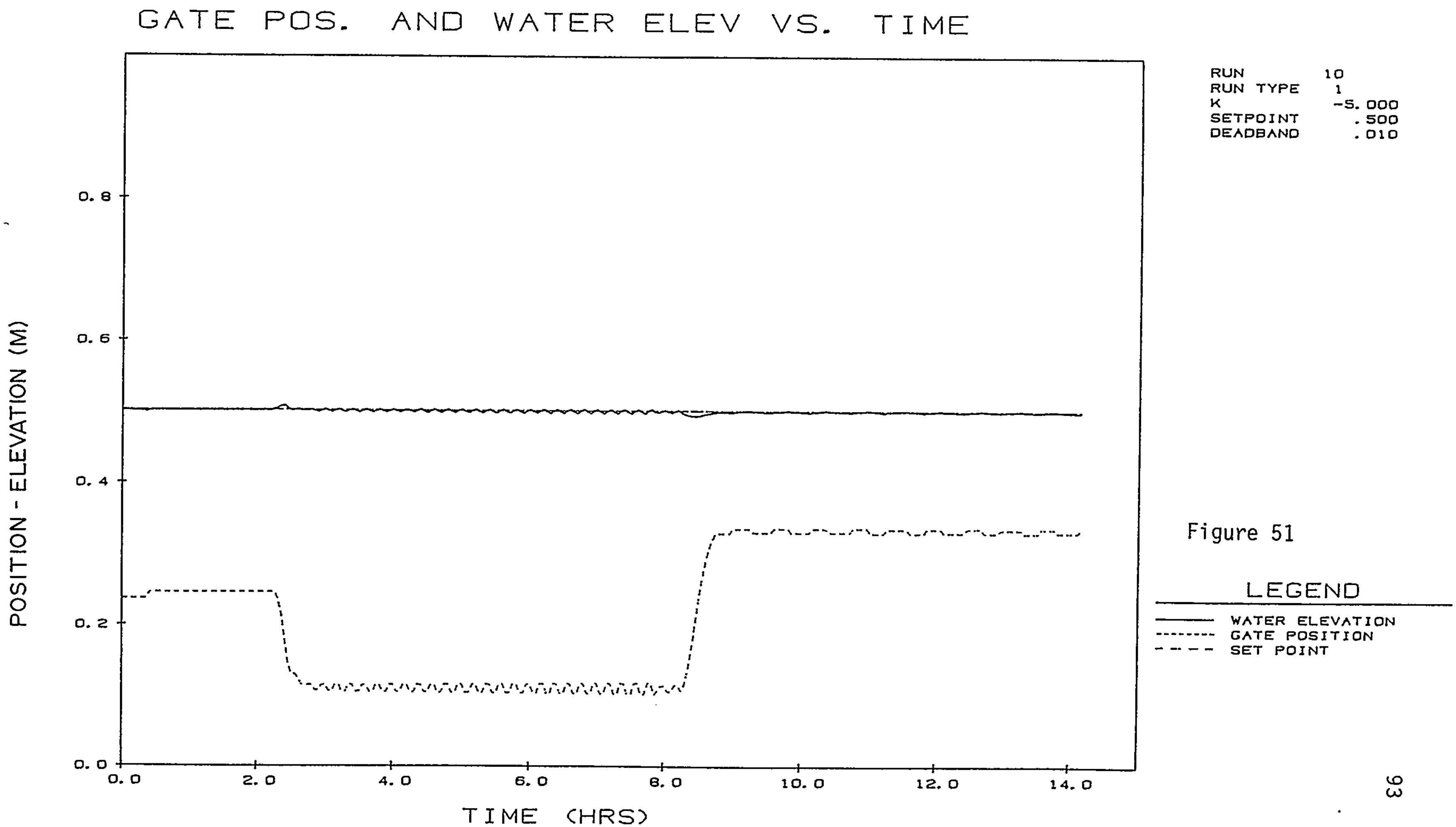

GATE POS. AND WATER ELEV VS. TIME
RUN 10
RUN TYPE 1
K -5.000
SETPOINT .500
DEADBAND .010
0.8
0.6
0.4
0.2
0.0
POSITION - ELEVATION (M)
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
TIME (HRS)
LEGEND
WATER ELEVATION
GATE POSITION
SET POINT

Figure 51

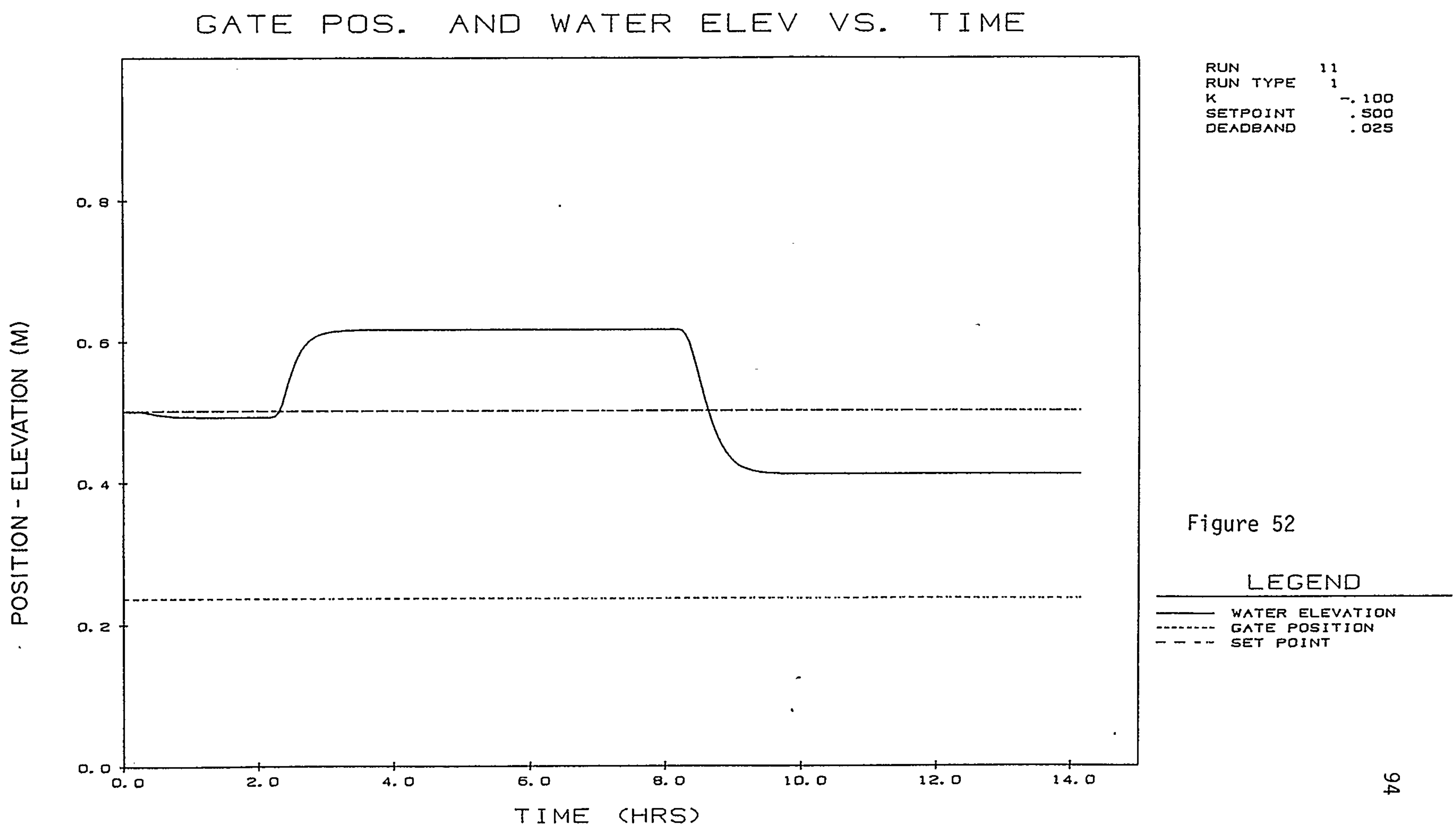

GATE POS. AND WATER ELEV VS. TIME
RUN 11
RUN TYPE 1
K -.100
SETPOINT .500
DEADBAND .025
POSITION - ELEVATION (M)
0.0
0.2
0.4
0.6
0.8
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
TIME (HRS)
LEGEND
WATER ELEVATION
GATE POSITION
SET POINT

Figure 52

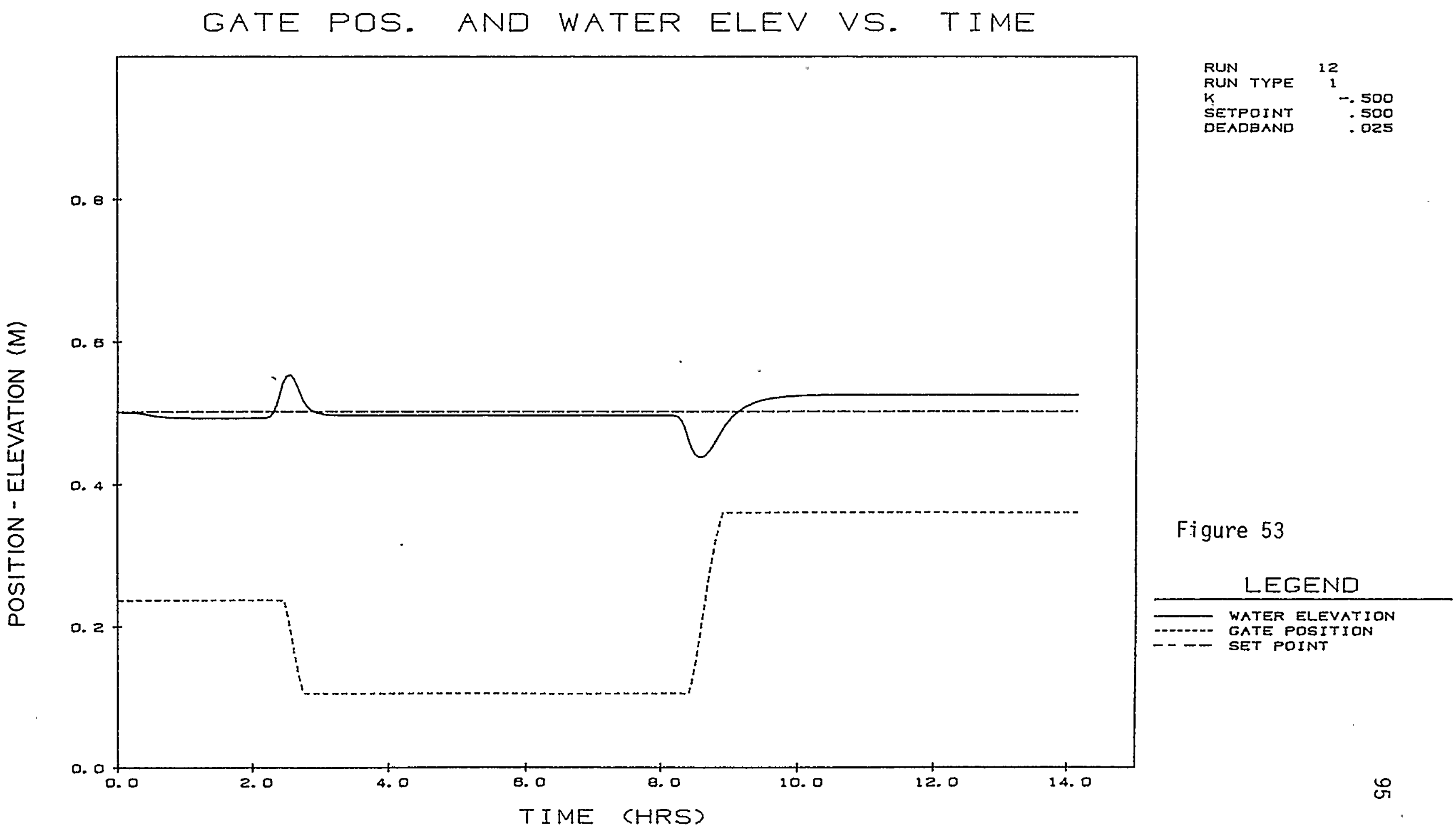

GATE POS. AND WATER ELEV VS. TIME
RUN 12
RUN TYPE 1
K -.500
SETPOINT .500
DEADBAND .025
POSITION - ELEVATION (M)
0.0
0.2
0.4
0.6
0.8
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
TIME (HRS)
LEGEND
WATER ELEVATION
GATE POSITION
SET POINT

Figure 53

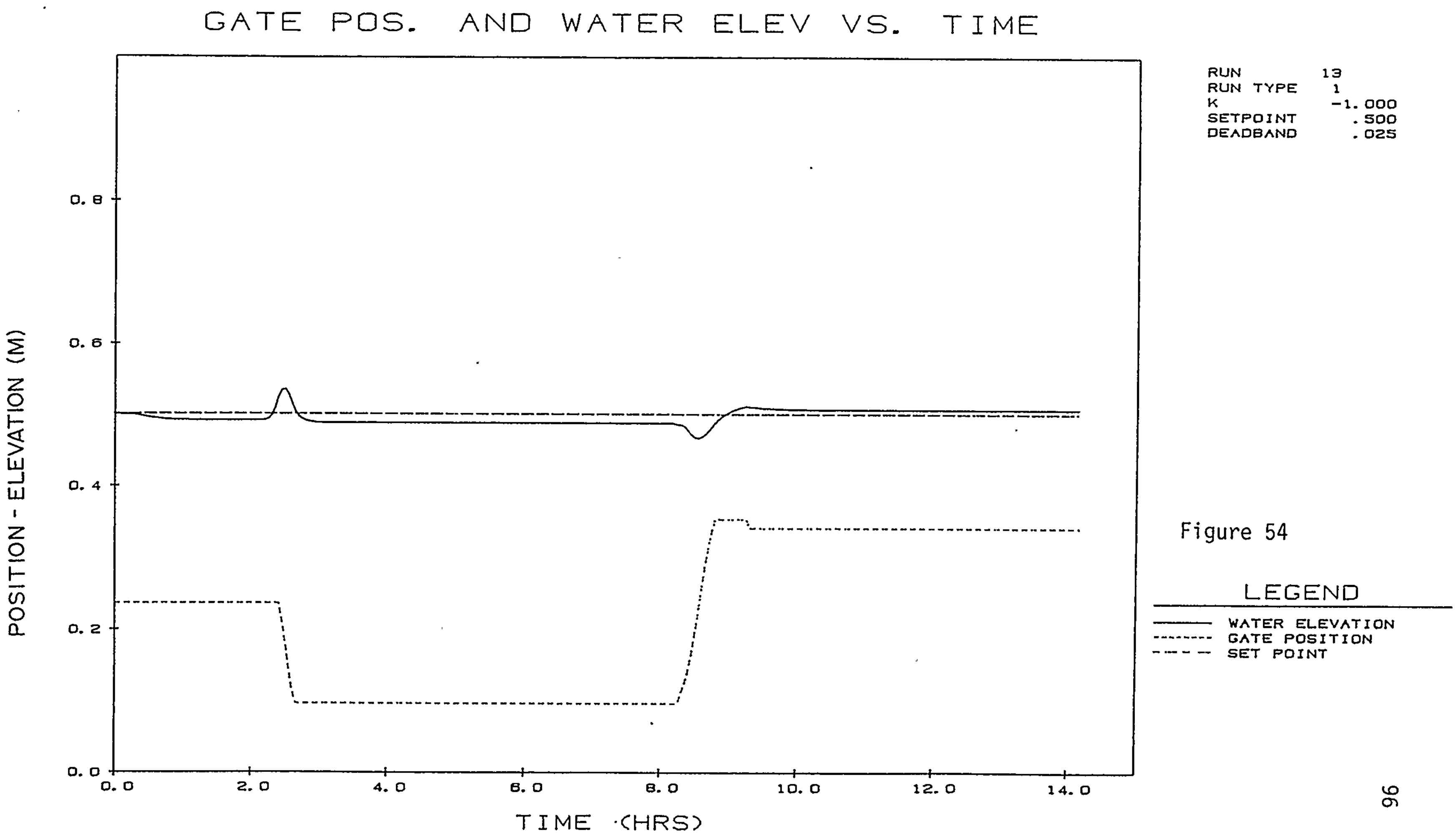

GATE POS. AND WATER ELEV VS. TIME
RUN 13
RUN TYPE 1
K -1.000
SETPOINT .500
DEADBAND .025
POSITION - ELEVATION (M)
0.0
0.2
0.4
0.6
0.8
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
TIME (HRS)
LEGEND
WATER ELEVATION
GATE POSITION
SET POINT

Figure 54

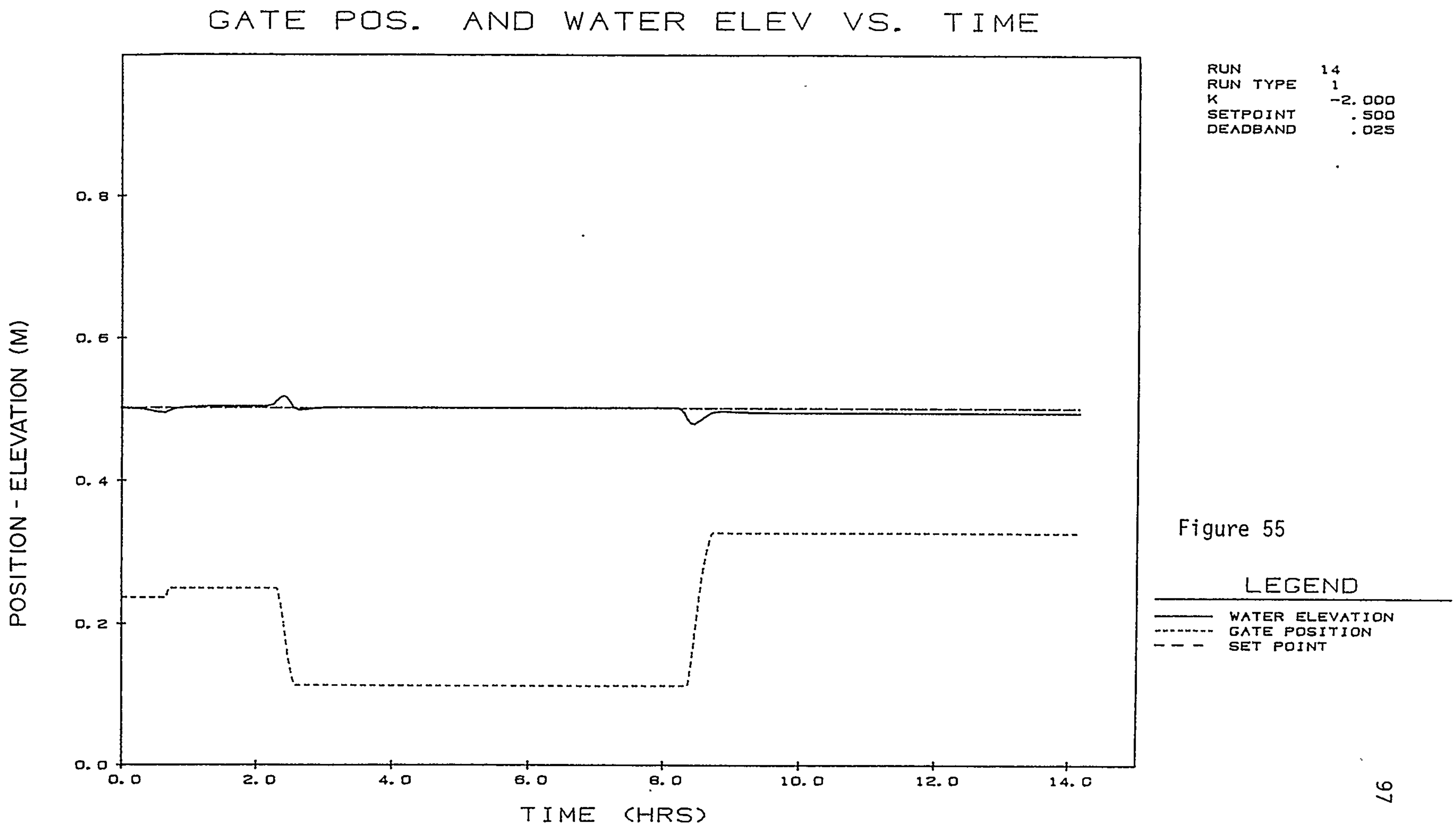
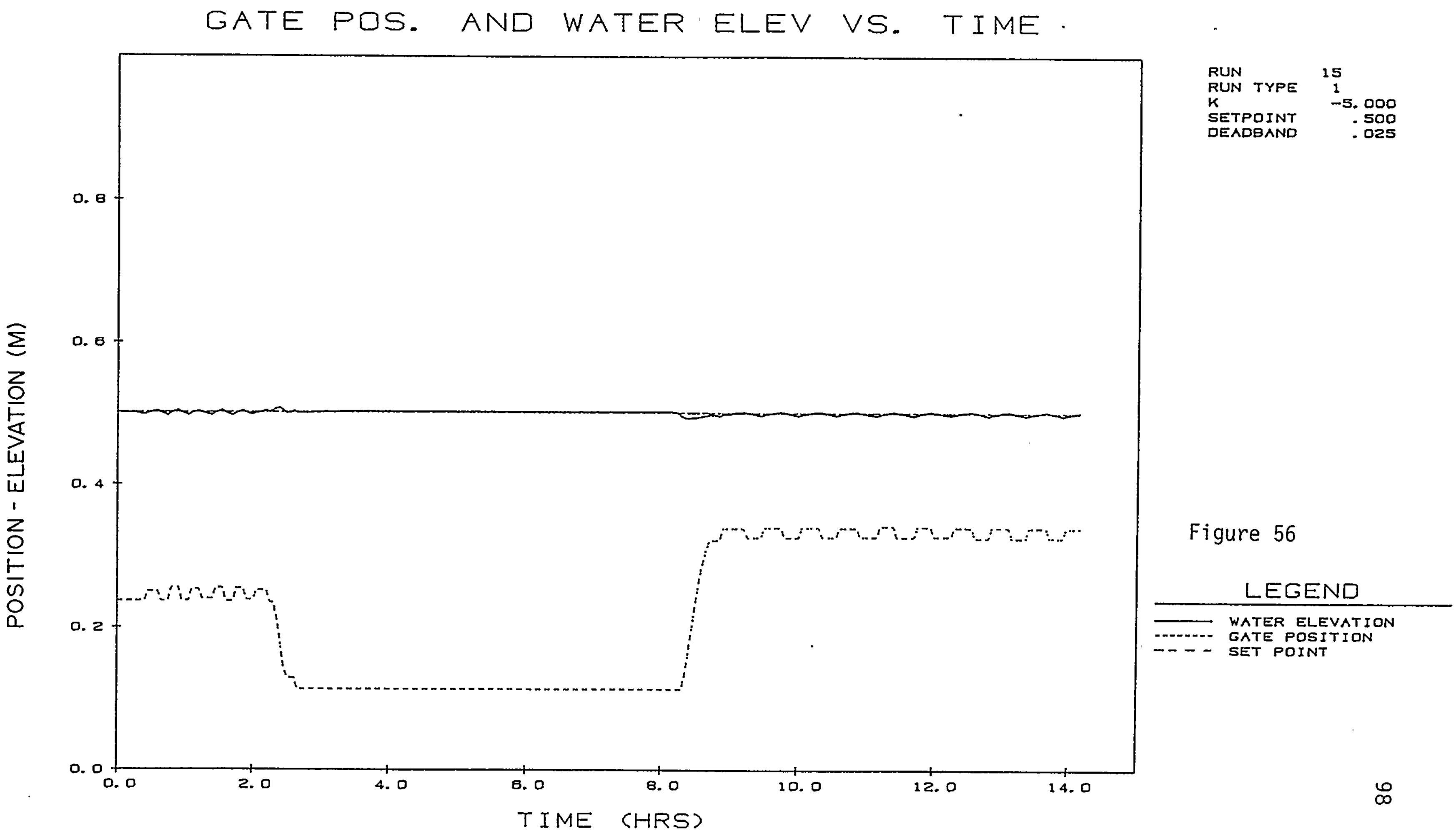

GATE POS. AND WATER ELEV VS. TIME
RUN 14
RUN TYPE 1
K -2.000
SETPOINT .500
DEADBAND .025
0.8
0.6
0.4
0.2
0.0
POSITION - ELEVATION (M)
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
TIME (HRS)
LEGEND
WATER ELEVATION
GATE POSITION
SET POINT

Figure 55



GATE POS. AND WATER ELEV VS. TIME
POSITION - ELEVATION (M)
0.0
0.2
0.4
0.6
0.8
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
TIME (HRS)
RUN 15
RUN TYPE 1
K -5.000
SETPOINT .500
DEADBAND .025
LEGEND
WATER ELEVATION
GATE POSITION
SET POINT

Figure 56

GATE POS. AND WATER ELEV VS. TIME

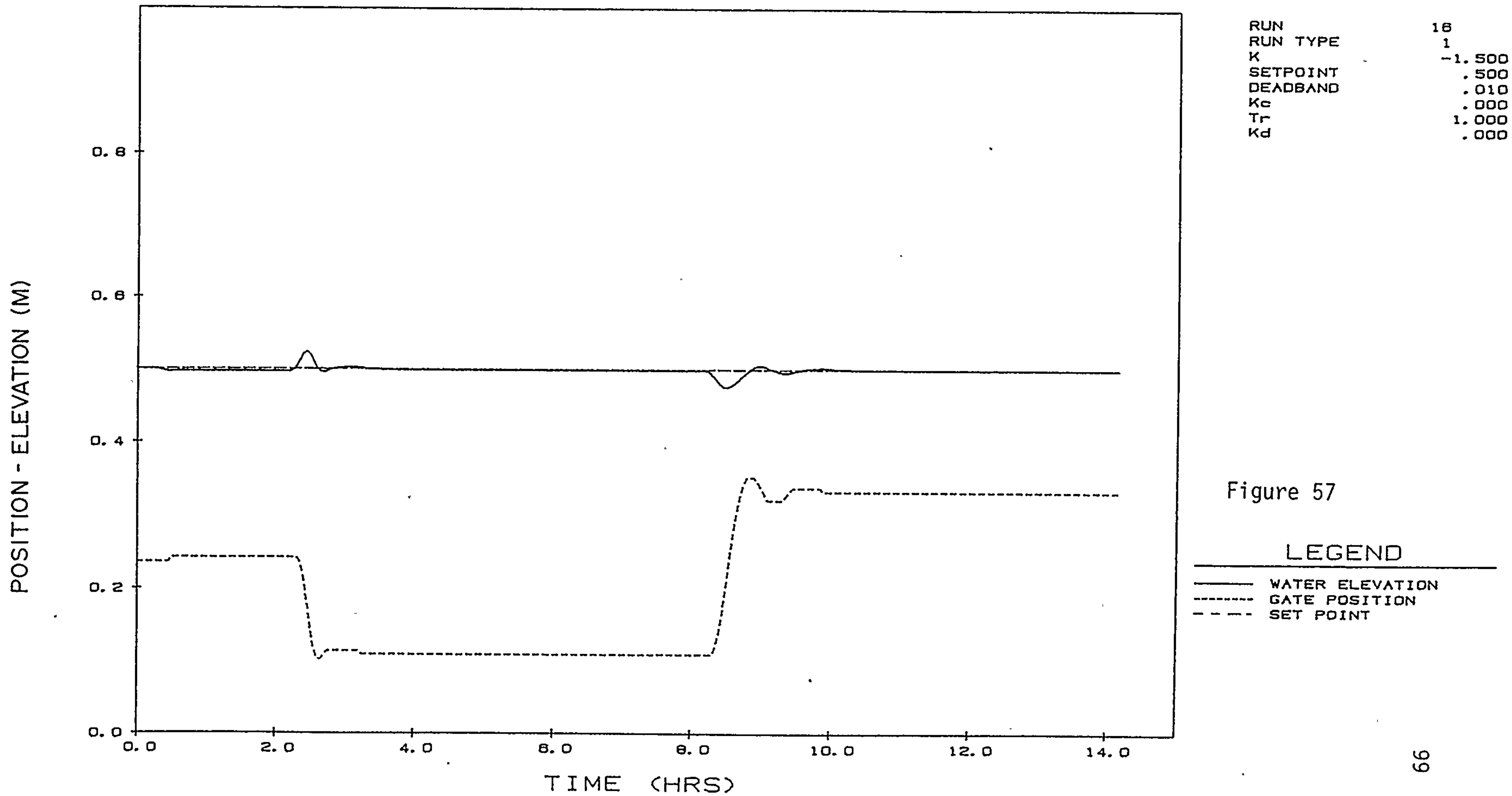


Figure 57

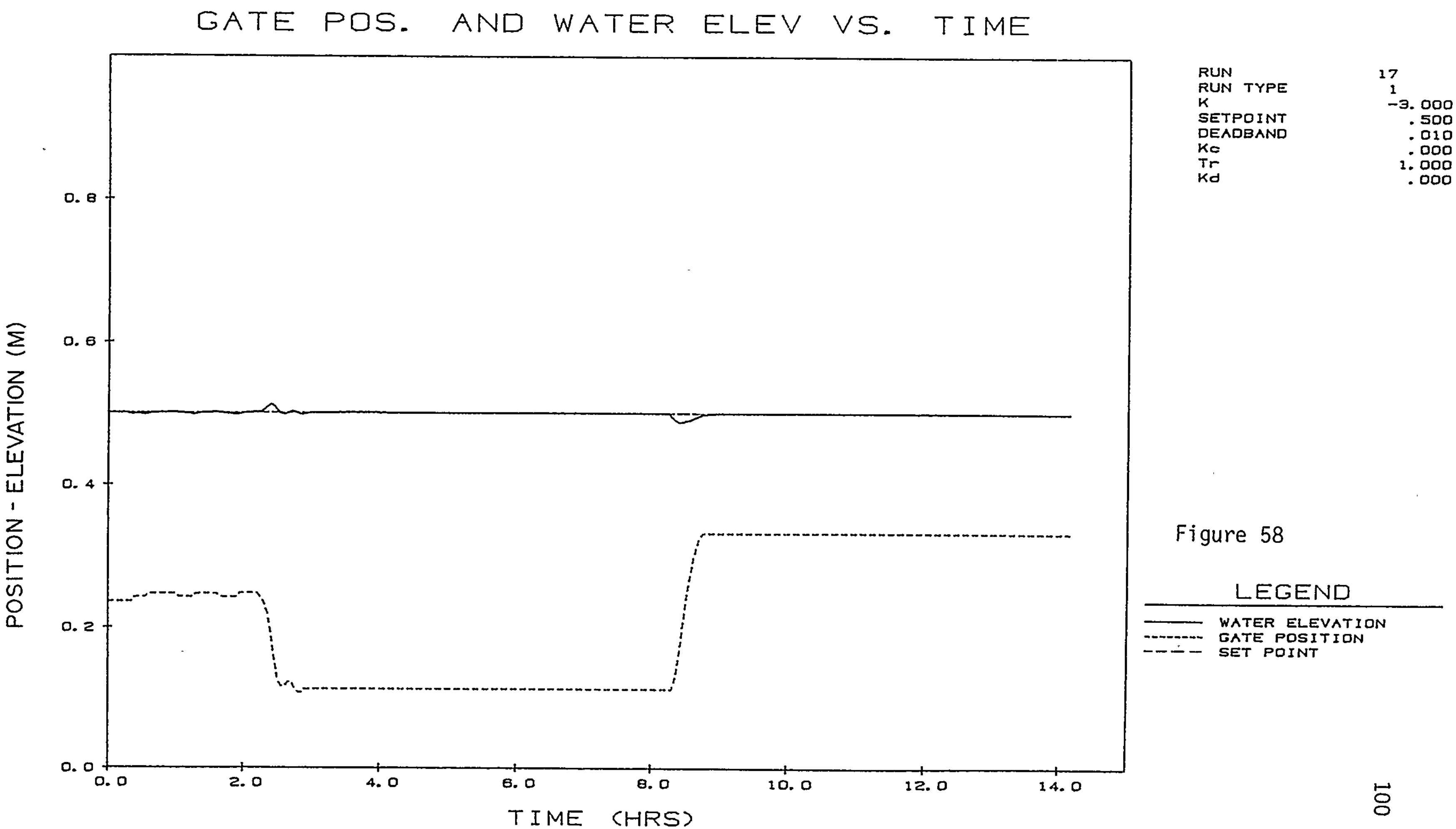

GATE POS. AND WATER ELEV VS. TIME
POSITION - ELEVATION (M)
0.0
0.2
0.4
0.6
0.8
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
TIME (HRS)
RUN 17
RUN TYPE 1
K -3.000
SETPOINT .500
DEADBAND .010
Kc .000
Tr 1.000
Kd .000
LEGEND
WATER ELEVATION
GATE POSITION
SET POINT

Figure 58

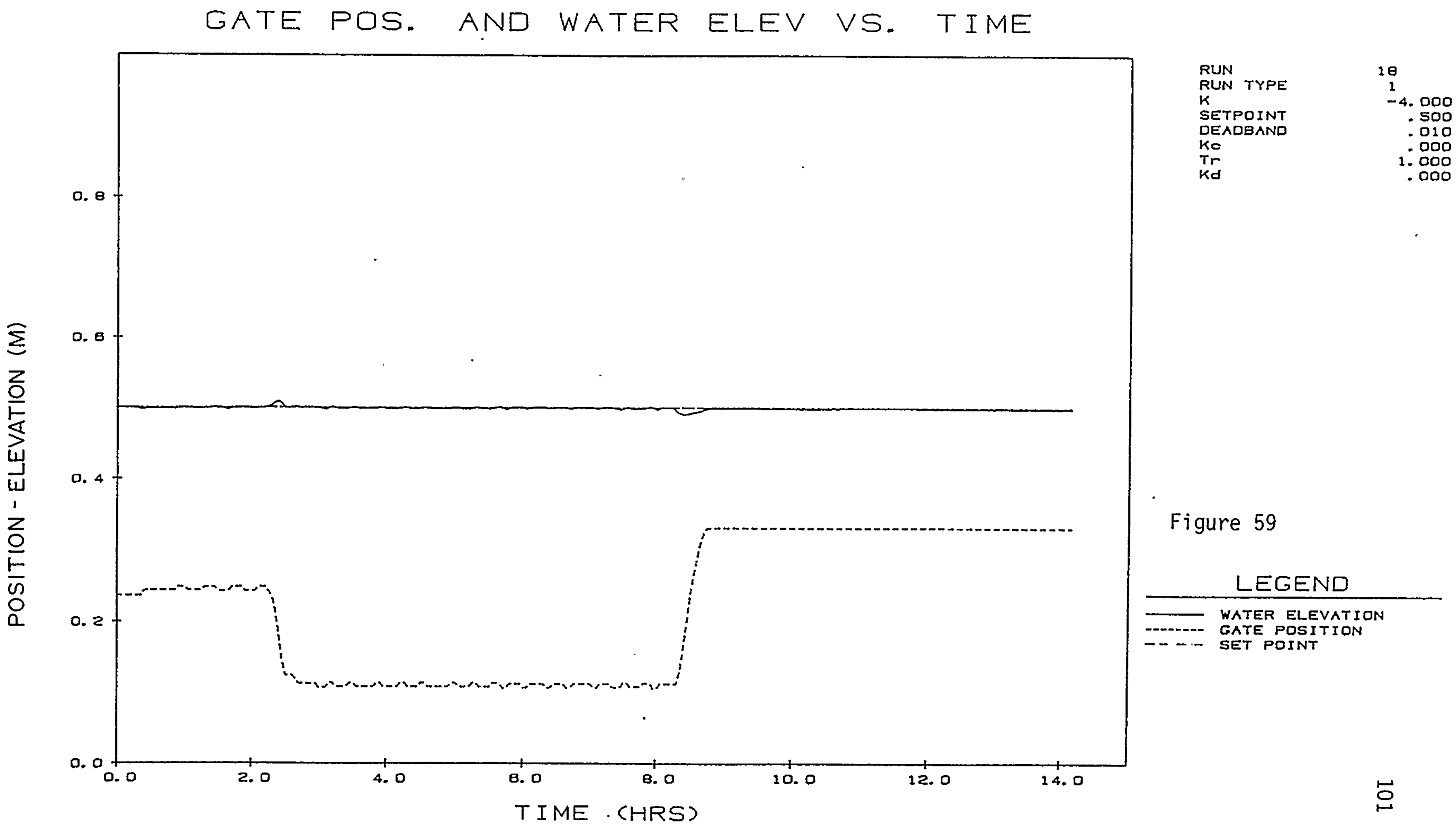

GATE POS. AND WATER ELEV VS. TIME
RUN 18
RUN TYPE 1
K -4.000
SETPOINT .500
DEADBAND .010
Kc .000
Tr 1.000
Kd .000
0.8
0.6
0.4
0.2
0.0
POSITION - ELEVATION (M)
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
TIME (HRS)
LEGEND
WATER ELEVATION
GATE POSITION
SET POINT

Figure 59

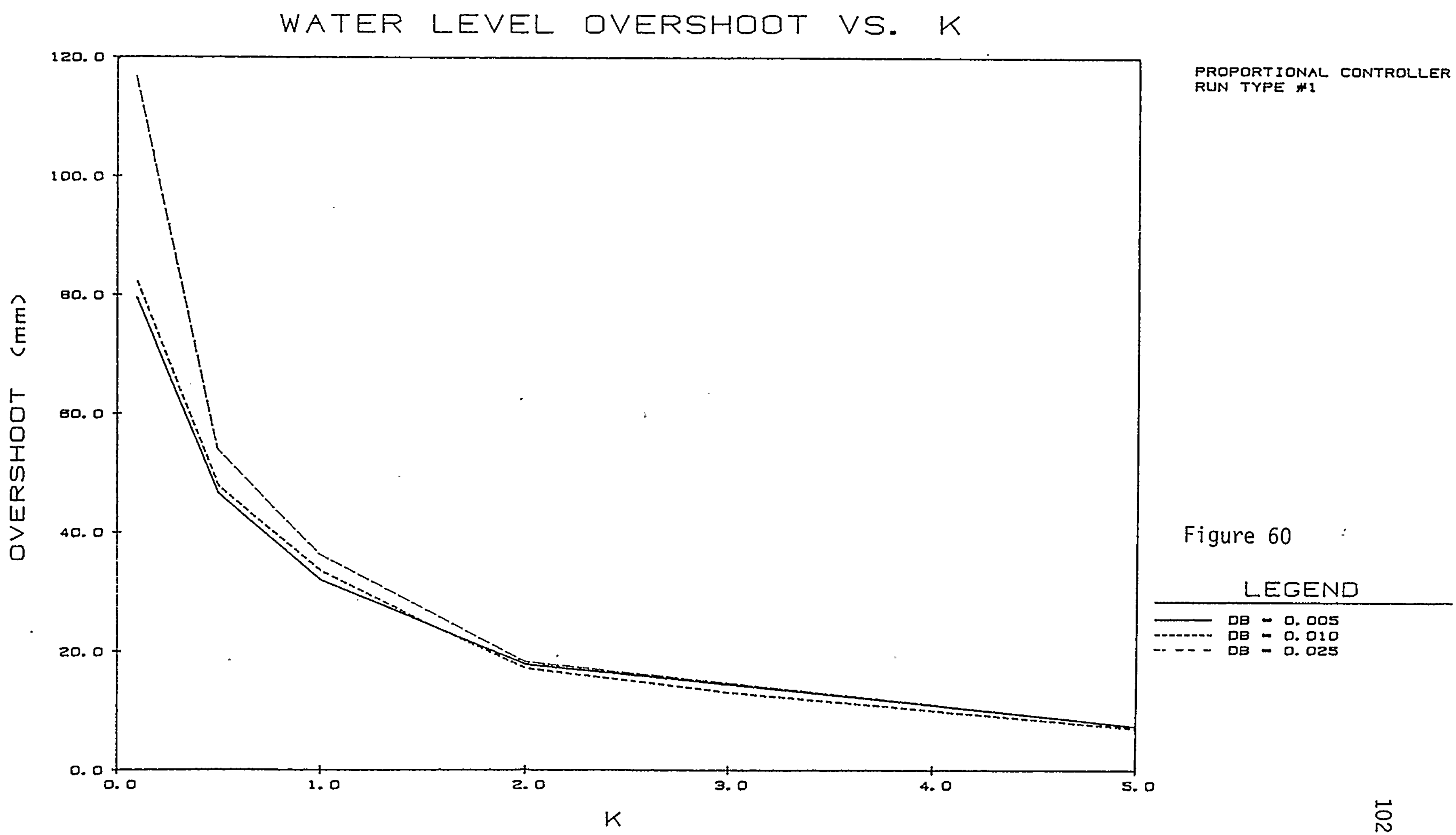

WATER LEVEL OVERSHOOT VS. K
PROPORTIONAL CONTROLLER
RUN TYPE #1
OVERSHOOT (mm)
120.0
100.0
80.0
60.0
40.0
20.0
0.0
0.0
1.0
2.0
3.0
4.0
5.0
K
LEGEND
DB = 0.005
DB = 0.010
DB = 0.025

Figure 60

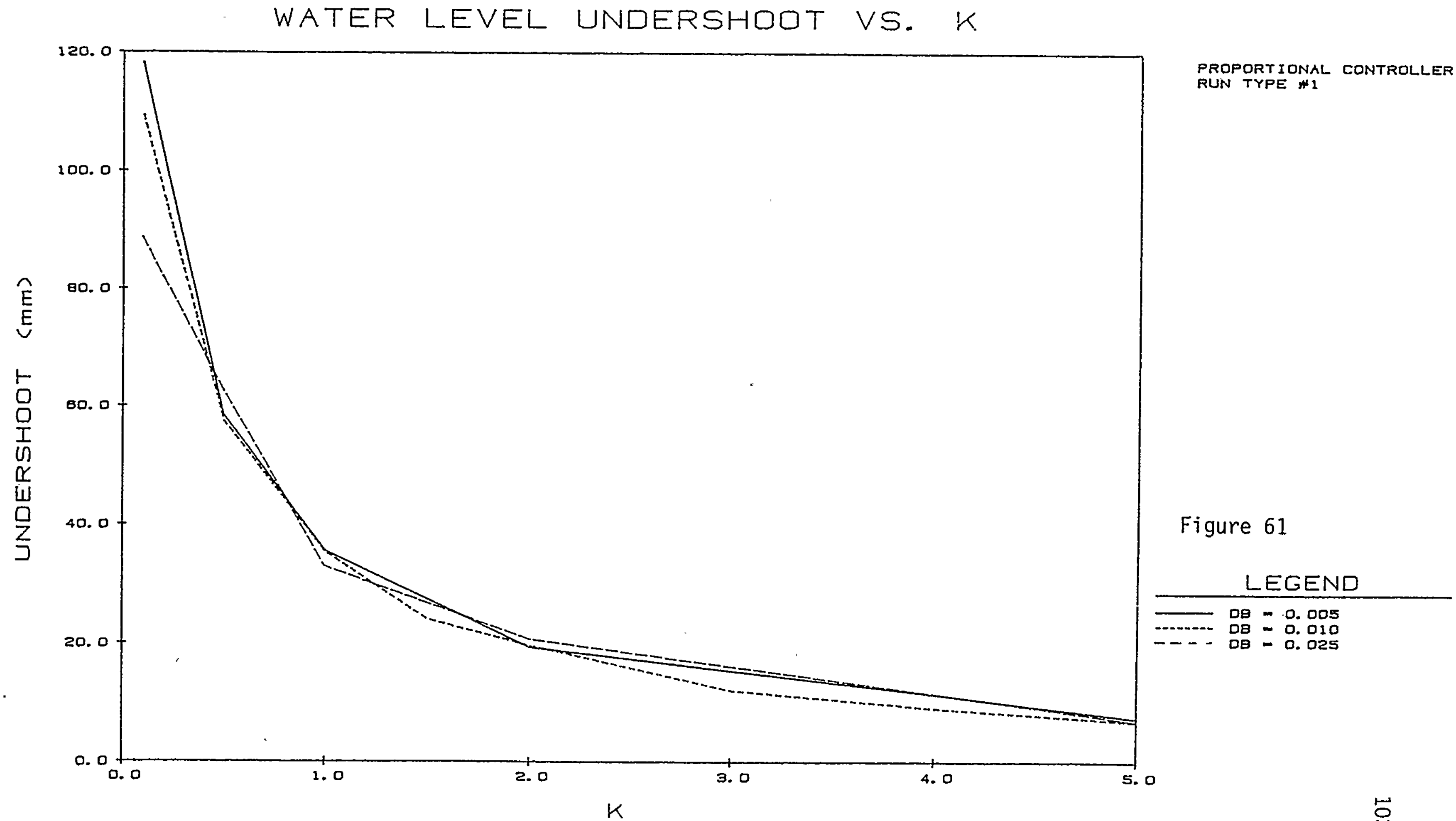

WATER LEVEL UNDERSHOOT VS. K
120.0
100.0
80.0
60.0
40.0
20.0
0.0
UNDERSHOOT (mm)
0.0
1.0
2.0
3.0
4.0
5.0
K
PROPORTIONAL CONTROLLER
RUN TYPE #1
LEGEND
DB = 0.005
DB = 0.010
DB = 0.025

Figure 61

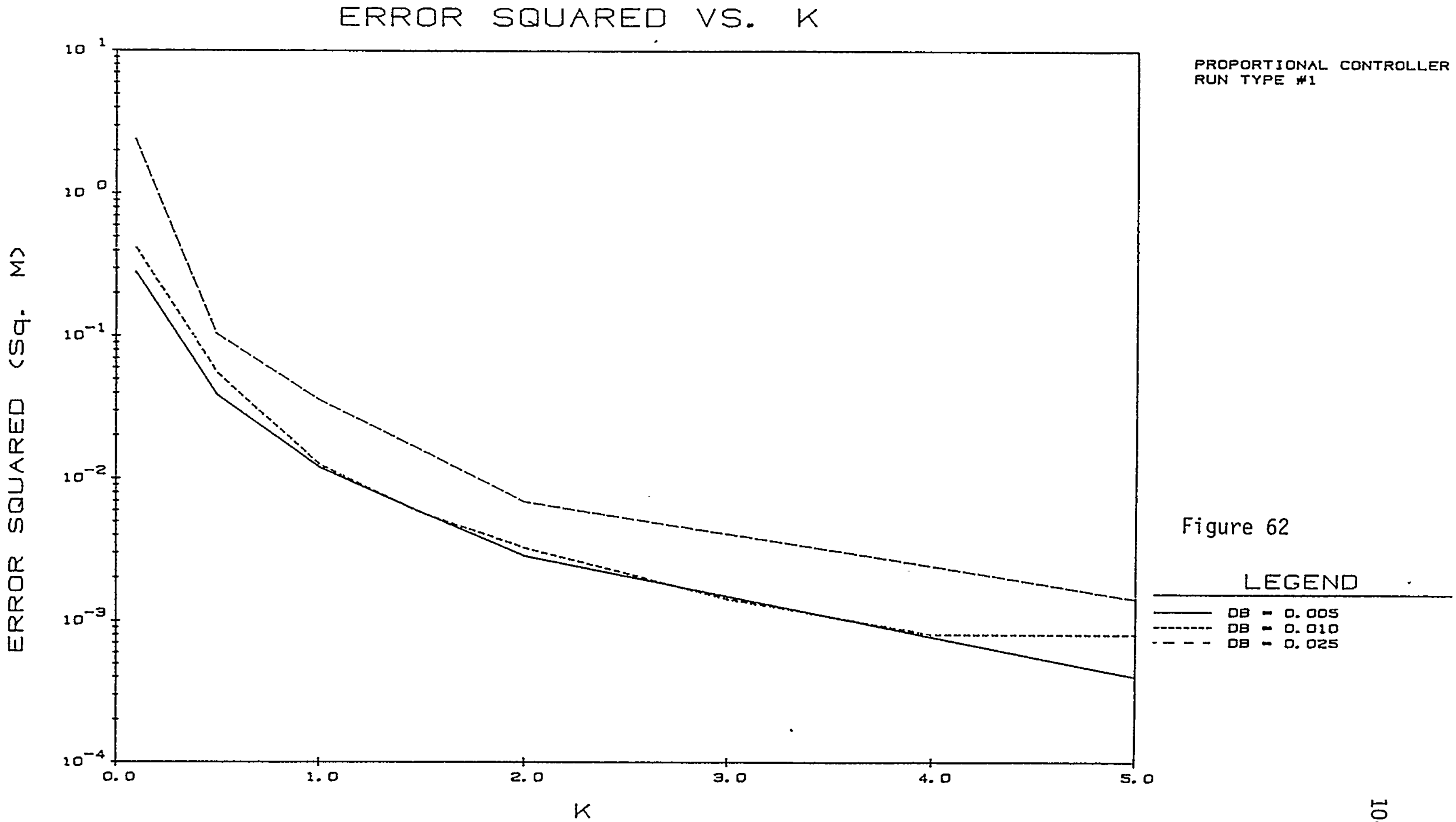

ERROR SQUARED VS. K
PROPORTIONAL CONTROLLER
RUN TYPE #1
ERROR SQUARED (Sq. M)
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0.0
1.0
2.0
3.0
4.0
5.0
K
LEGEND
DB = 0.005
DB = 0.010
DB = 0.025

Figure 62

undershoot seems to be exponential. The reduction in the e^2 term diminishes even more rapidly than the overshoot and undershoot terms.

Table 11. Proportional Controller; Maximum Overshoot, Undershoot and sum of e^2 terms for different parameter settings.

K_p	Overshoot (mm)	Undershoot (mm)	Sum of e^2 $(mm)^2$	Deadband (M)	Run #
0.1	79.4	118.1	0.2787	0.005	1
0.5	46.6	58.3	0.0384	0.005	2
1.0	31.9	35.4	0.0118	0.005	3
2.0	17.9	19.3	0.0028	0.005	4
5.0	7.4	7.4	0.0004	0.005	5
0.1	82.2	109.3	0.4160	0.010	6
0.5	47.8	57.3	0.0546	0.010	7
1.0	33.4	35.2	0.0124	0.010	8
1.5	25.0	24.0	0.0057	0.010	16
2.0	17.2	19.6	0.0032	0.010	9
3.0	13.0	12.0	0.0014	0.010	17
4.0	10.0	9.0	0.0008	0.010	18
5.0	7.0	6.8	0.0008	0.010	19
0.1	16.6	88.7	2.3845	0.025	11
0.5	53.8	62.7	0.1022	0.025	12
1.0	36.1	32.7	0.0357	0.025	13
2.0	18.3	20.6	0.0068	0.025	14
5.0	7.3	6.8	0.0014	0.025	15

The best values of the overshoot, undershoot and the e^2 term occur in run numbers 5, 10 and 15. As discussed previously, however, the controller mechanism has become unstable and thus the mathematical evaluation cannot be relied upon for a complete evaluation of the controller.

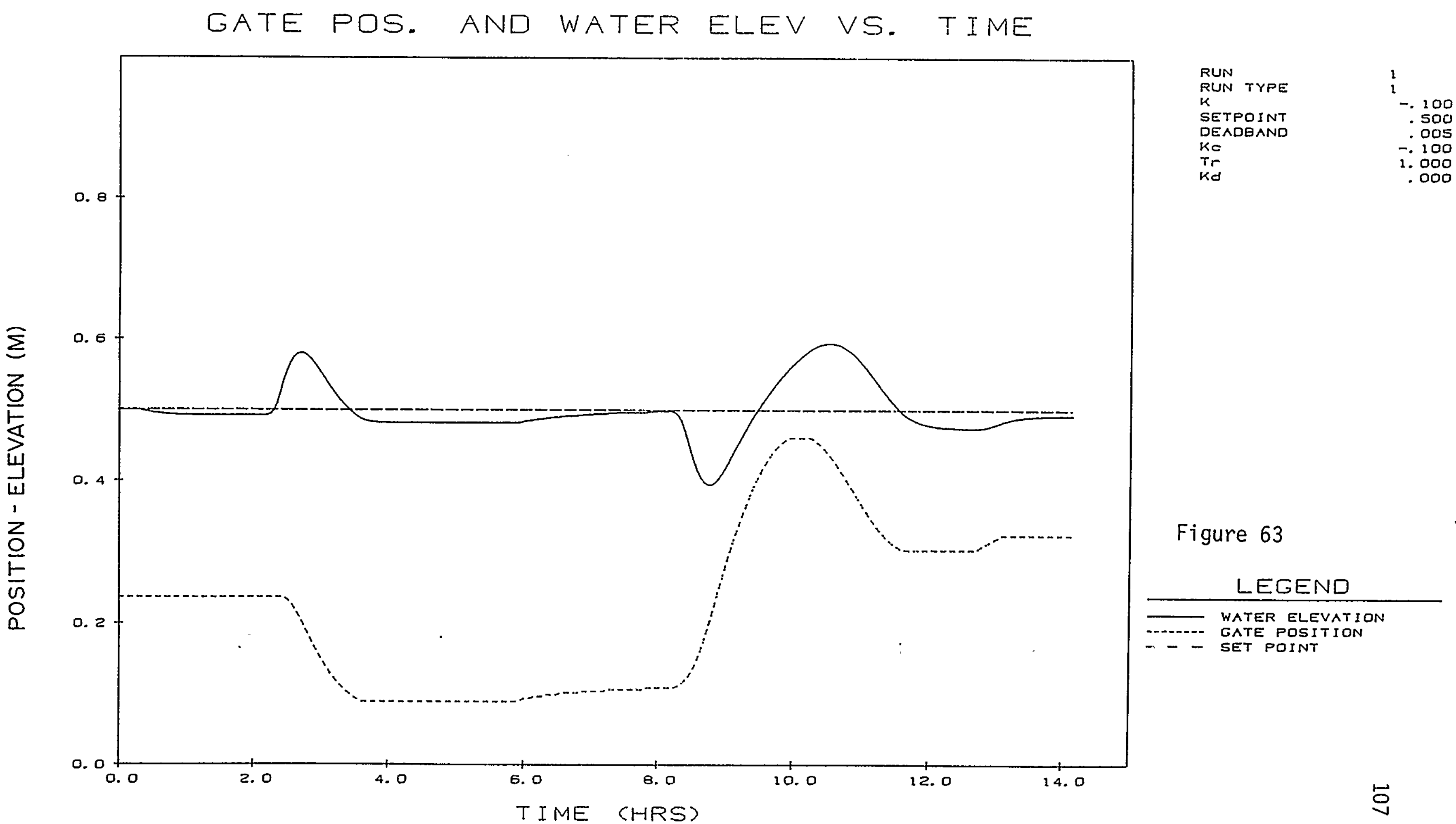
Run numbers 1 through 5 are basically duplicated within runs 6 through 10 and 11 through 15 using different deadbands. The differences in the operation of the controller is most noticeable when the values of K_p are small. Comparing Run numbers 1, 6 and 11 (Figures 42, 47 and 52) it is evident that the ability of the controller to converge to the desired water level is diminished as the deadband grows larger. Comparing the e^2 term for these runs indicates that the quality of control becomes much less as the deadband increases. This large disparity can be explained by recalling the proportional control equation (Section 2.3.6) where the gate position correction factor is equal to K_p times the difference between the actual water level and the desired water level. Additionally, if the calculated gate position correction is less than the deadband, no movement of the gate takes place. It is easy to see that in this circumstance small values of K_p require larger errors if the calculated change in gate position is to be greater than the deadband.

Examining Figure 62 we can see that the e^2 term for the 0.005 m and 0.010 m deadbands quickly become very similar as the values of K_p become larger. The 0.025 m deadband e^2 term is always higher than either the 0.010 m or the 0.005 m deadbands. Note the larger e^2 term for the 0.010 m deadband when K_p is equal to 5. This larger value of e^2 is due to the instability of the controller.

In examining Figures 60 and 61 the water level overshoots and undershoots become very similar for all deadbands as the value of K_p increases.

7.4 PROPORTIONAL + INTEGRAL CONTROLLER

The gate and water responses to a type 1 input disturbance are presented in Figures 63 - 89. The values of K_p and K_i are assigned the same values for run numbers 1-18 (Figures 63-80). Runs 1-5, 6-10 and 11-15 have the same parameter settings with the exception of the gate deadband. The gate deadband is increased from 0.005 m to 0.010 m to 0.025 m respectively. Run numbers 16-18 are experiments performed with a deadband of 0.010 m and parameter settings chosen to fill in areas in run numbers 6-10.


GATE POS. AND WATER ELEV VS. TIME
POSITION - ELEVATION (M)
0.0
0.2
0.4
0.6
0.8
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
TIME (HRS)
RUN 1
RUN TYPE 1
K -.100
SETPOINT .500
DEADBAND .005
Kc -.100
Tr 1.000
Kd .000
LEGEND
WATER ELEVATION
GATE POSITION
SET POINT
Figure 63

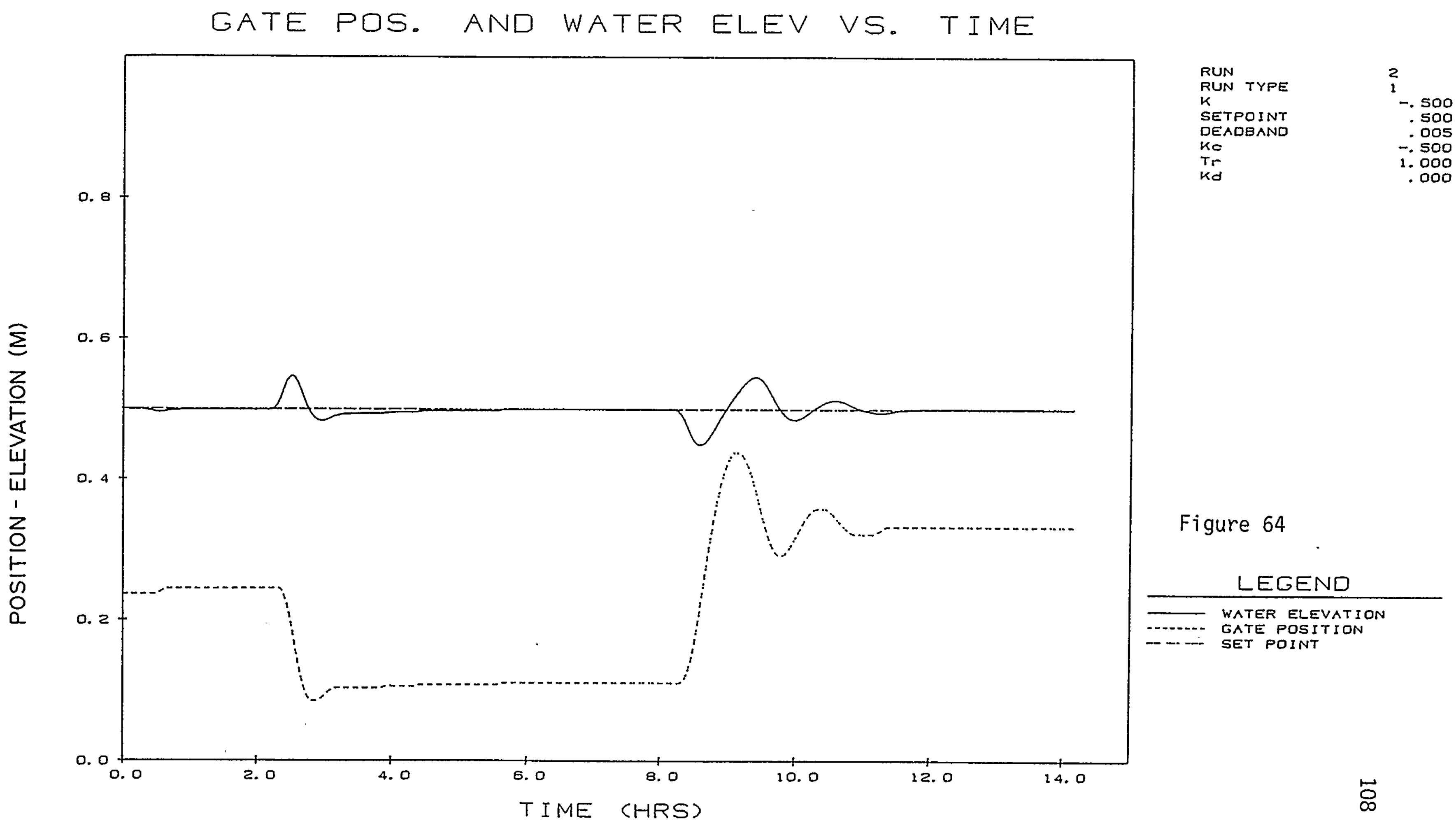

GATE POS. AND WATER ELEV VS. TIME
POSITION - ELEVATION (M)
0.0
0.2
0.4
0.6
0.8
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
TIME (HRS)
RUN 2
RUN TYPE 1
K -.500
SETPOINT .500
DEADBAND .005
Kc -.500
Tr 1.000
Kd .000
LEGEND
WATER ELEVATION
GATE POSITION
SET POINT

Figure 64

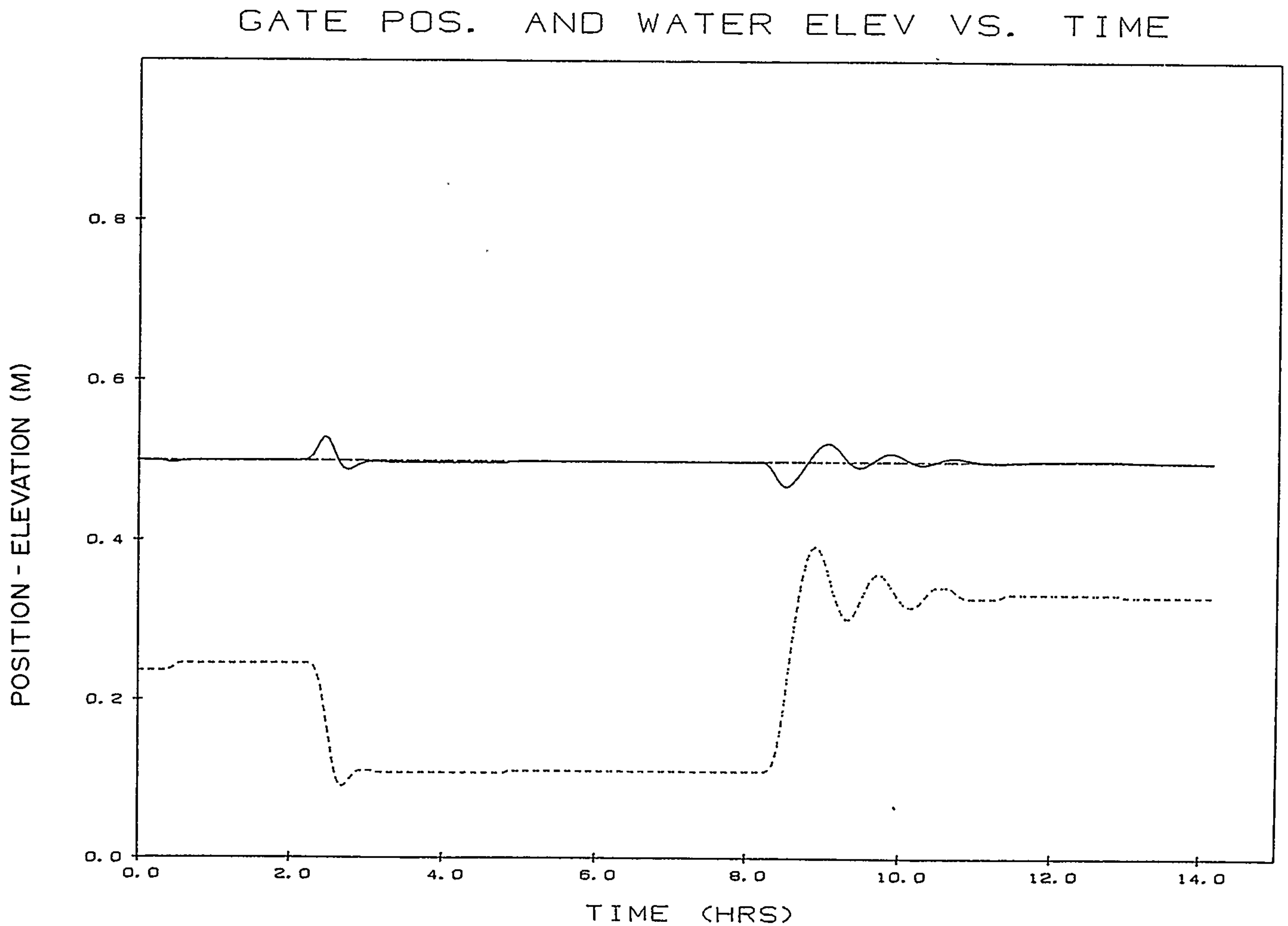

GATE POS. AND WATER ELEV VS. TIME
POSITION - ELEVATION (M)
0.0
0.2
0.4
0.6
0.8
TIME (HRS)
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
RUN 3
RUN TYPE 1
K -1.000
SETPOINT .500
DEADBAND .005
Kc -1.000
Tr 1.000
Kd .000
LEGEND
WATER ELEVATION
GATE POSITION
SET POINT

Figure 65

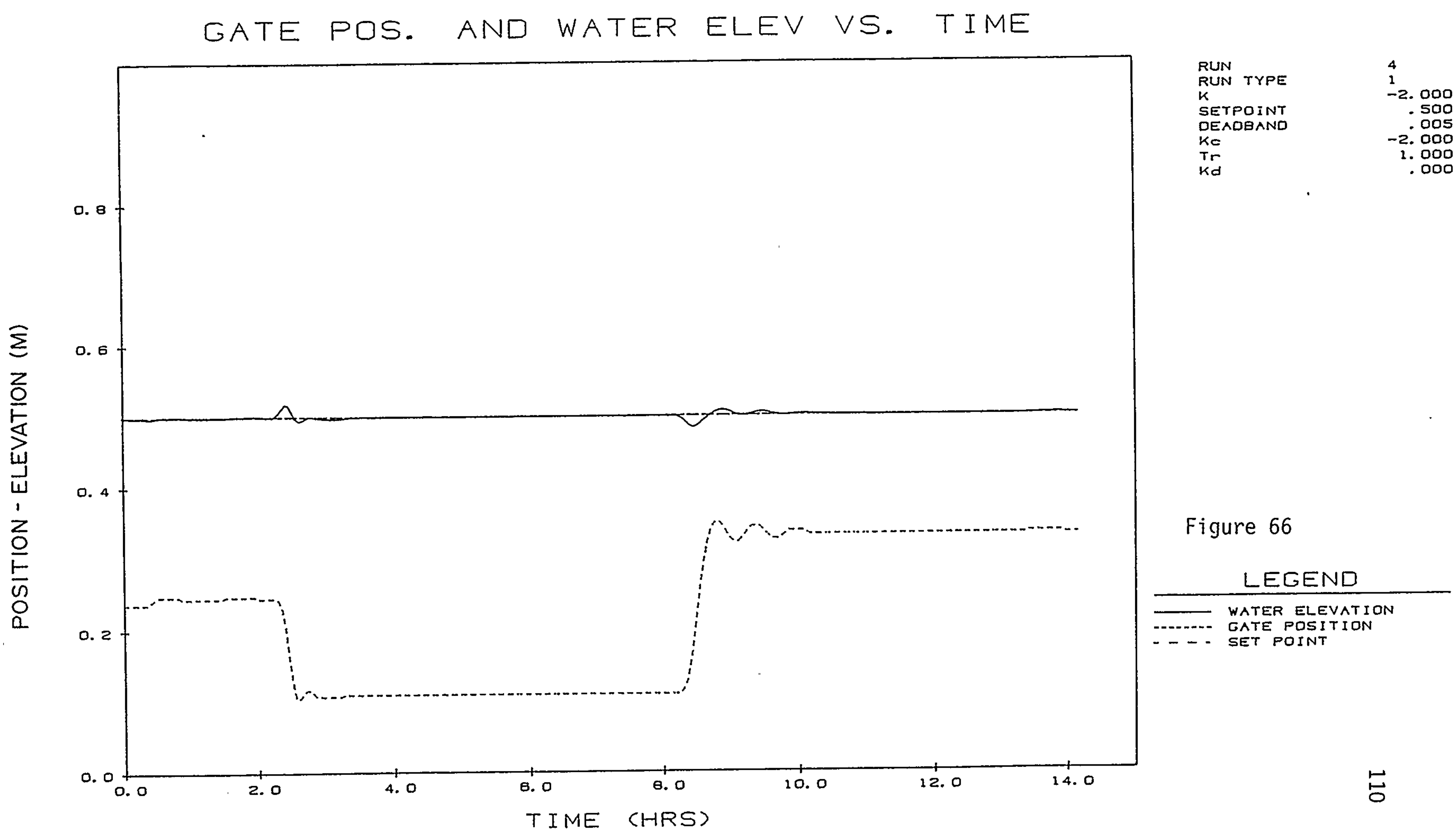
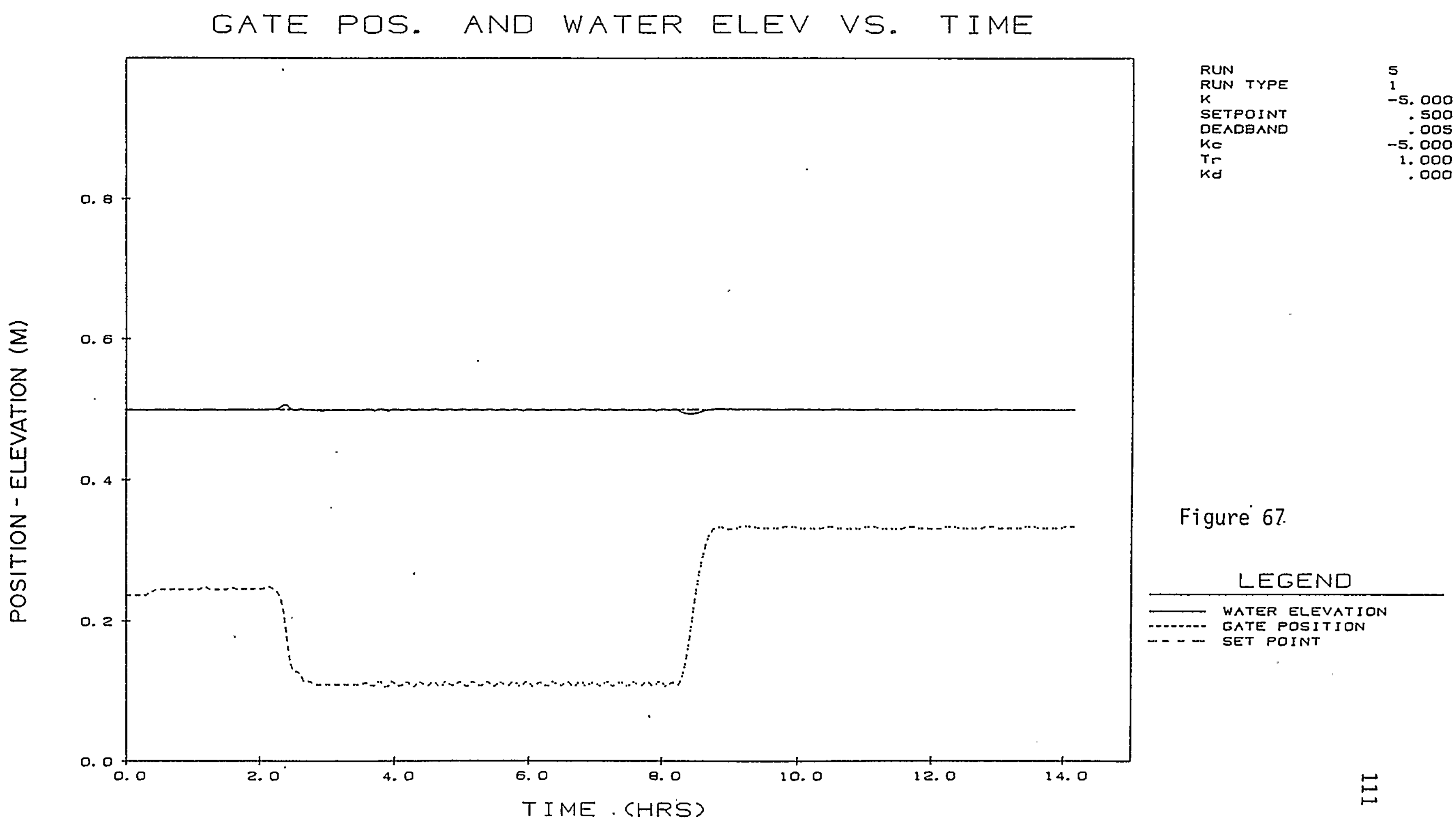

GATE POS. AND WATER ELEV VS. TIME
POSITION - ELEVATION (M)
0.0
0.2
0.4
0.6
0.8
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
TIME (HRS)
RUN 4
RUN TYPE 1
K -2.000
SETPOINT .500
DEADBAND .005
Kc -2.000
Tr 1.000
Kd .000
LEGEND
WATER ELEVATION
GATE POSITION
SET POINT

Figure 66



GATE POS. AND WATER ELEV VS. TIME
RUN 5
RUN TYPE 1
K -5.000
SETPOINT .500
DEADBAND .005
Kc -5.000
Tr 1.000
Kd .000
POSITION - ELEVATION (M)
0.0
0.2
0.4
0.6
0.8
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
TIME (HRS)
LEGEND
WATER ELEVATION
GATE POSITION
SET POINT

Figure 67

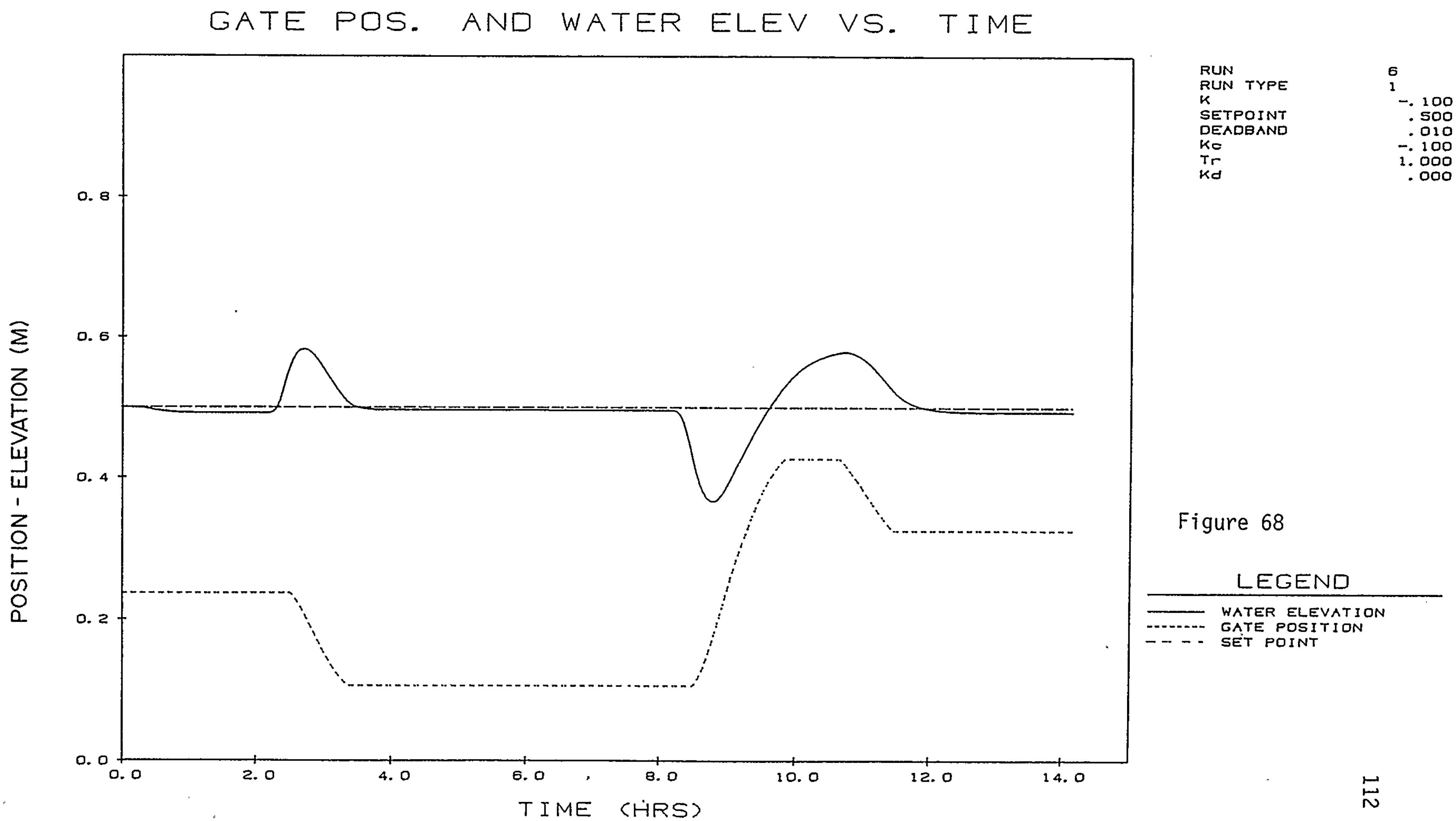
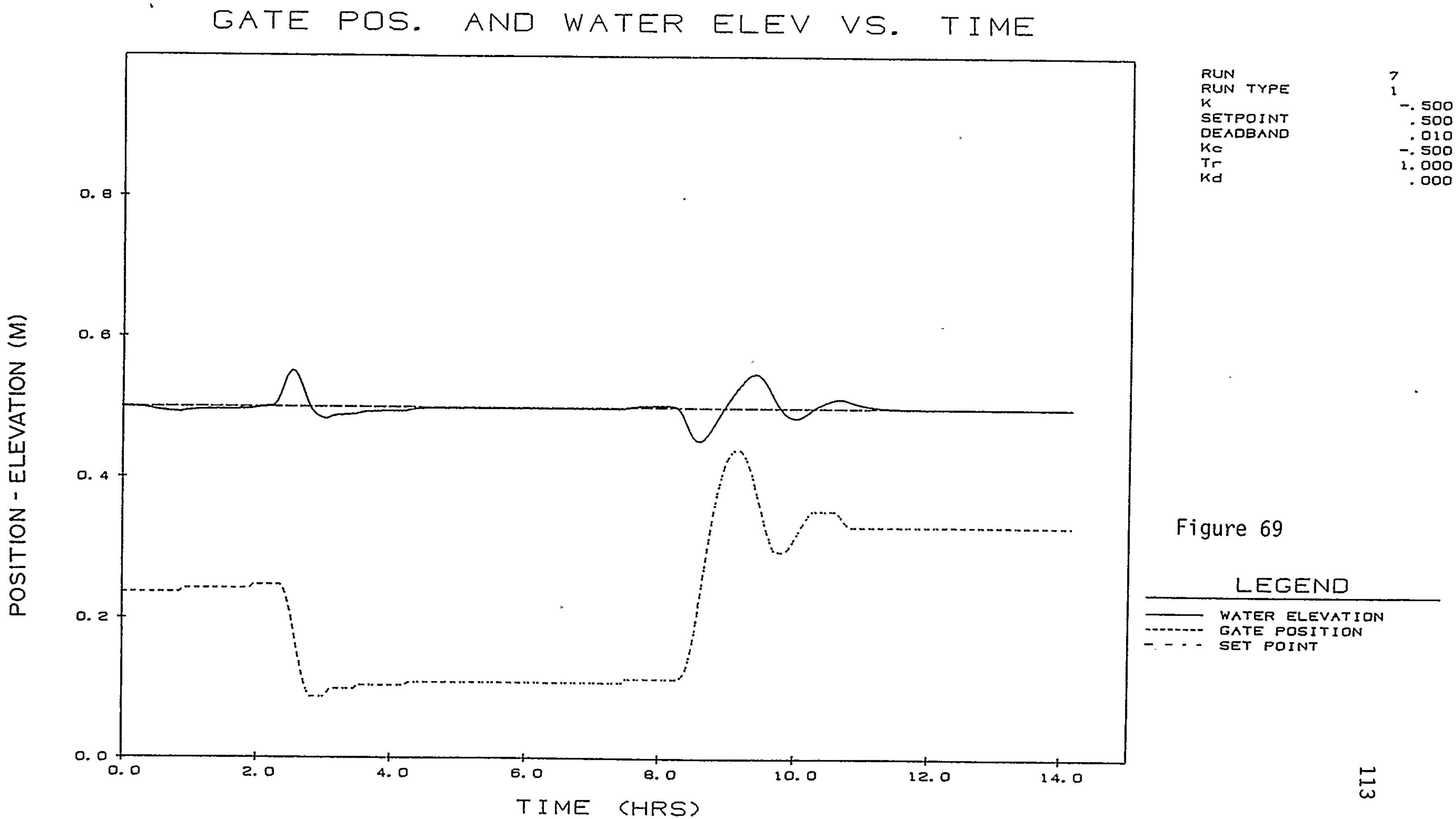

GATE POS. AND WATER ELEV VS. TIME
RUN 6
RUN TYPE 1
K -.100
SETPOINT .500
DEADBAND .010
Kc -.100
Tr 1.000
Kd .000
0.8
0.6
0.4
0.2
0.0
POSITION - ELEVATION (M)
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
TIME (HRS)
LEGEND
WATER ELEVATION
GATE POSITION
SET POINT

Figure 68



GATE POS. AND WATER ELEV VS. TIME
POSITION - ELEVATION (M)
0.0
0.2
0.4
0.6
0.8
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
TIME (HRS)
RUN 7
RUN TYPE 1
K -.500
SETPOINT .500
DEADBAND .010
Kc -.500
Tr 1.000
Kd .000
LEGEND
WATER ELEVATION
GATE POSITION
SET POINT

Figure 69

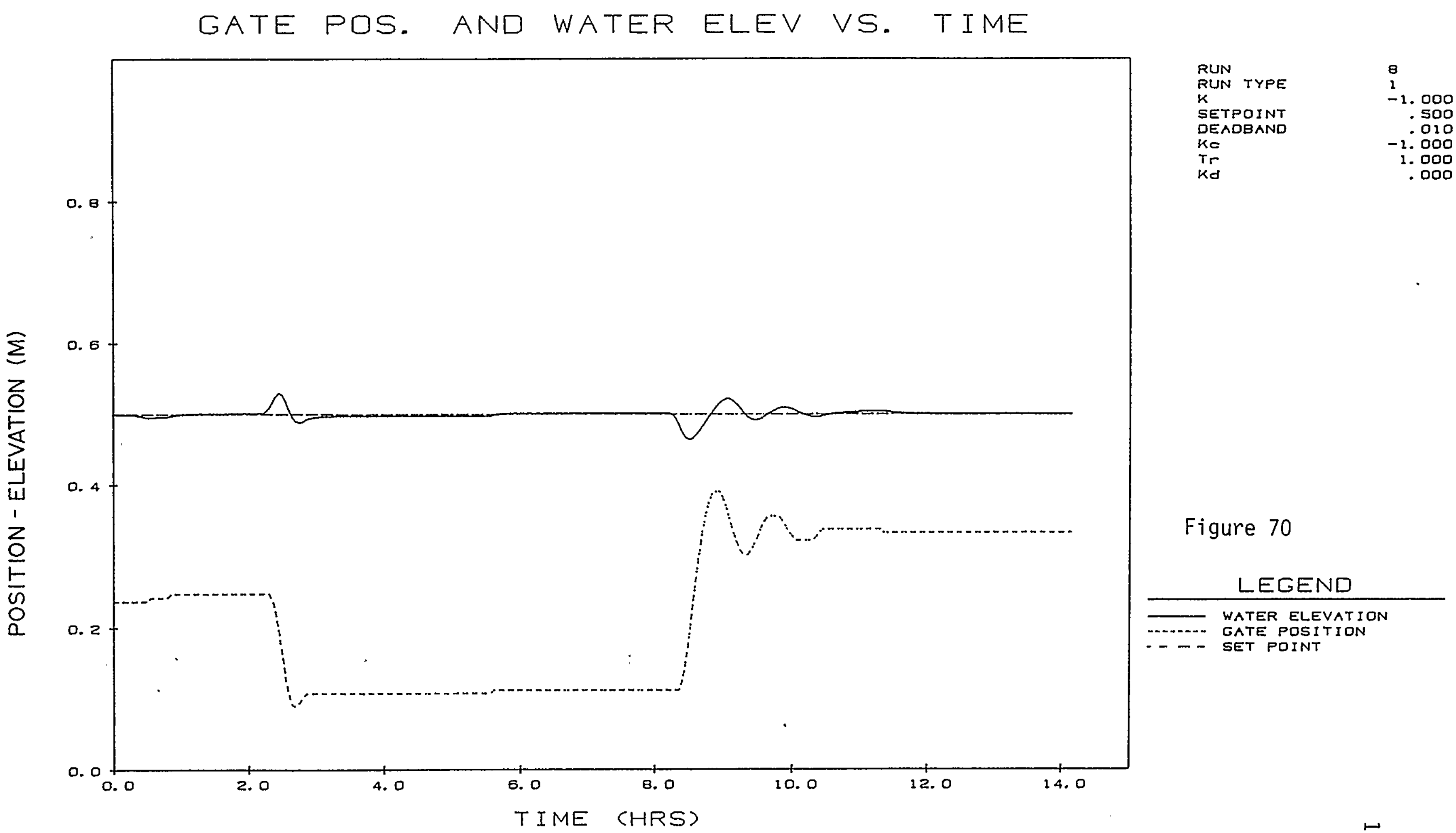

GATE POS. AND WATER ELEV VS. TIME
POSITION - ELEVATION (M)
0.0
0.2
0.4
0.6
0.8
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
TIME (HRS)
RUN 8
RUN TYPE 1
K -1.000
SETPOINT .500
DEADBAND .010
Kc -1.000
Tr 1.000
Kd .000
LEGEND
WATER ELEVATION
GATE POSITION
SET POINT

Figure 70

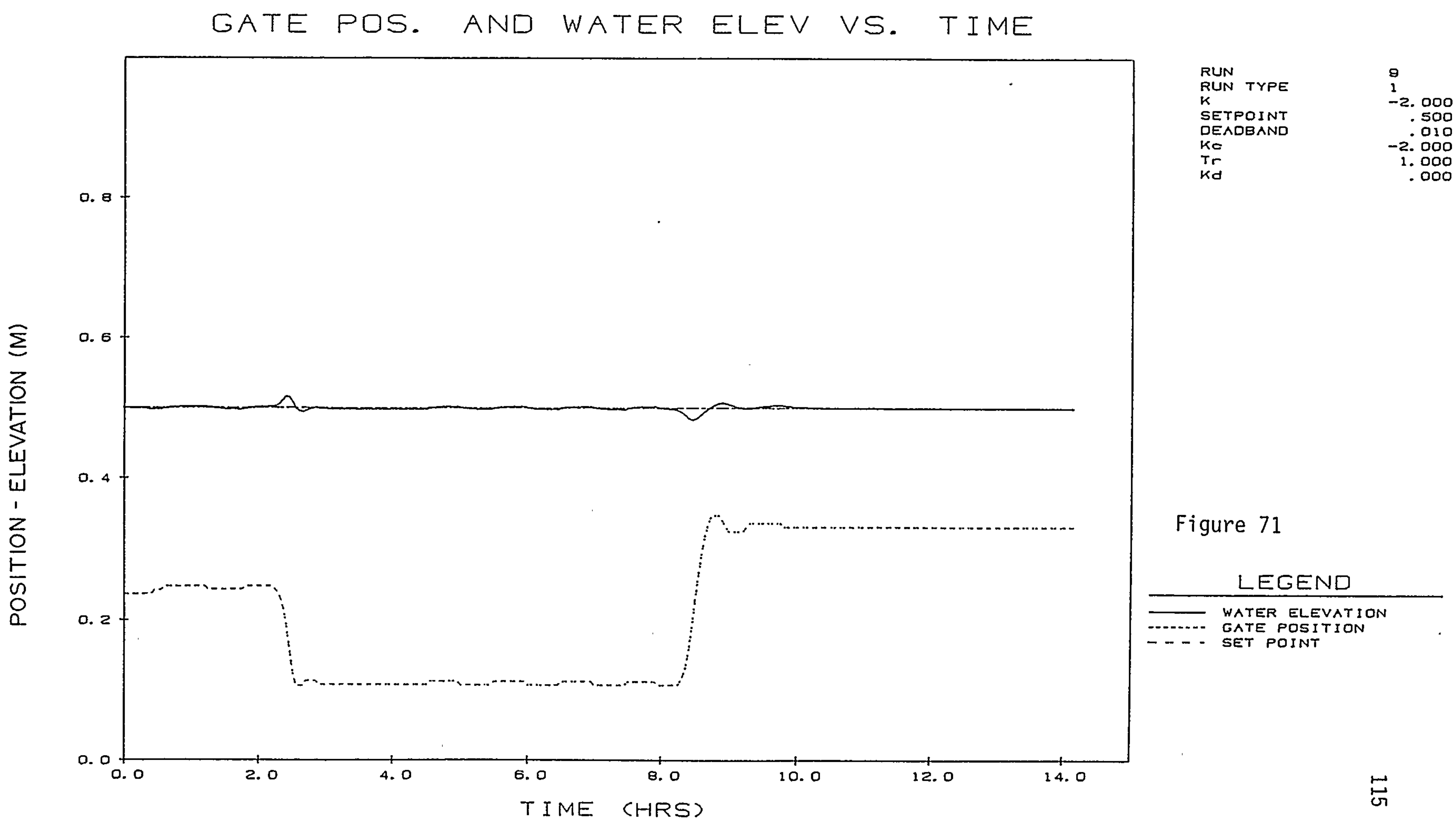

GATE POS. AND WATER ELEV VS. TIME
POSITION - ELEVATION (M)
TIME (HRS)
0.0
0.2
0.4
0.6
0.8
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
RUN 9
RUN TYPE 1
K -2.000
SETPOINT .500
DEADBAND .010
Kc -2.000
Tr 1.000
Kd .000
LEGEND
WATER ELEVATION
GATE POSITION
SET POINT

Figure 71

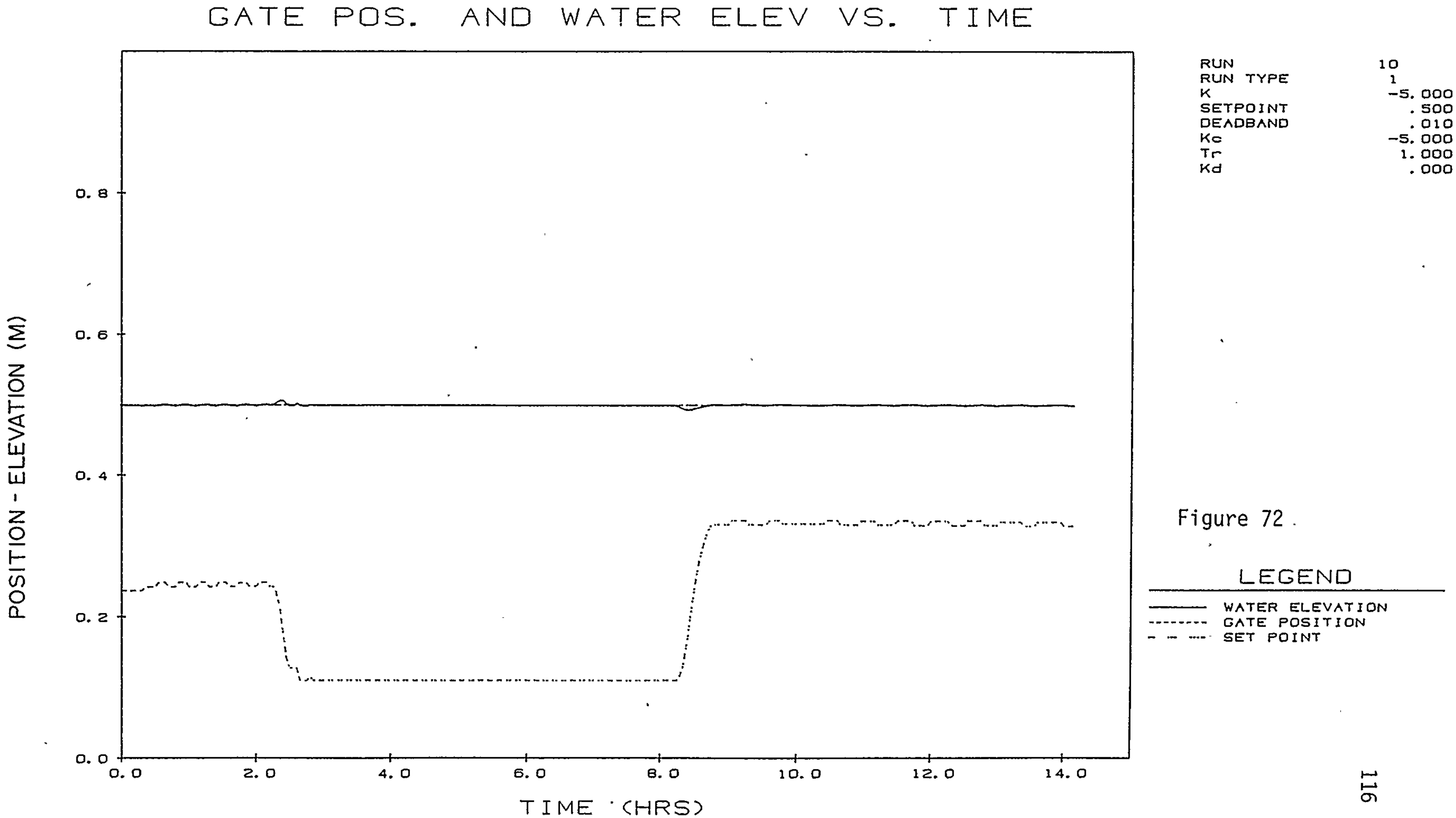
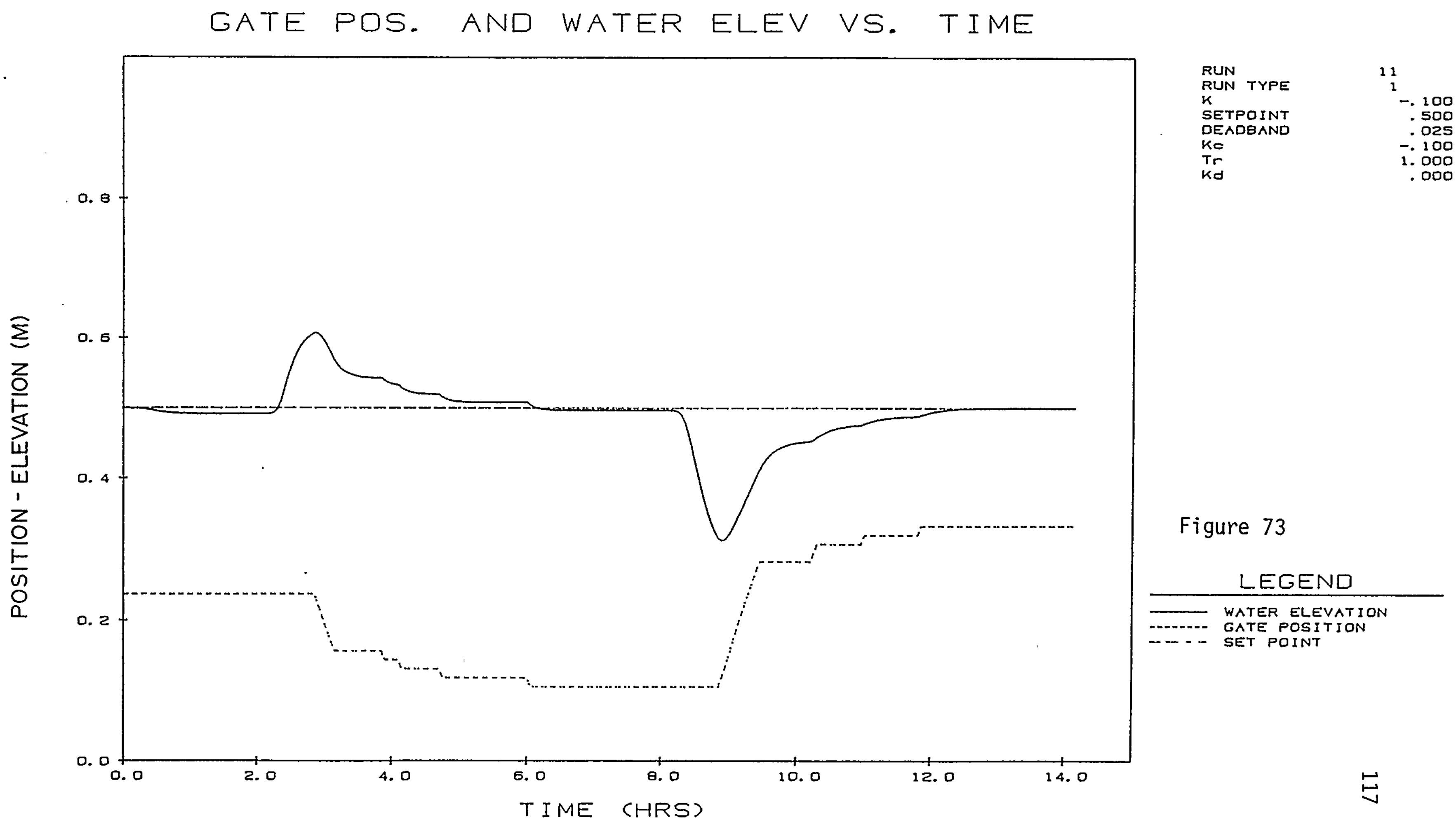

GATE POS. AND WATER ELEV VS. TIME
POSITION - ELEVATION (M)
TIME (HRS)
0.0
0.2
0.4
0.6
0.8
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
RUN 10
RUN TYPE 1
K -5.000
SETPOINT .500
DEADBAND .010
Kc -5.000
Tr 1.000
Kd .000
LEGEND
WATER ELEVATION
GATE POSITION
SET POINT

Figure 72



GATE POS. AND WATER ELEV VS. TIME
RUN 11
RUN TYPE 1
K -.100
SETPOINT .500
DEADBAND .025
Kc -.100
Tr 1.000
Kd .000
0.8
0.6
0.4
0.2
0.0
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
TIME (HRS)
POSITION - ELEVATION (M)
LEGEND
WATER ELEVATION
GATE POSITION
SET POINT

Figure 73

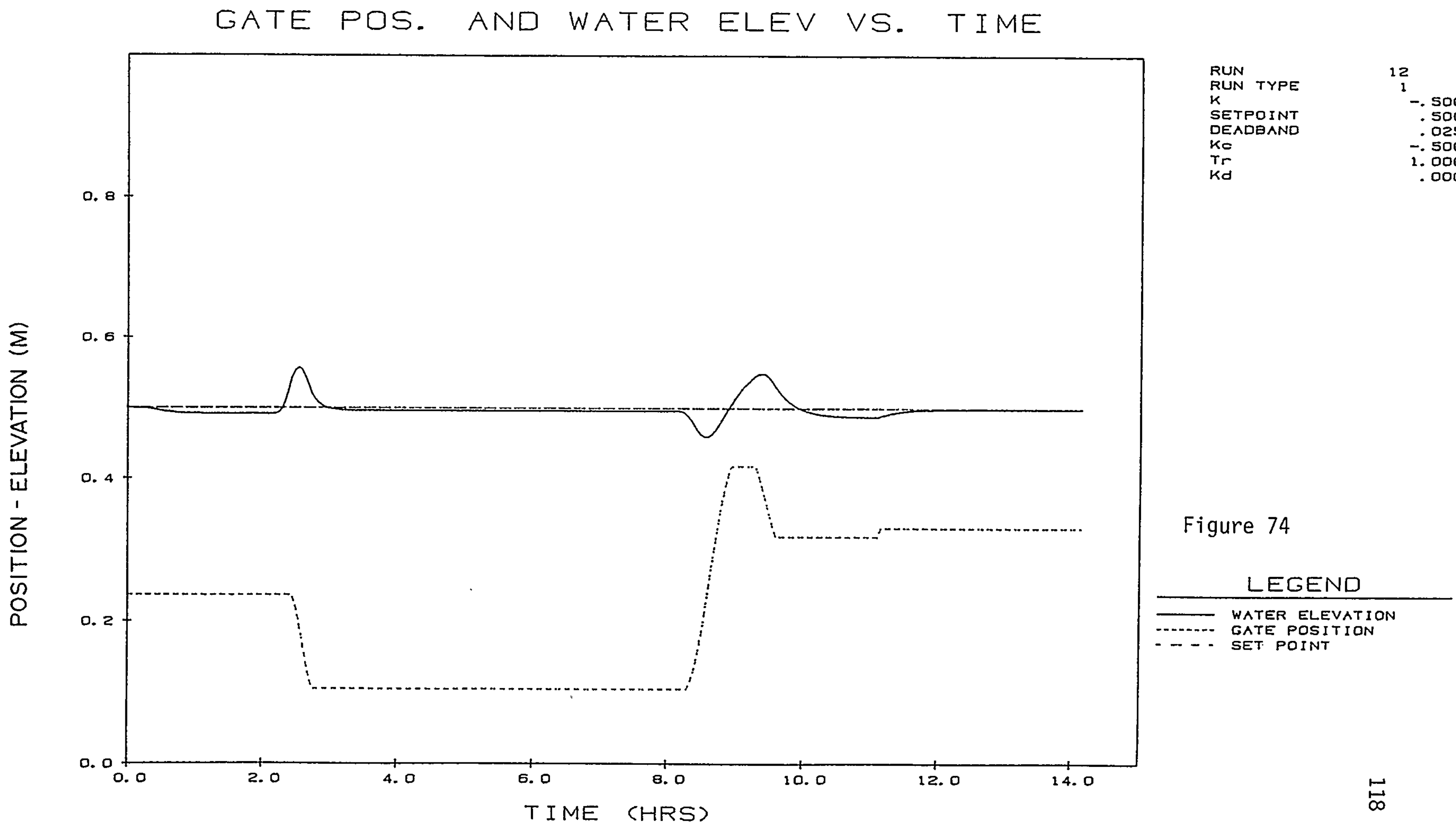

GATE POS. AND WATER ELEV VS. TIME
RUN 12
RUN TYPE 1
K -.500
SETPOINT .500
DEADBAND .025
Kc -.500
Tr 1.000
Kd .000
0.8
0.6
0.4
0.2
0.0
POSITION - ELEVATION (M)
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
TIME (HRS)
LEGEND
WATER ELEVATION
GATE POSITION
SET POINT

Figure 74

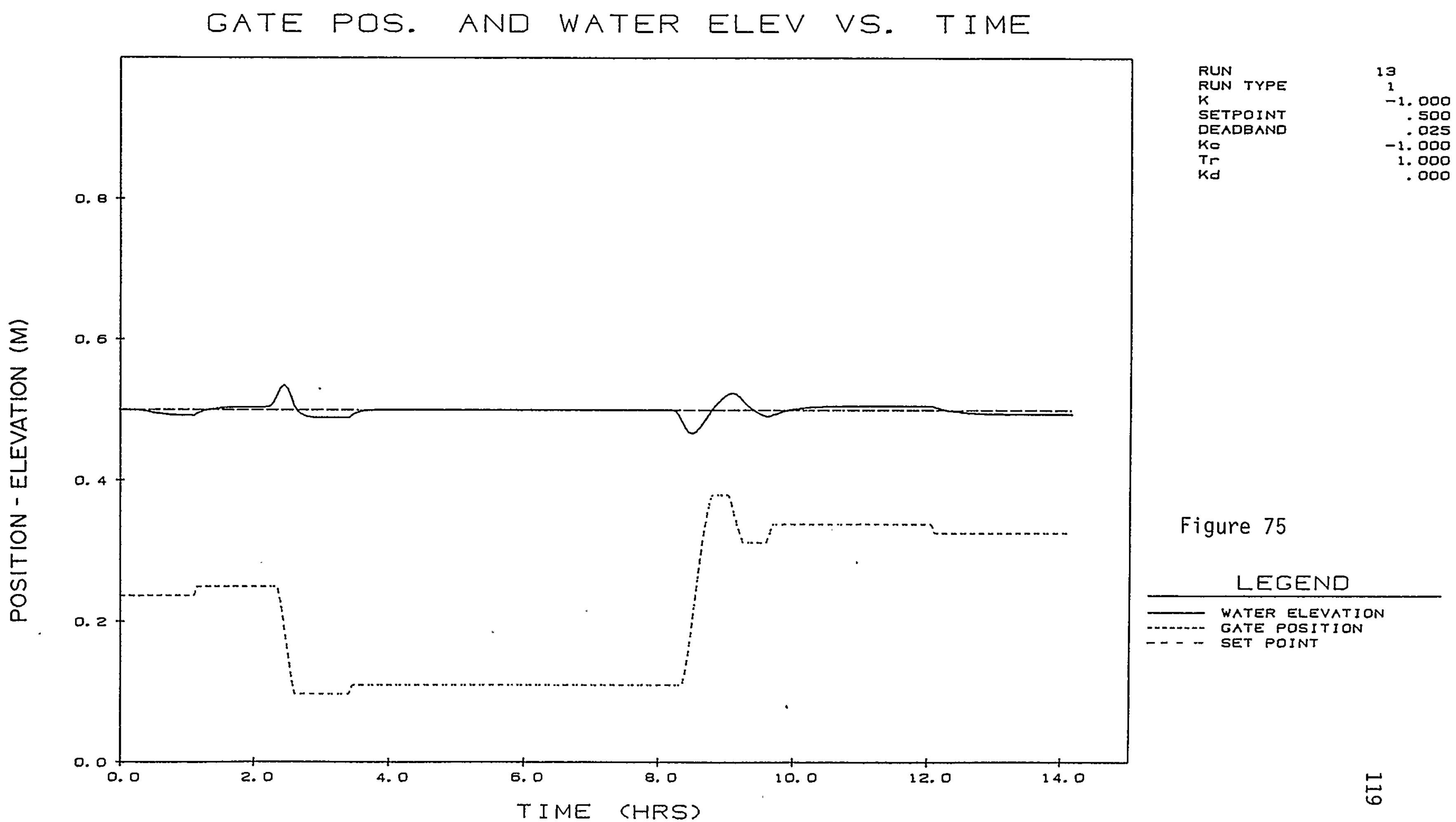
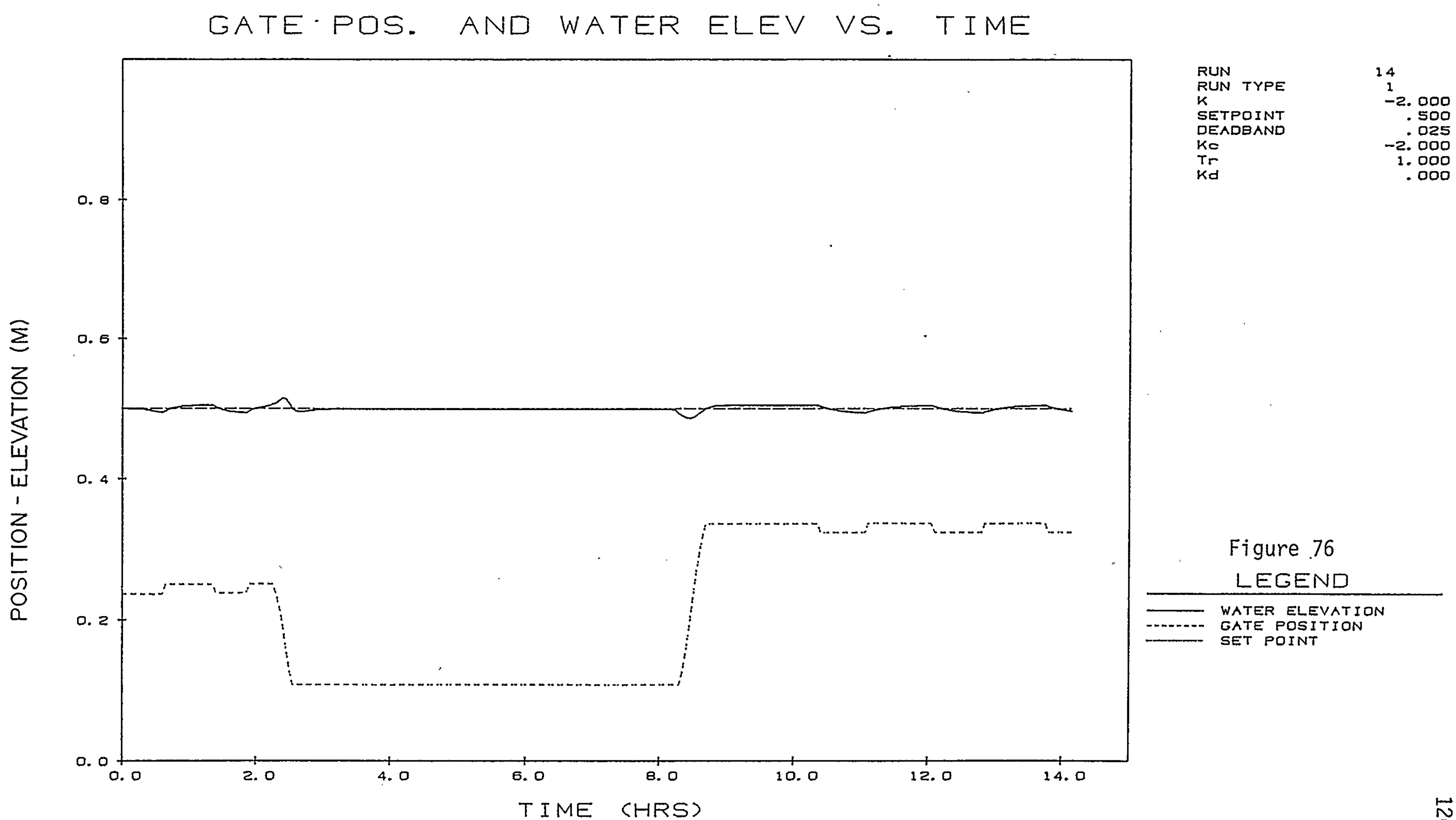

GATE POS. AND WATER ELEV VS. TIME
POSITION - ELEVATION (M)
0.0
0.2
0.4
0.6
0.8
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
TIME (HRS)
RUN 13
RUN TYPE 1
K -1.000
SETPOINT .500
DEADBAND .025
Ko -1.000
Tr 1.000
Kd .000
LEGEND
WATER ELEVATION
GATE POSITION
SET POINT

Figure 75



GATE POS. AND WATER ELEV VS. TIME
POSITION - ELEVATION (M)
0.0
0.2
0.4
0.6
0.8
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
TIME (HRS)
RUN 14
RUN TYPE 1
K -2.000
SETPOINT .500
DEADBAND .025
Kc -2.000
Tr 1.000
Kd .000
LEGEND
WATER ELEVATION
GATE POSITION
SET POINT

Figure 76

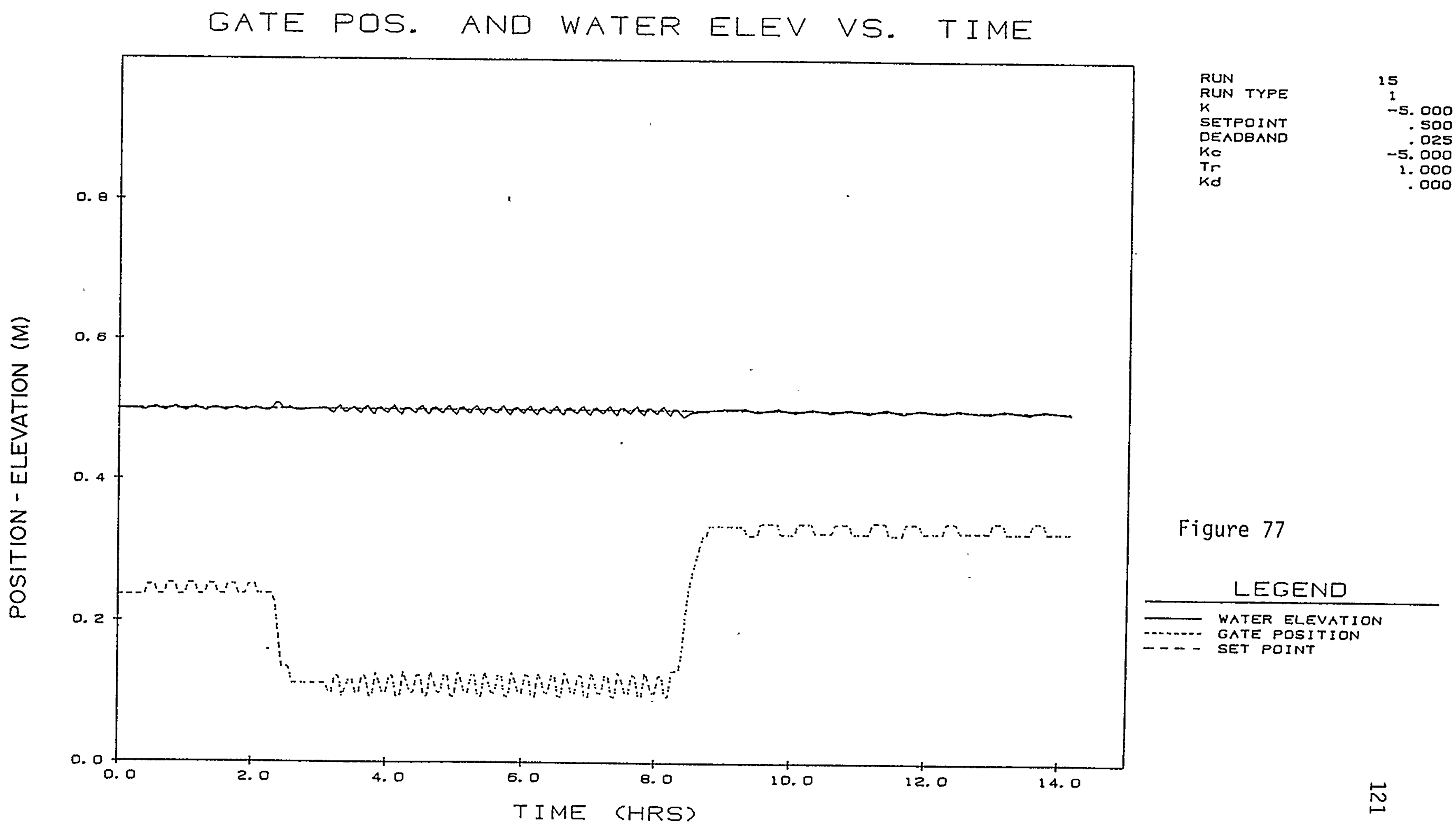

GATE POS. AND WATER ELEV VS. TIME
RUN 15
RUN TYPE 1
K -5.000
SETPOINT .500
DEADBAND .025
Kc -5.000
Tr 1.000
Kd .000
POSITION - ELEVATION (M)
0.0
0.2
0.4
0.6
0.8
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
TIME (HRS)
LEGEND
WATER ELEVATION
GATE POSITION
SET POINT

Figure 77

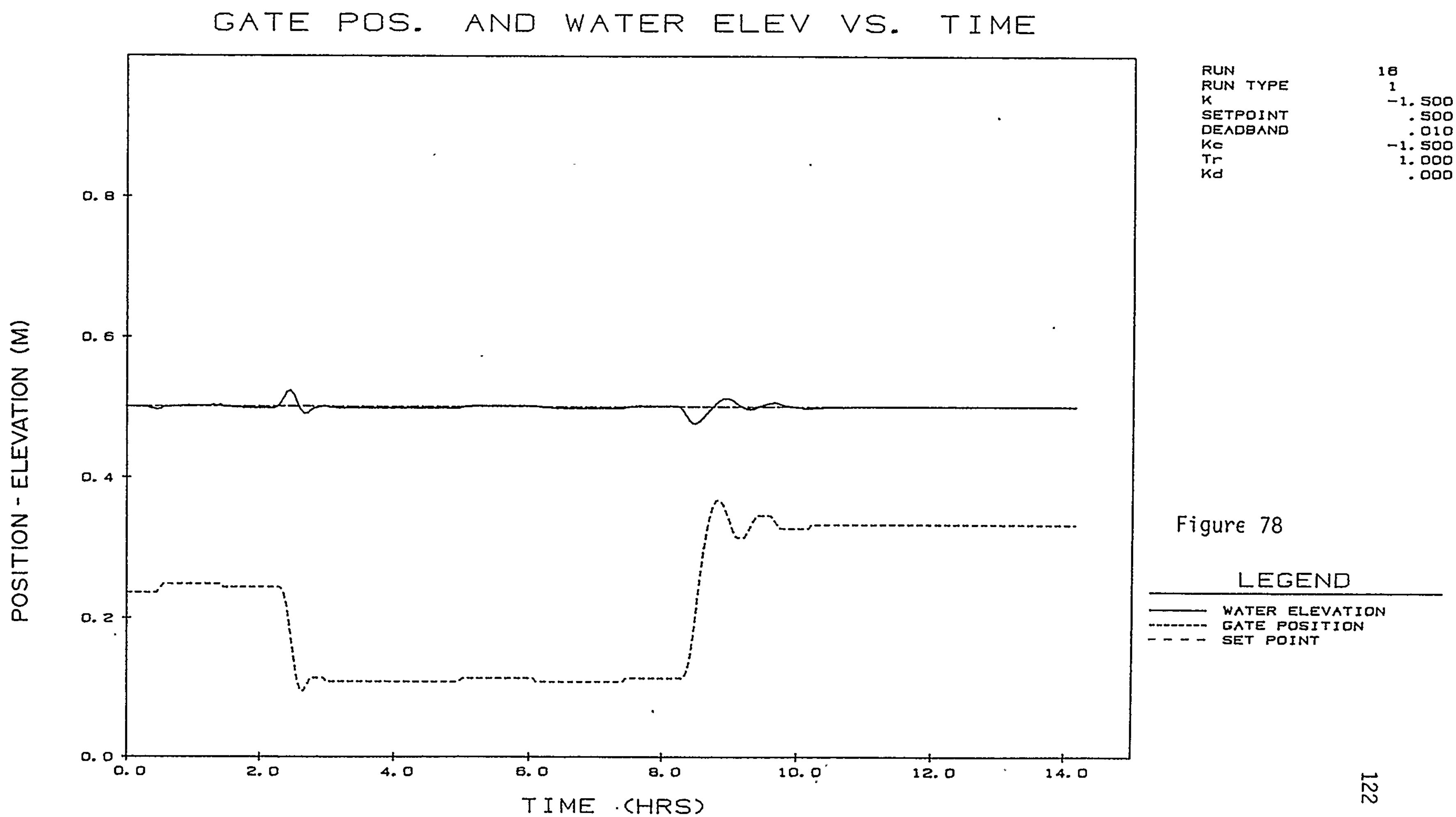

GATE POS. AND WATER ELEV VS. TIME
POSITION - ELEVATION (M)
0.0
0.2
0.4
0.6
0.8
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
TIME (HRS)
RUN 18
RUN TYPE 1
K -1.500
SETPOINT .500
DEADBAND .010
Kc -1.500
Tr 1.000
Kd .000
LEGEND
WATER ELEVATION
GATE POSITION
SET POINT

Figure 78

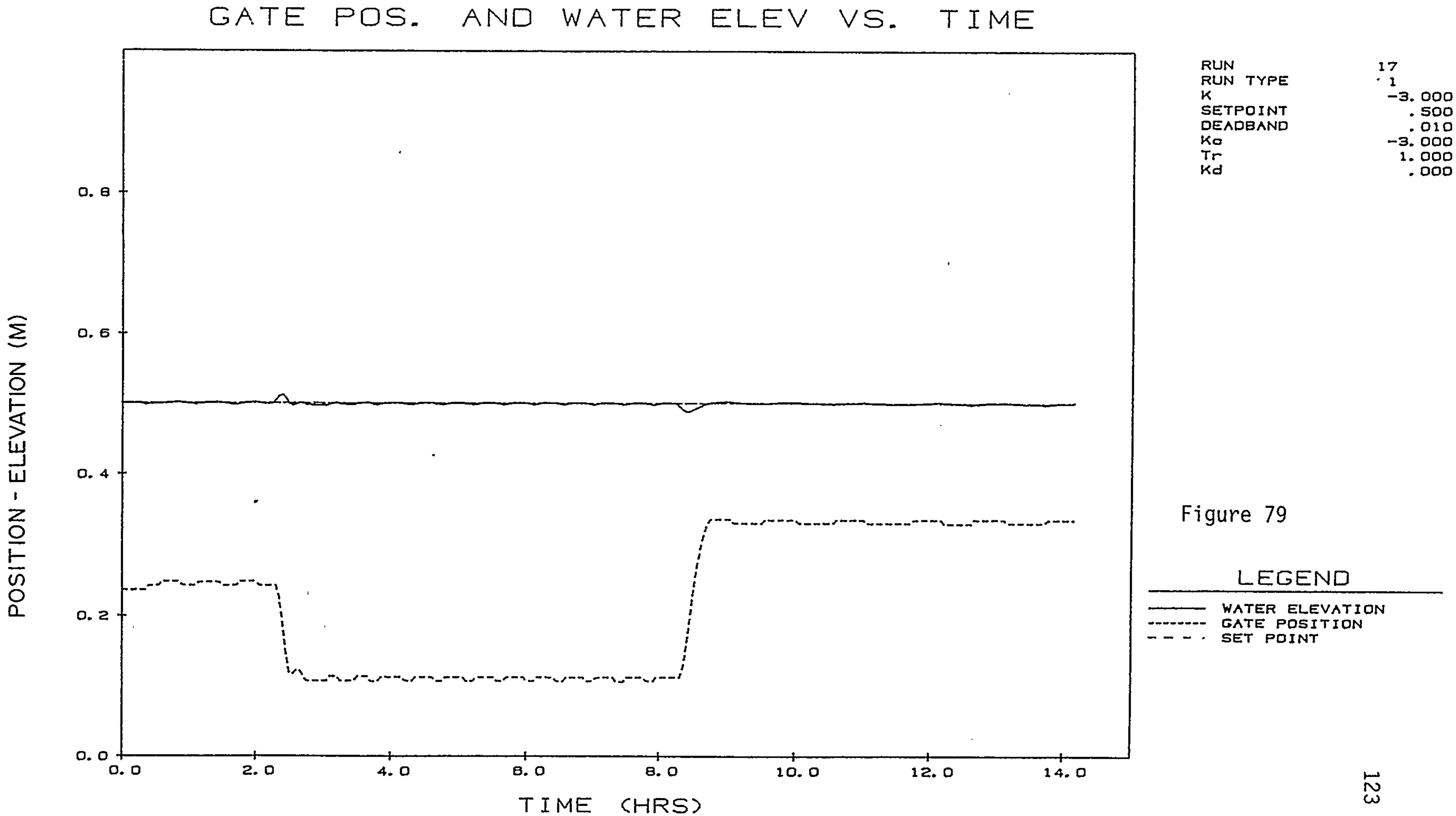

GATE POS. AND WATER ELEV VS. TIME
POSITION - ELEVATION (M)
0.0
0.2
0.4
0.6
0.8
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
TIME (HRS)
RUN 17
RUN TYPE 1
K -3.000
SETPOINT .500
DEADBAND .010
Kc -3.000
Tr 1.000
Kd .000
LEGEND
WATER ELEVATION
GATE POSITION
SET POINT

Figure 79

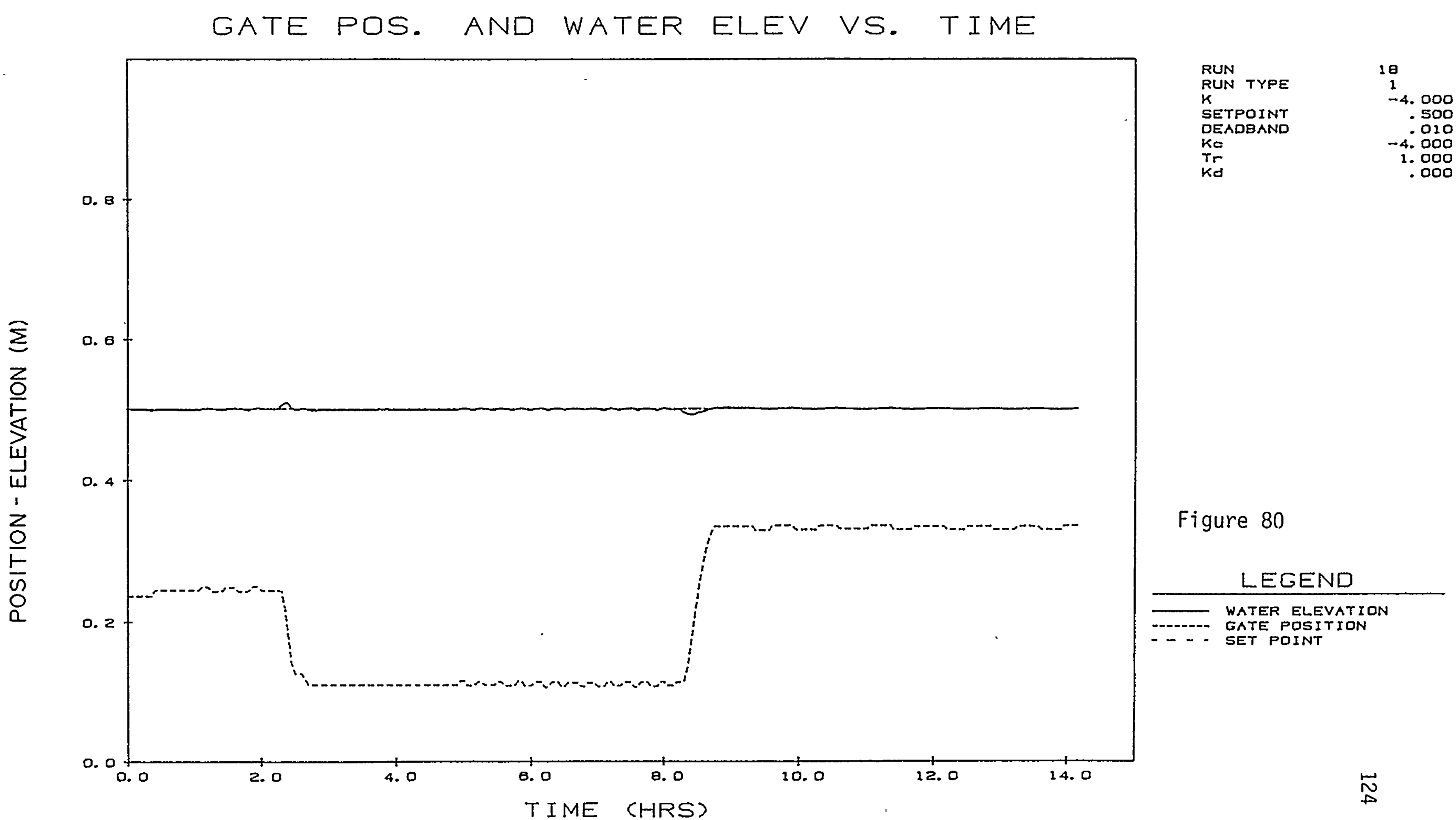

GATE POS. AND WATER ELEV VS. TIME
RUN 18
RUN TYPE 1
K -4.000
SETPOINT .500
DEADBAND .010
Kc -4.000
Tr 1.000
Kd .000
POSITION - ELEVATION (M)
0.0
0.2
0.4
0.6
0.8
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
TIME (HRS)
LEGEND
WATER ELEVATION
GATE POSITION
SET POINT

Figure 80

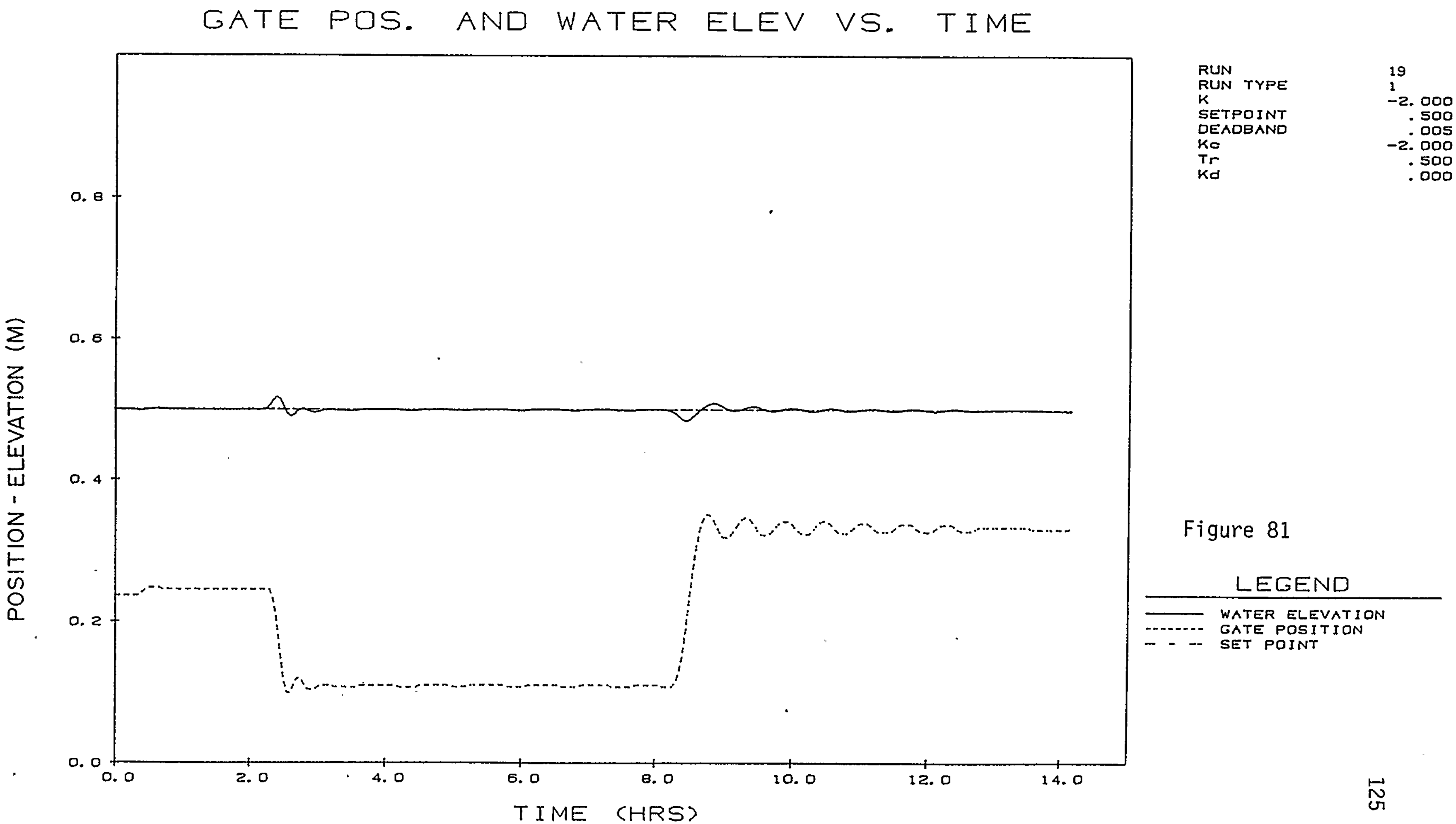

GATE POS. AND WATER ELEV VS. TIME
RUN 19
RUN TYPE 1
K -2.000
SETPOINT .500
DEADBAND .005
Kc -2.000
Tr .500
Kd .000
POSITION - ELEVATION (M)
0.0
0.2
0.4
0.6
0.8
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
TIME (HRS)
LEGEND
WATER ELEVATION
GATE POSITION
SET POINT

Figure 81

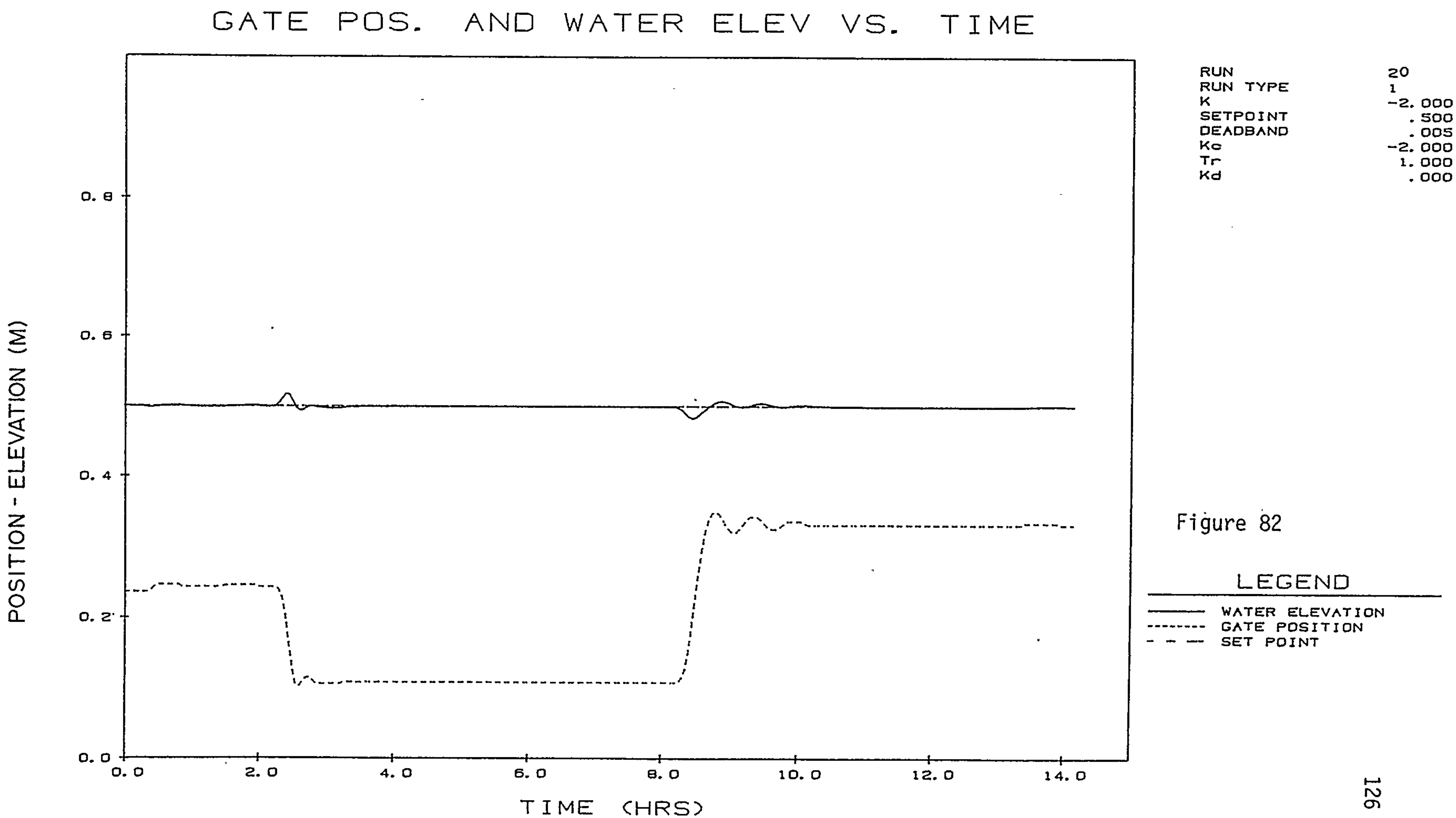
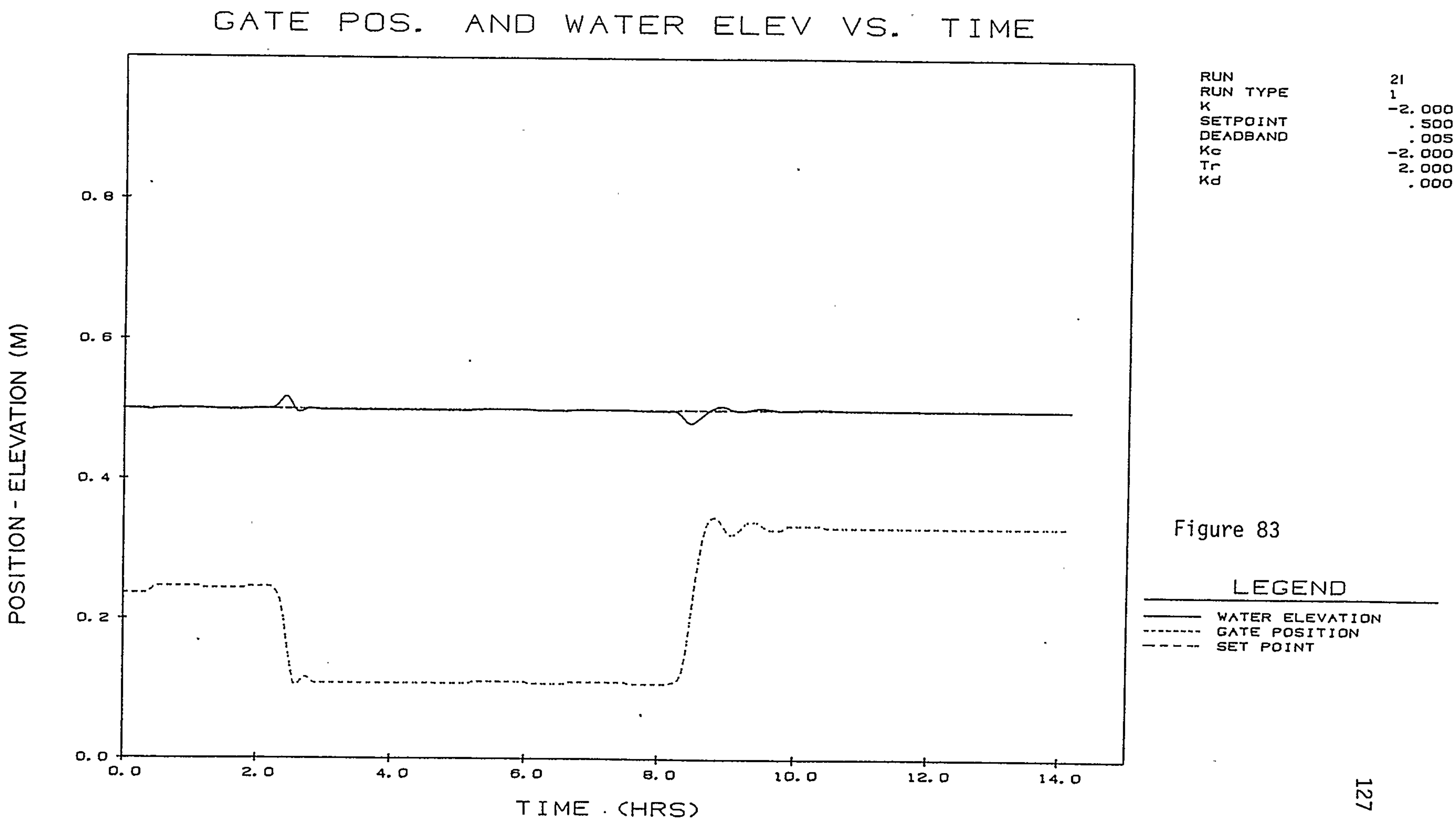

GATE POS. AND WATER ELEV VS. TIME
POSITION - ELEVATION (M)
0.0
0.2
0.4
0.6
0.8
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
TIME (HRS)
RUN 20
RUN TYPE 1
K -2.000
SETPOINT .500
DEADBAND .005
Kc -2.000
Tr 1.000
Kd .000
LEGEND
WATER ELEVATION
GATE POSITION
SET POINT

Figure 82



GATE POS. AND WATER ELEV VS. TIME
POSITION - ELEVATION (M)
0.0
0.2
0.4
0.6
0.8
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
TIME (HRS)
RUN 21
RUN TYPE 1
K -2.000
SETPOINT .500
DEADBAND .005
Kc -2.000
Tr 2.000
Kd .000
LEGEND
WATER ELEVATION
GATE POSITION
SET POINT

Figure 83

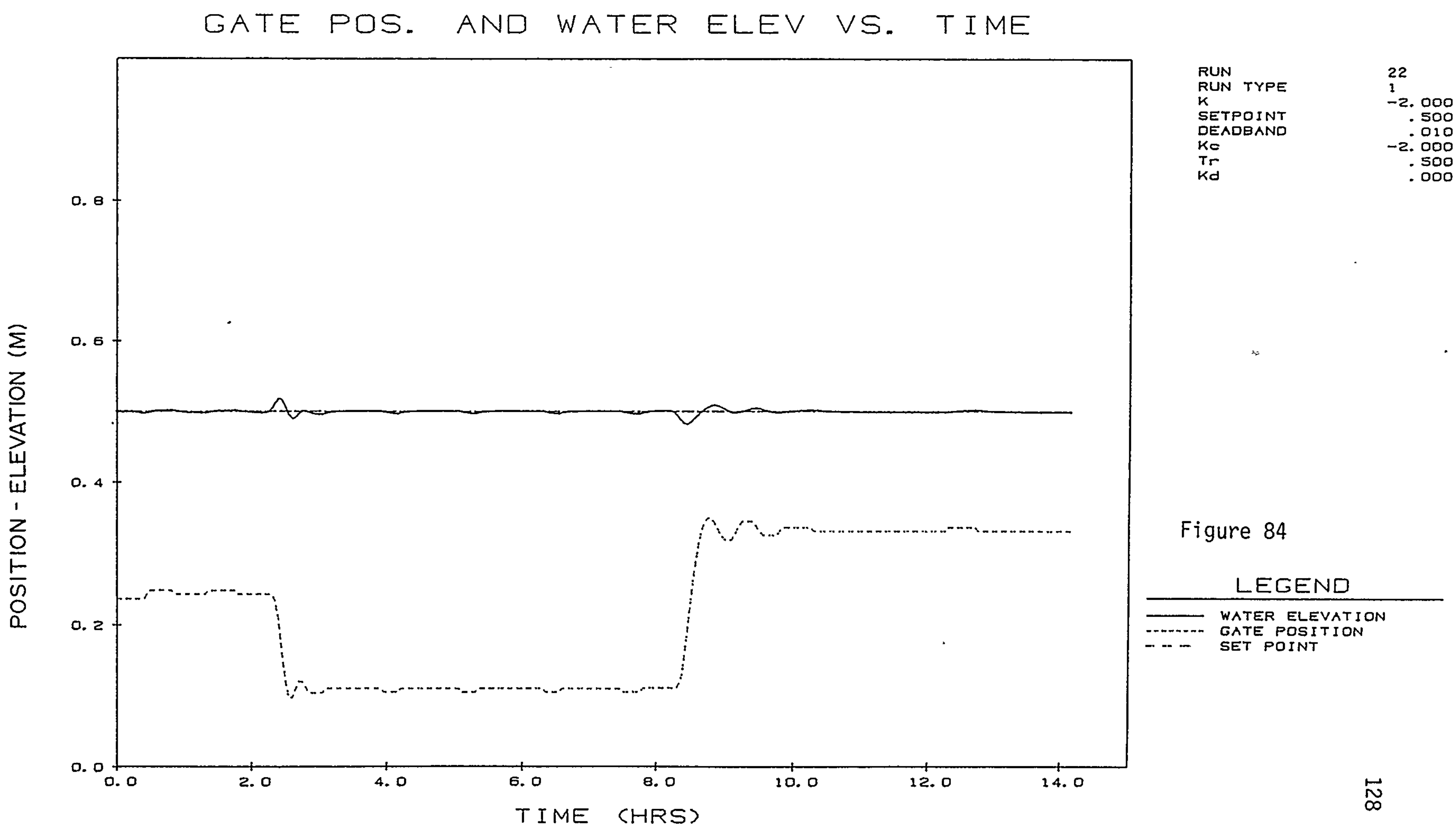

GATE POS. AND WATER ELEV VS. TIME
POSITION - ELEVATION (M)
0.0
0.2
0.4
0.6
0.8
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
TIME (HRS)
RUN 22
RUN TYPE 1
K -2.000
SETPOINT .500
DEADBAND .010
Kc -2.000
Tr .500
Kd .000
LEGEND
WATER ELEVATION
GATE POSITION
SET POINT

Figure 84

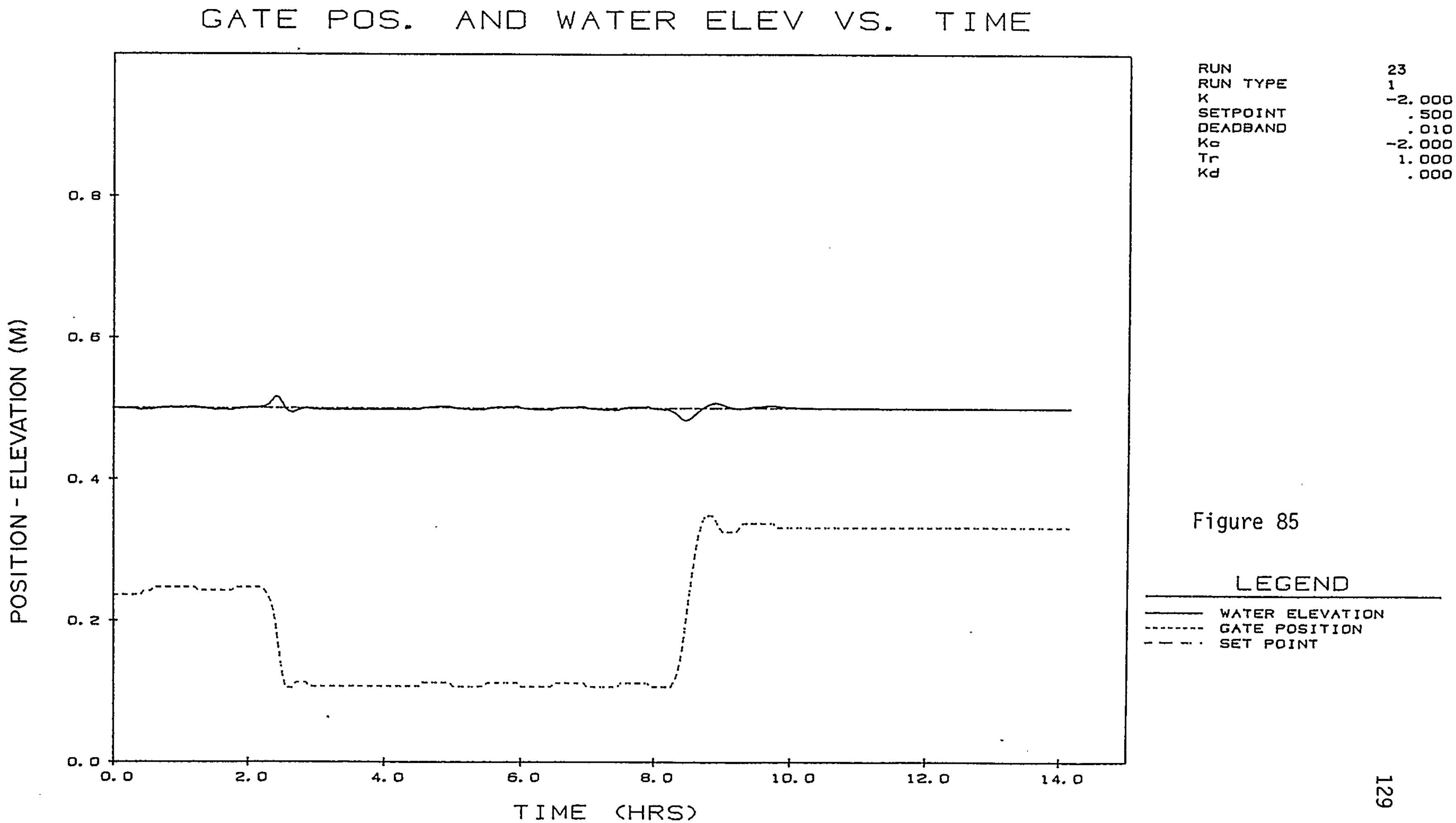

GATE POS. AND WATER ELEV VS. TIME
POSITION - ELEVATION (M)
0.0
0.2
0.4
0.6
0.8
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
TIME (HRS)
RUN 23
RUN TYPE 1
K -2.000
SETPOINT .500
DEADBAND .010
Kc -2.000
Tr 1.000
Kd .000
LEGEND
WATER ELEVATION
GATE POSITION
SET POINT

Figure 85

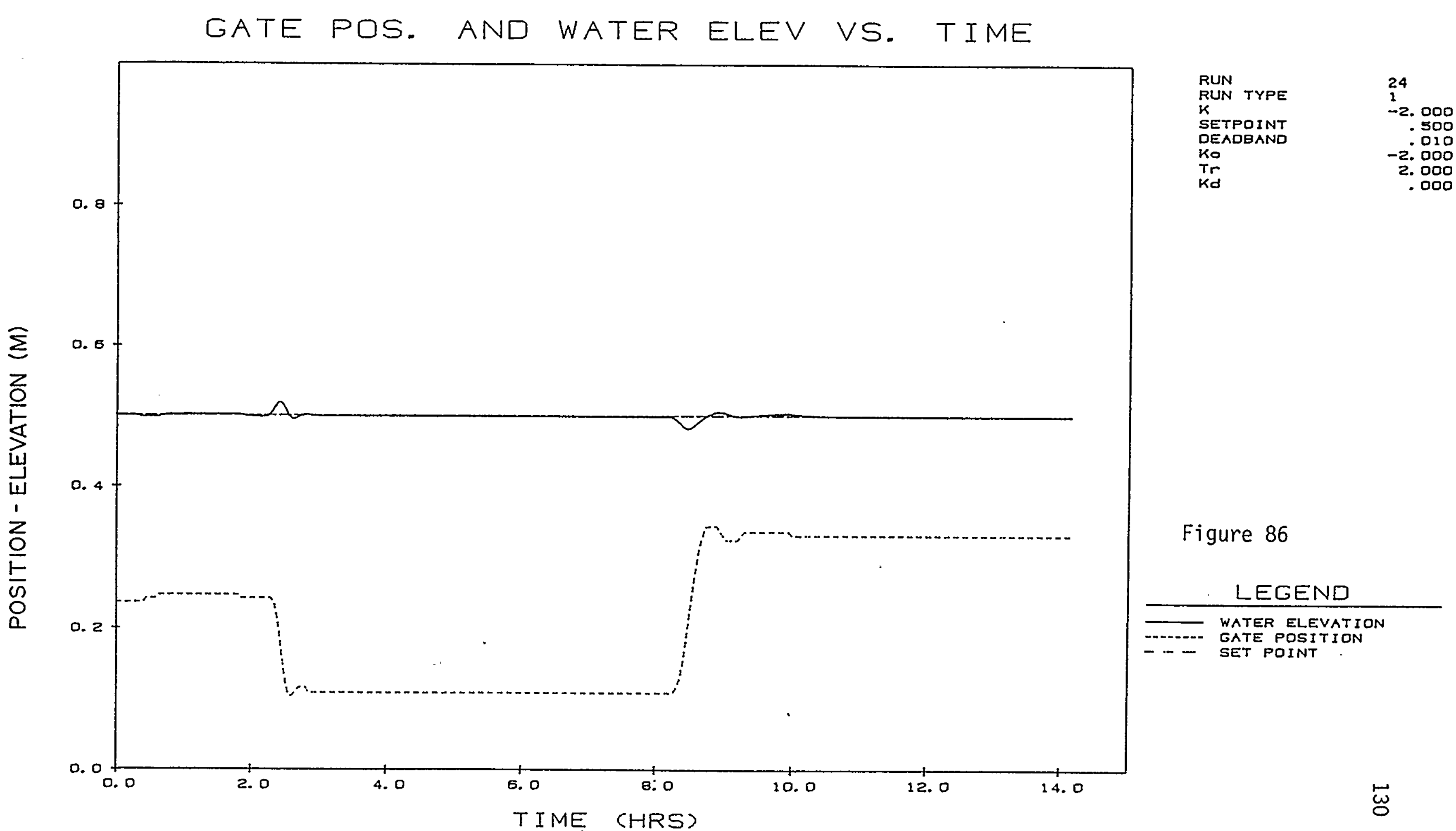

GATE POS. AND WATER ELEV VS. TIME
POSITION - ELEVATION (M)
TIME (HRS)
0.0
0.2
0.4
0.6
0.8
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
RUN 24
RUN TYPE 1
K -2.000
SETPOINT .500
DEADBAND .010
Ko -2.000
Tr 2.000
Kd .000
LEGEND
WATER ELEVATION
GATE POSITION
SET POINT

Figure 86

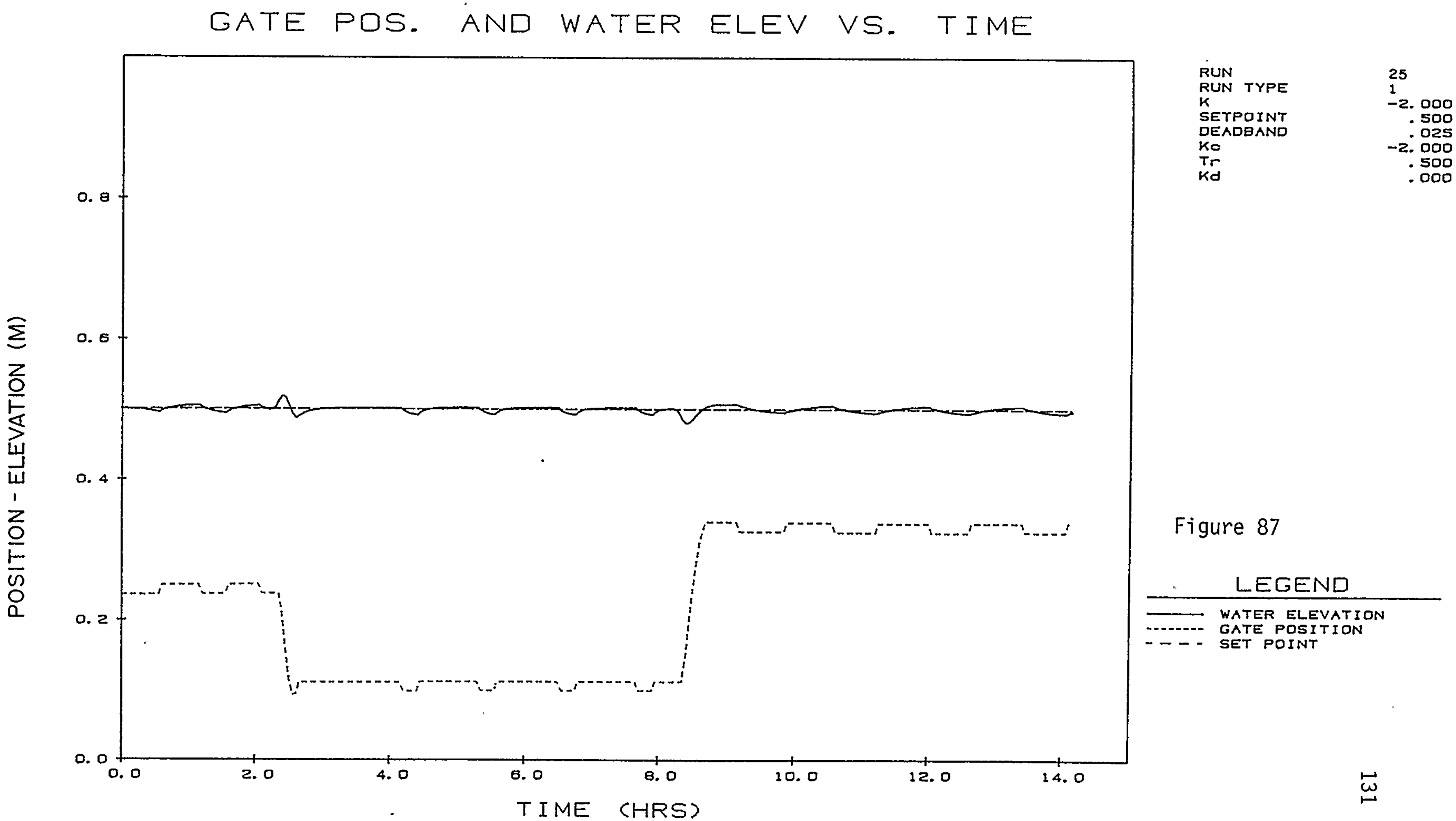
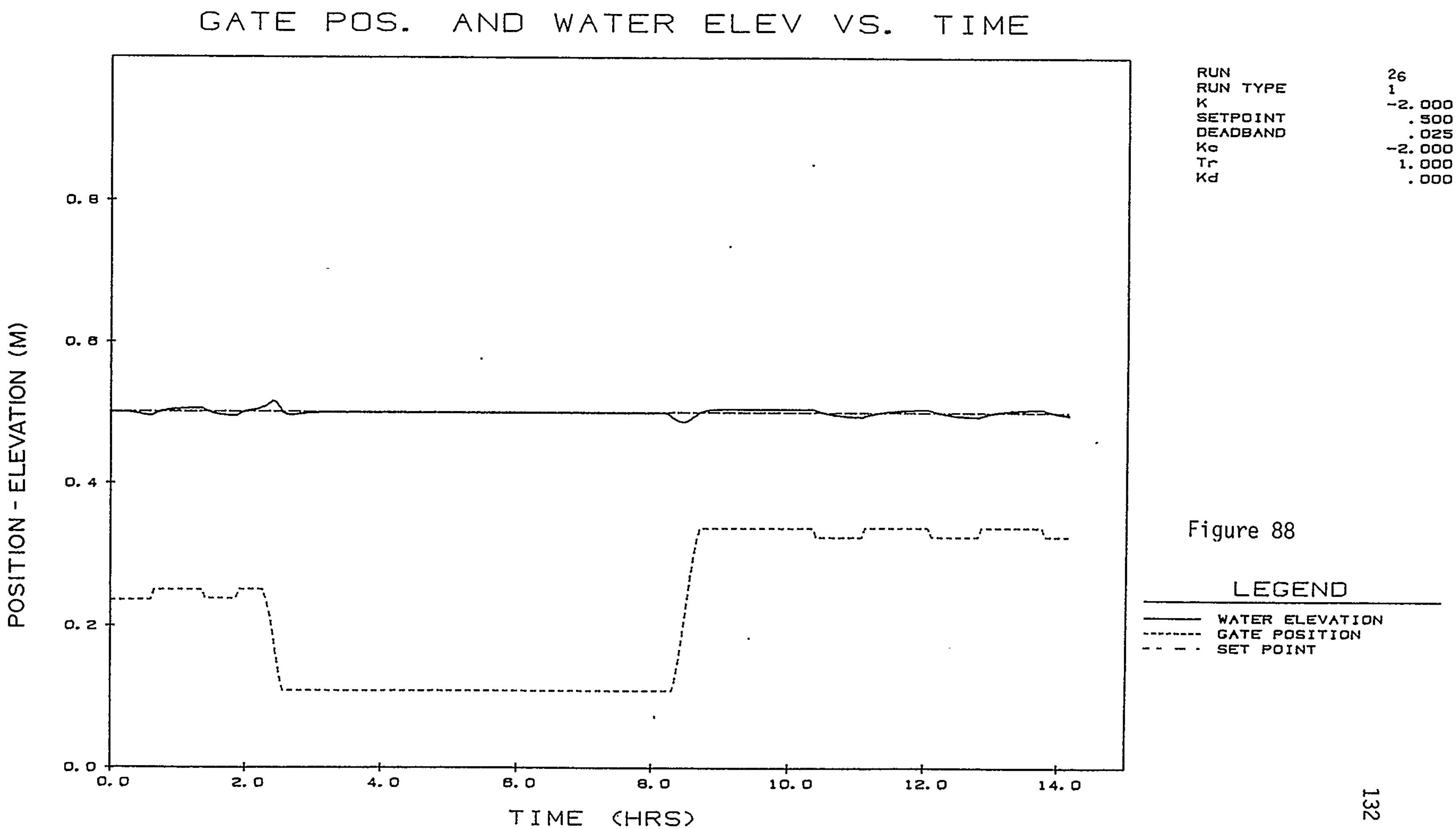

GATE POS. AND WATER ELEV VS. TIME
POSITION - ELEVATION (M)
0.0
0.2
0.4
0.6
0.8
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
TIME (HRS)
RUN 25
RUN TYPE 1
K -2.000
SETPOINT .500
DEADBAND .025
Ko -2.000
Tr .500
Kd .000
LEGEND
WATER ELEVATION
GATE POSITION
SET POINT

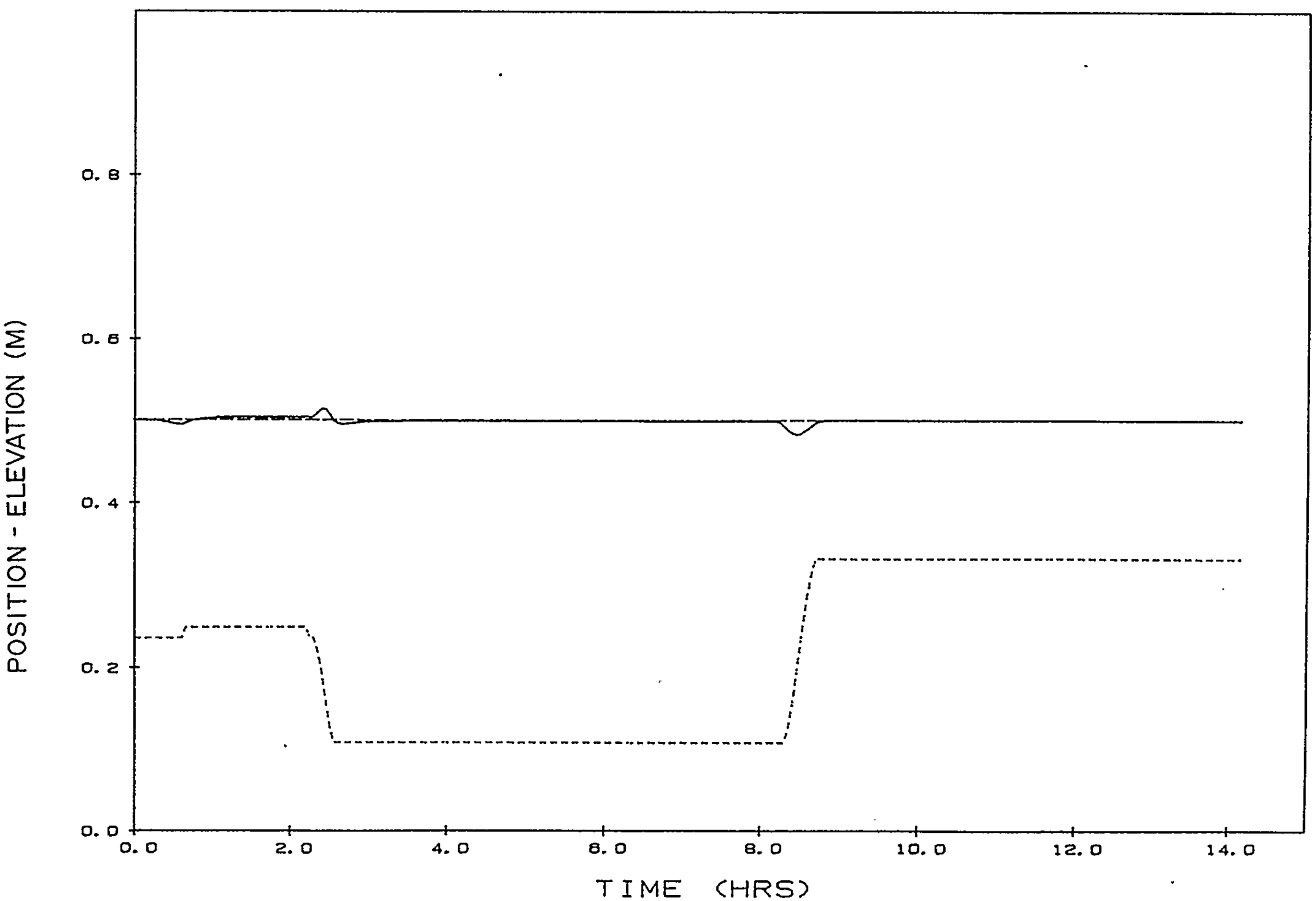
Figure 87



GATE POS. AND WATER ELEV VS. TIME
POSITION - ELEVATION (M)
0.0
0.2
0.4
0.6
0.8
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
TIME (HRS)
RUN 26
RUN TYPE 1
K -2.000
SETPOINT .500
DEADBAND .025
Kc -2.000
Tr 1.000
Kd .000
LEGEND
WATER ELEVATION
GATE POSITION
SET POINT

Figure 88

GATE POS. AND WATER ELEV VS. TIME

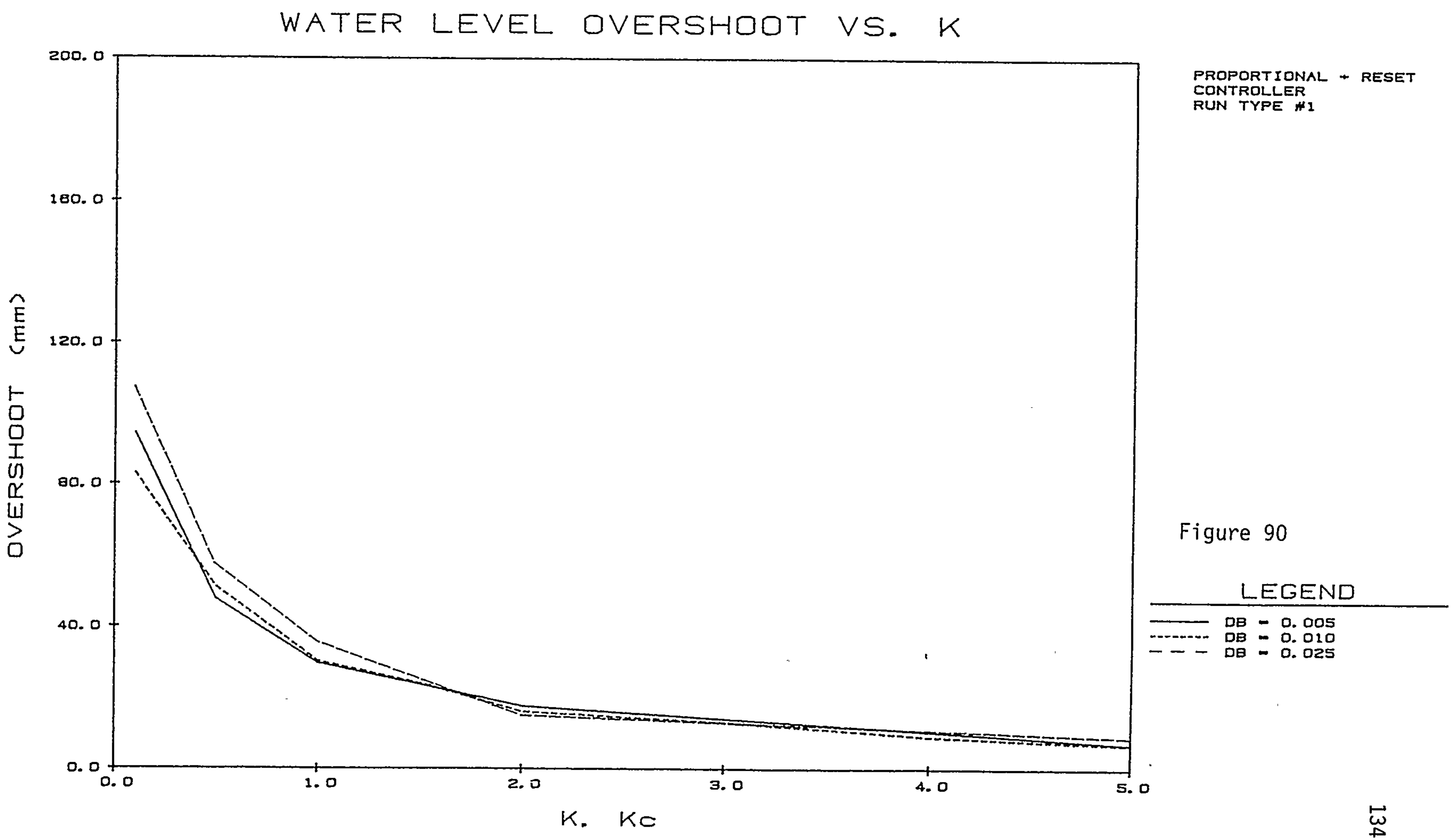


RUN	27
RUN TYPE	1
K	-2.000
SETPOINT	.500
DEADBAND	.025
Ko	-2.000
Tr	2.000
Kd	.000

Figure 89

LEGEND

WATER ELEVATION
GATE POSITION
SET POINT



WATER LEVEL OVERSHOOT VS. K
200.0
160.0
120.0
80.0
40.0
0.0
OVERSHOOT (mm)
0.0
1.0
2.0
3.0
4.0
5.0
K, Kc
PROPORTIONAL + RESET
CONTROLLER
RUN TYPE #1
LEGEND
DB = 0.005
DB = 0.010
DB = 0.025

Figure 90

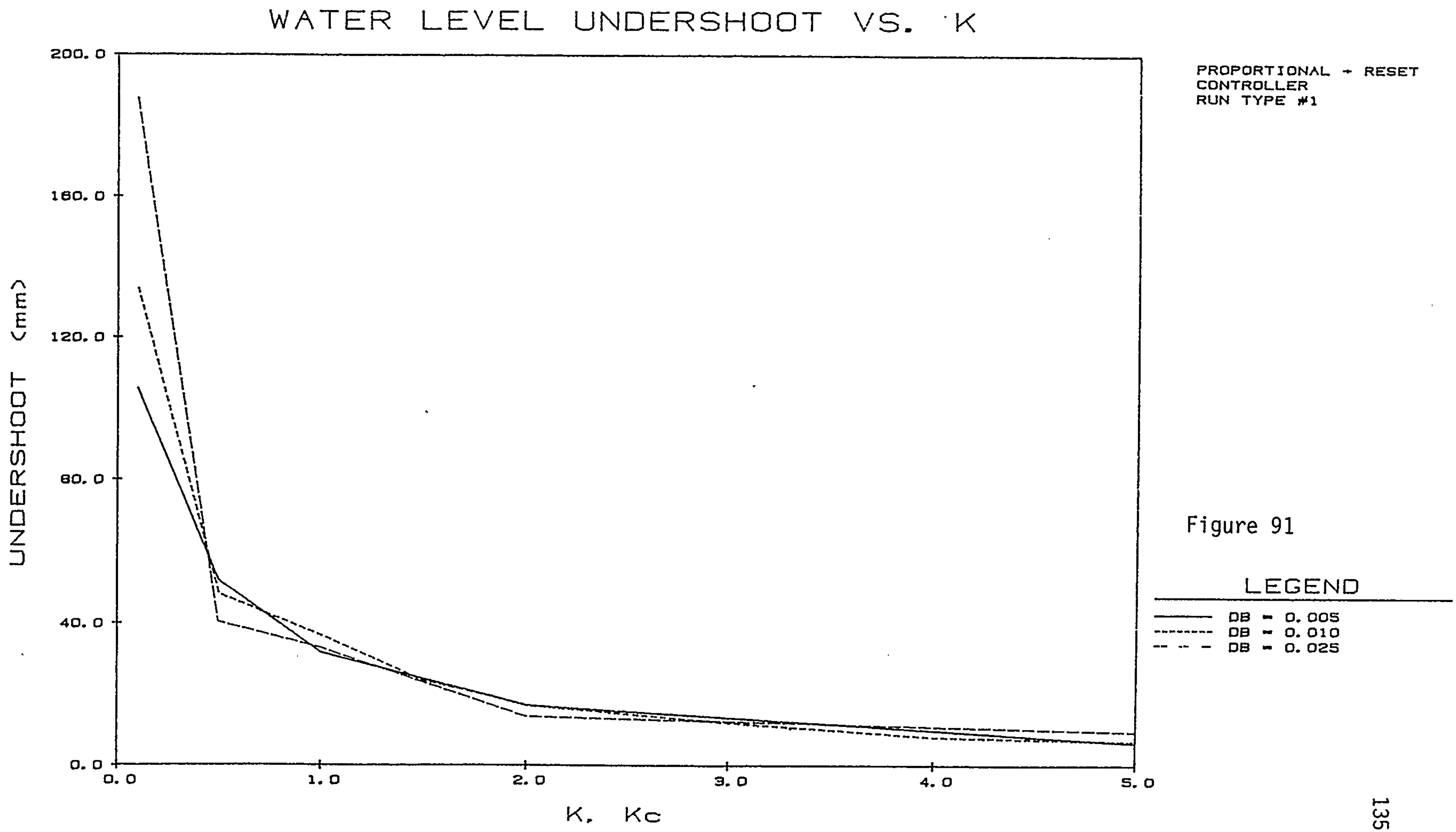
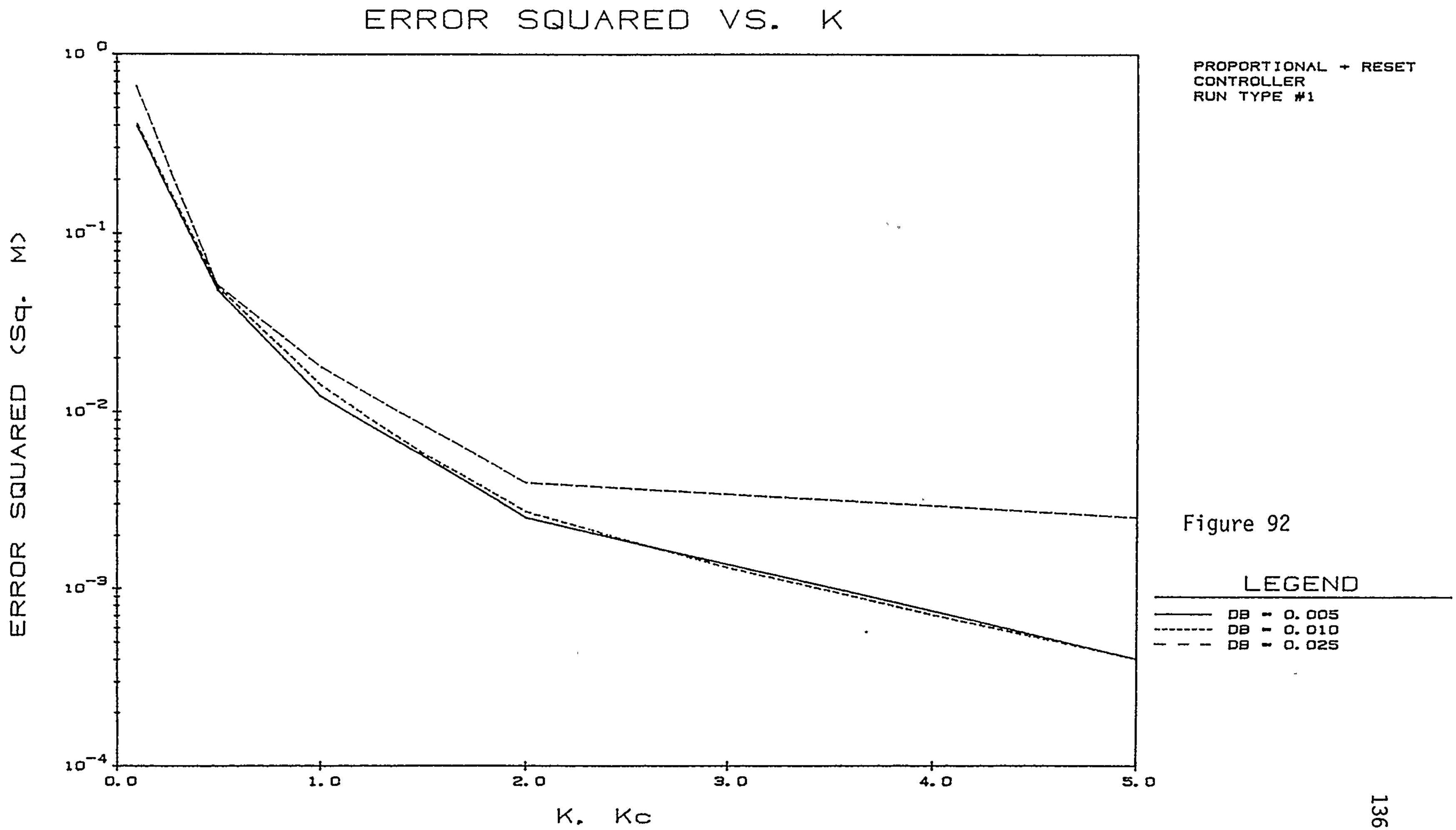

WATER LEVEL UNDERSHOOT VS. K
200.0
160.0
120.0
80.0
40.0
0.0
0.0
1.0
2.0
3.0
4.0
5.0
UNDERSHOOT (mm)
K, Kc
PROPORTIONAL + RESET
CONTROLLER
RUN TYPE #1
LEGEND
DB = 0.005
DB = 0.010
DB = 0.025

Figure 91



ERROR SQUARED VS. K
PROPORTIONAL + RESET
CONTROLLER
RUN TYPE #1
ERROR SQUARED (Sq. M)
K, Kc
10 0
10−1
10−2
10−3
10−4
0.0
1.0
2.0
3.0
4.0
5.0
LEGEND
DB = 0.005
DB = 0.010
DB = 0.025

Figure 92

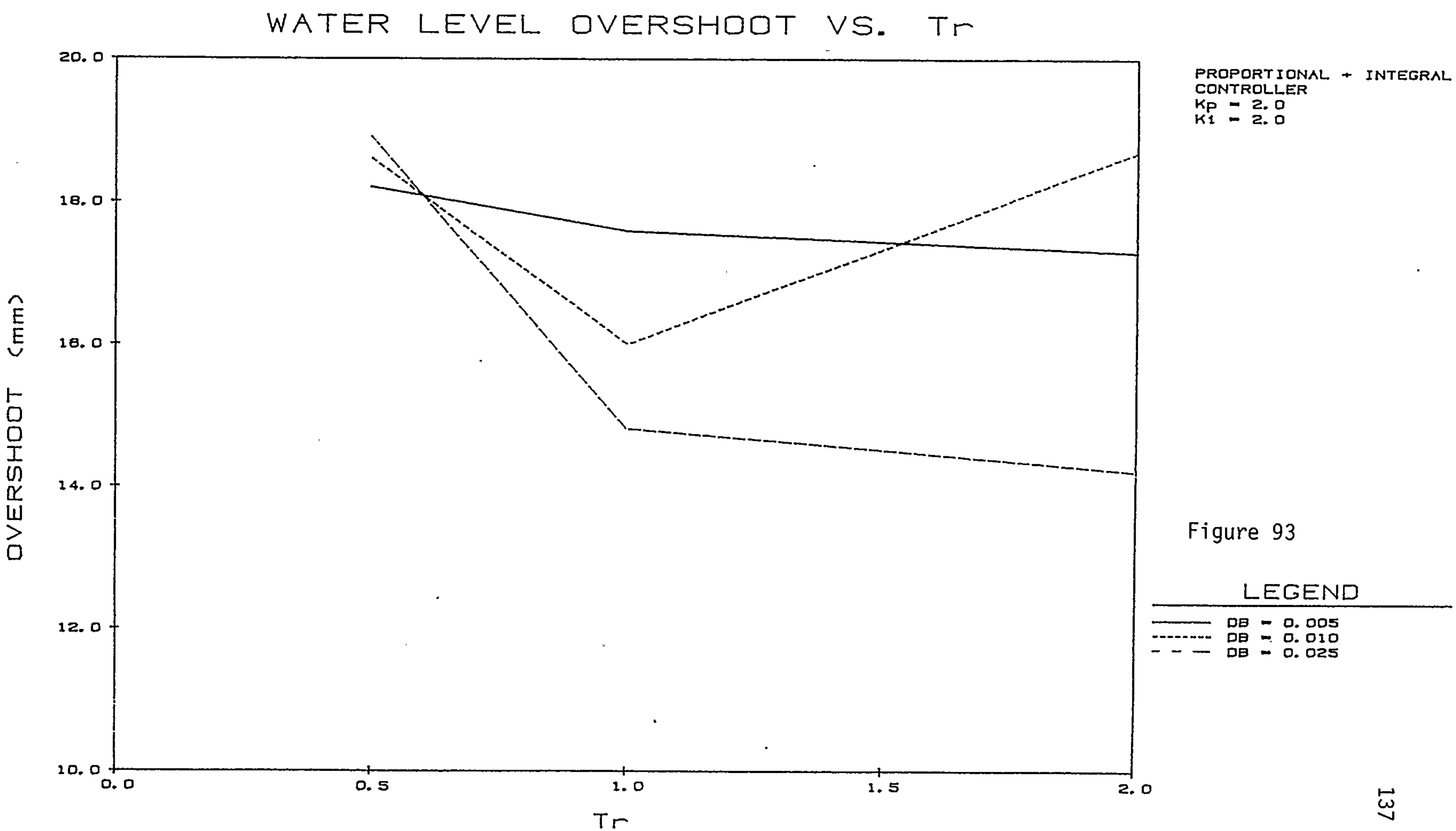
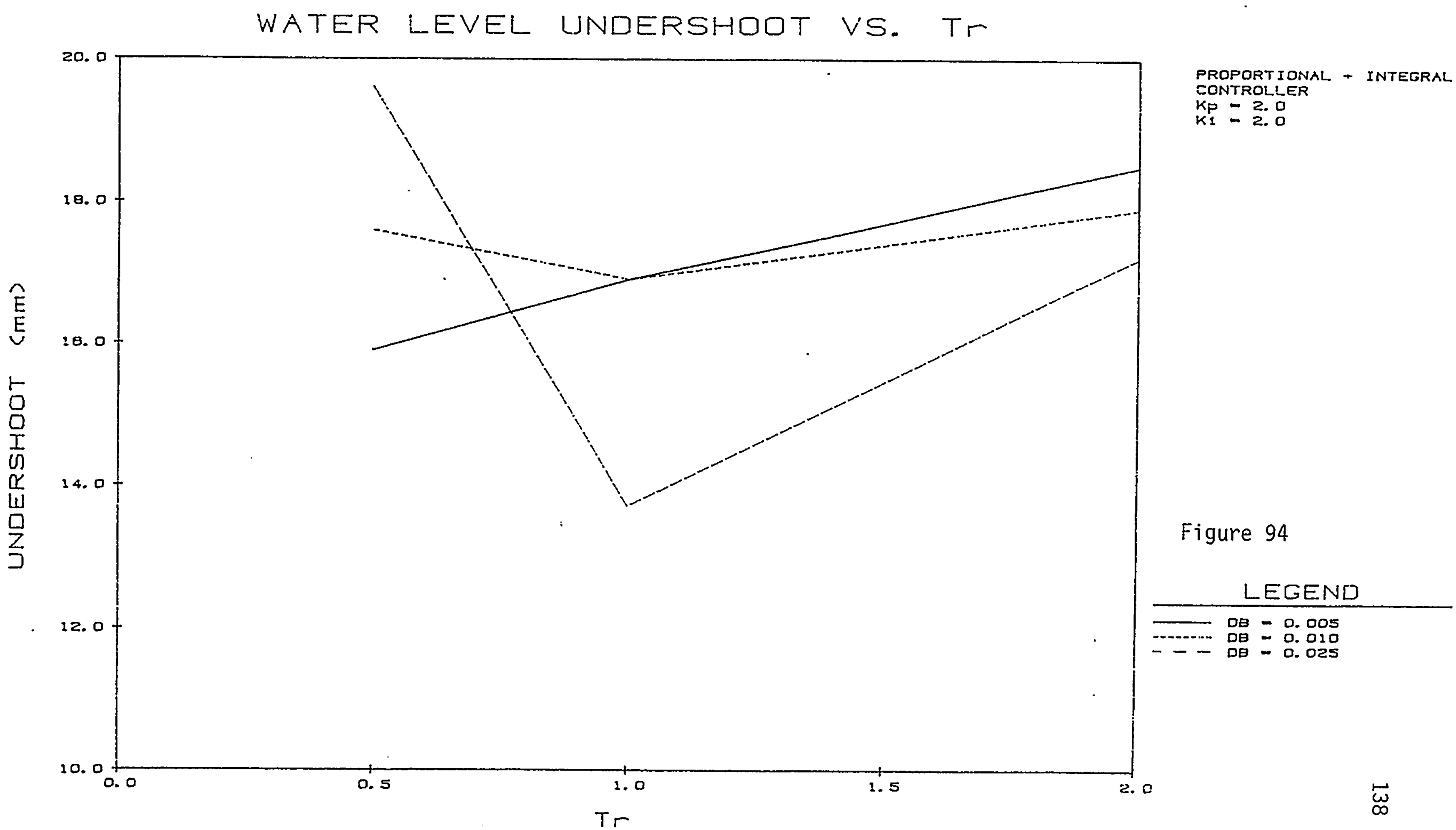

WATER LEVEL OVERSHOOT VS. Tr
OVERSHOOT (mm)
20.0
18.0
16.0
14.0
12.0
10.0
0.0
0.5
1.0
1.5
2.0
Tr
PROPORTIONAL + INTEGRAL CONTROLLER
Kp = 2.0
Ki = 2.0
LEGEND
DB = 0.005
DB = 0.010
DB = 0.025

Figure 93



WATER LEVEL UNDERSHOOT VS. Tr
UNDERSHOOT (mm)
20.0
18.0
16.0
14.0
12.0
10.0
0.0
0.5
1.0
1.5
2.0
Tr
PROPORTIONAL + INTEGRAL CONTROLLER
Kp = 2.0
Ki = 2.0
LEGEND
DB = 0.005
DB = 0.010
DB = 0.025

Figure 94

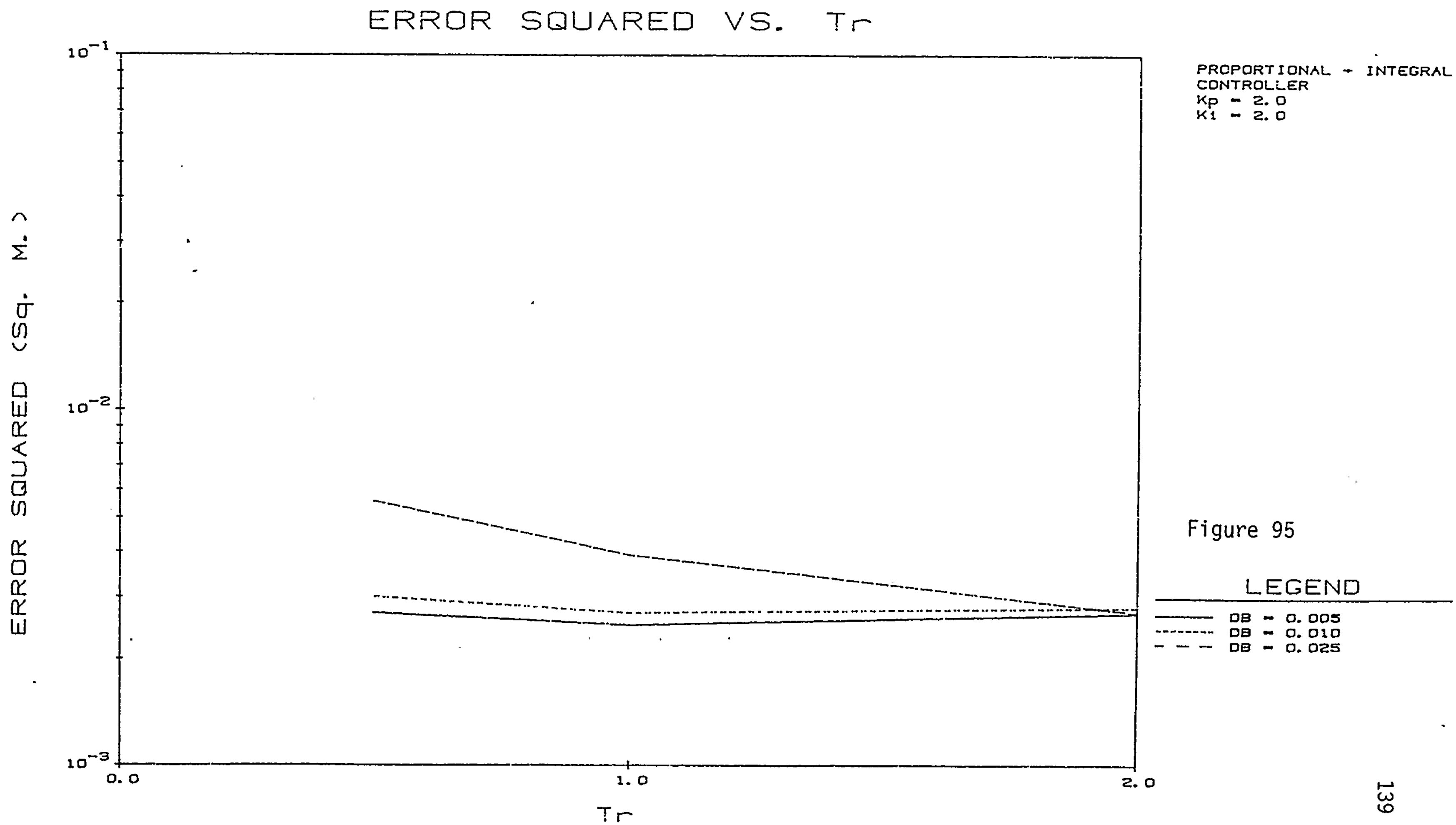

ERROR SQUARED VS. Tr
PROPORTIONAL + INTEGRAL CONTROLLER
Kp = 2.0
Ki = 2.0
ERROR SQUARED (Sq. M.)
10^{-1}
10^{-2}
10^{-3}
0.0
1.0
2.0
Tr
LEGEND
DB = 0.005
DB = 0.010
DB = 0.025

Figure 95

Low values of K_p and K_i respond slower to a disturbance than higher values. This slow response may be illustrated by examining the length of individual oscillations (The slower the response the longer the oscillation). The number of oscillations required to bring the gate to a stable state also increases as the values of K_p and K_i increases until the operation of the gate becomes unstable (Figure 67, 72, 77, 79 and 80).

Small values of K_p and K_i also serve an instructional purpose in that the action of the Integral part of the controller can be seen. Figure 73 illustrates this very well. After the initial disturbance at two hours the controller reacts. At approximately 3 hours the controller becomes stable, but has not been successful in bringing the actual water level to the desired water level. At approximately 3.75 hours the gate begins to adjust, converging towards the desired water elevation. This same phenomenon can be witnessed from 8 to 14 hours.

The convergence towards the setpoint is a direct result of integral part of the controller. Although the integral part of the controller plays a major role in making the actual water level converge to the desired water level, it must not be forgotten that this part is also active during the initial adjustments of the gate. The following is an explanation of how this controller works.

The change in gate position is calculated based on the addition of the proportional and integral terms. The integral term sums all of the errors from the start of operations. As the initial errors can be very large, the integral term acts to accelerate the movement of the controller initially. Because the value of the integral term accumulates a large error it is prone to overshoot the desired water level, thus introducing errors of an opposite sign which reduces the value of the integral term. Once the calculated change in gate movement is less than the deadband no further movement of the gate takes place. However, if the controller was not successful in setting the actual water level to the desired water level, an error still exists. This error will accumulate in the integral term until once again the calculated change in gate position is greater than the deadband. At this time an adjustment will be made to the gate, and the actual water level will come closer to the desired water level. This process continues until the actual water level and desired water level match exactly, or another disturbance is introduced.

Reviewing run numbers 1 and 6 (Figures 63 and 68) we can see this tendency to overshoot the desired water level. With a larger deadband (0.025 m) however, this tendency seems to be diminished. Comparing all other runs with a 0.025 m deadband against the 0.005 and 0.010 m deadbands we see that the number of oscillations required to return the controller to a stable state decreases (Tendency to overshoot decreases). This type of operation is a result of the controller being allowed more time to accumulate the error values. (Remember that the controller will not move until the change in gate position exceeds the deadband. The errors are still accumulated during this time period. Thus no gate adjustments may be made for multiple time periods) Thus when gate movements are made they can be quite large, in turn reducing the error a large amount. The next gate movement, when it occurs will not be as large. Smaller deadband values will result in many large movements in the place of only one for the 0.025 m deadband.

Table 12 lists the values of maximum overshoot, undershoot and the summation of e^2. These values are presented in graphical form in Figures 90-92. As with the proportional controller the overshoot, undershoot and e^2 terms rapidly diminish as the value of K_p and K_i increases. The values of the overshoot and the undershoot become similar with increasing K_p and K_i.

Table 12. Proportional + Integral Controller; Maximum Overshoot, Undershoot and Summation of e^2 terms for different parameter settings.

K_p	K_i	T_r	Overshoot (mm)	Undershoot (mm)	Sum of $e^2 (mm)^2$	Dead-band (m)	Run #
0.1	0.1	1.0	94.4	105.6	0.3921	0.005	1
0.5	0.5	1.0	47.5	51.7	0.0478	0.005	2
1.0	1.0	1.0	29.7	31.8	0.0122	0.005	3
2.0	2.0	1.0	17.6	16.9	0.0025	0.005	4
5.0	5.0	1.0	6.9	6.3	0.0004	0.005	5
0.1	0.1	1.0	82.8	133.8	0.4034	0.010	6
0.5	0.5	1.0	50.8	48.0	0.0498	0.010	7
1.0	1.0	1.0	30.4	36.6	0.0140	0.010	8
1.5	1.5	1.0	24.0	24.0	0.0057	0.010	16
2.0	2.0	1.0	16.0	16.9	0.0027	0.010	9
3.0	3.0	1.0	13.0	12.0	0.0013	0.010	17
4.0	4.0	1.0	9.0	8.0	0.0007	0.010	18
5.0	5.0	1.0	6.7	6.8	0.0004	0.010	10
0.1	0.1	1.0	107.2	187.5	0.6579	0.025	11
0.5	0.5	1.0	57.1	40.2	0.0514	0.025	12
1.0	1.0	1.0	35.5	33.1	0.0178	0.025	13
2.0	2.0	1.0	14.8	13.7	0.0039	0.025	14
5.0	5.0	1.0	8.7	9.4	0.0025	0.025	15
2.0	2.0	0.5	18.2	15.9	0.0027	0.005	19
2.0	2.0	1.0	17.6	16.9	0.0025	0.005	20
2.0	2.0	2.0	17.3	18.5	0.0027	0.005	21
2.0	2.0	0.5	18.6	17.6	0.0030	0.010	22
2.0	2.0	1.0	16.0	16.9	0.0027	0.010	23
2.0	2.0	2.0	18.7	17.9	0.0028	0.010	24
2.0	2.0	0.5	18.9	19.6	0.0055	0.025	25
2.0	2.0	1.0	14.8	13.7	0.0039	0.025	26
2.0	2.0	2.0	14.2	17.2	0.0027	0.025	27

Figure 92 shows the e^2 term as a function of K_p and K_i. The e^2 value for a deadband of 0.005 m and 0.010 m are very similar. With the deadband equal to 0.025 m the e^2 term is larger than with a deadband of 0.005 m and 0.010 m. This relates to the coarseness with which adjustments must take place. (Only when the gate requires an adjustment of 0.025 m or greater) The error for a deadband of 0.025 m departs dramatically from the others when the value of K_p and K_i is equal to 5.0. This is a result of the instability of the controller. (See run 15, Figure 77)

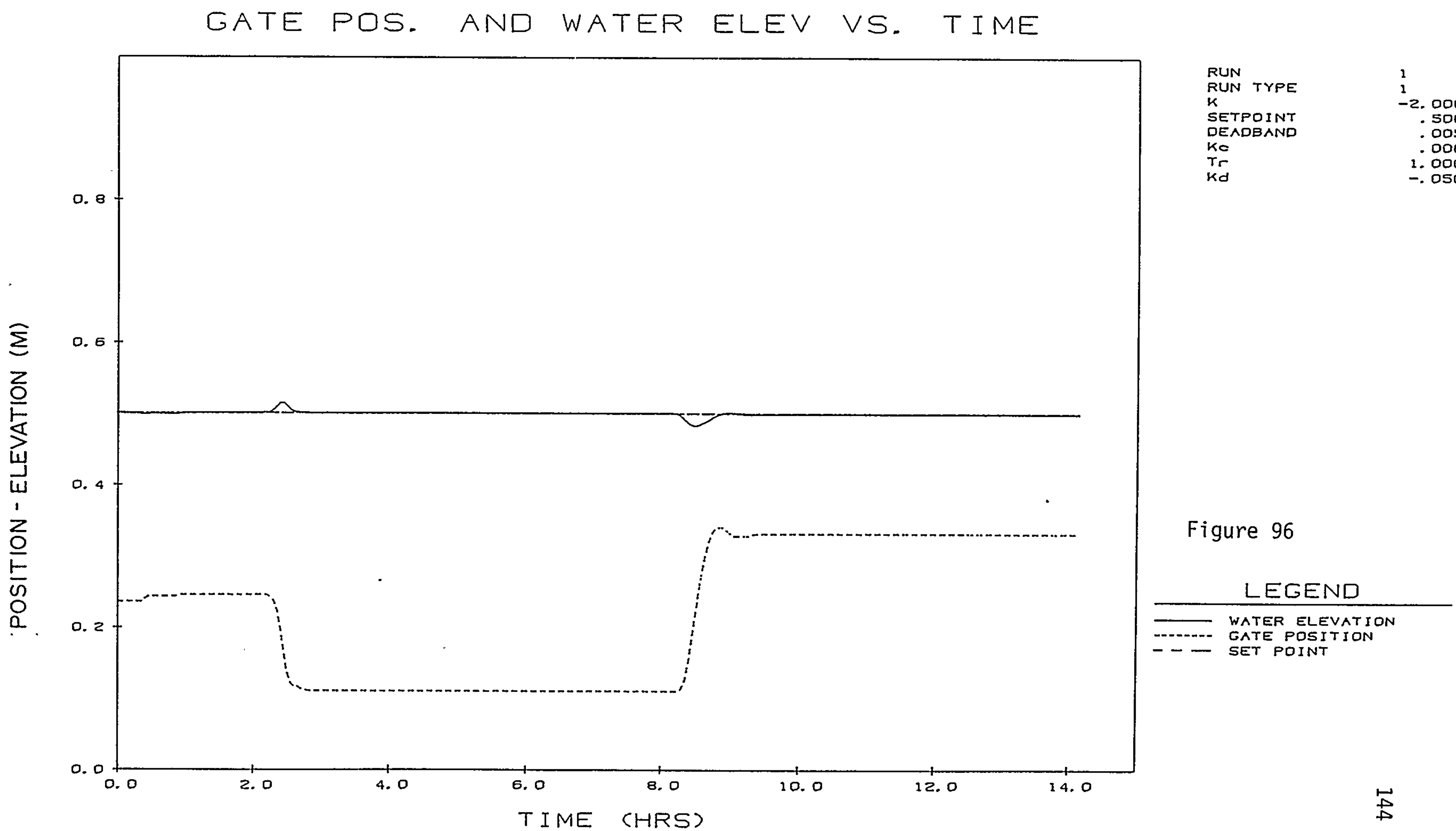
Run numbers 19 to 27 (Figures 81-89) demonstrate the action of the controller using different reset times T_r. Changing the value of the reset time has the effect of changing the operation of the integral portion of the controller only. Recall from section 3.3.7 that the K_i is simply divided by the reset time. The values of reset time used and their relation to K_i are shown below:

T_r	K_i
0.5	$K_i \times 2$
1.0	K_i
2.0	$K_i \times 0.5$

By doubling the value of K_i all of the deadbands became unstable. Decreasing the value of K_i by half has little effect when the deadband is set to 0.005 or 0.010 m. An increase in stability is noted comparing Figures 88 and 89 by the halving of the K_i value.
The changes in the maximum values of overshoot, undershoot and summation of e^2 do not change significantly as a result of the changes in K_i. These values are presented in Table 12 and in graphical form in Figures 93-95.

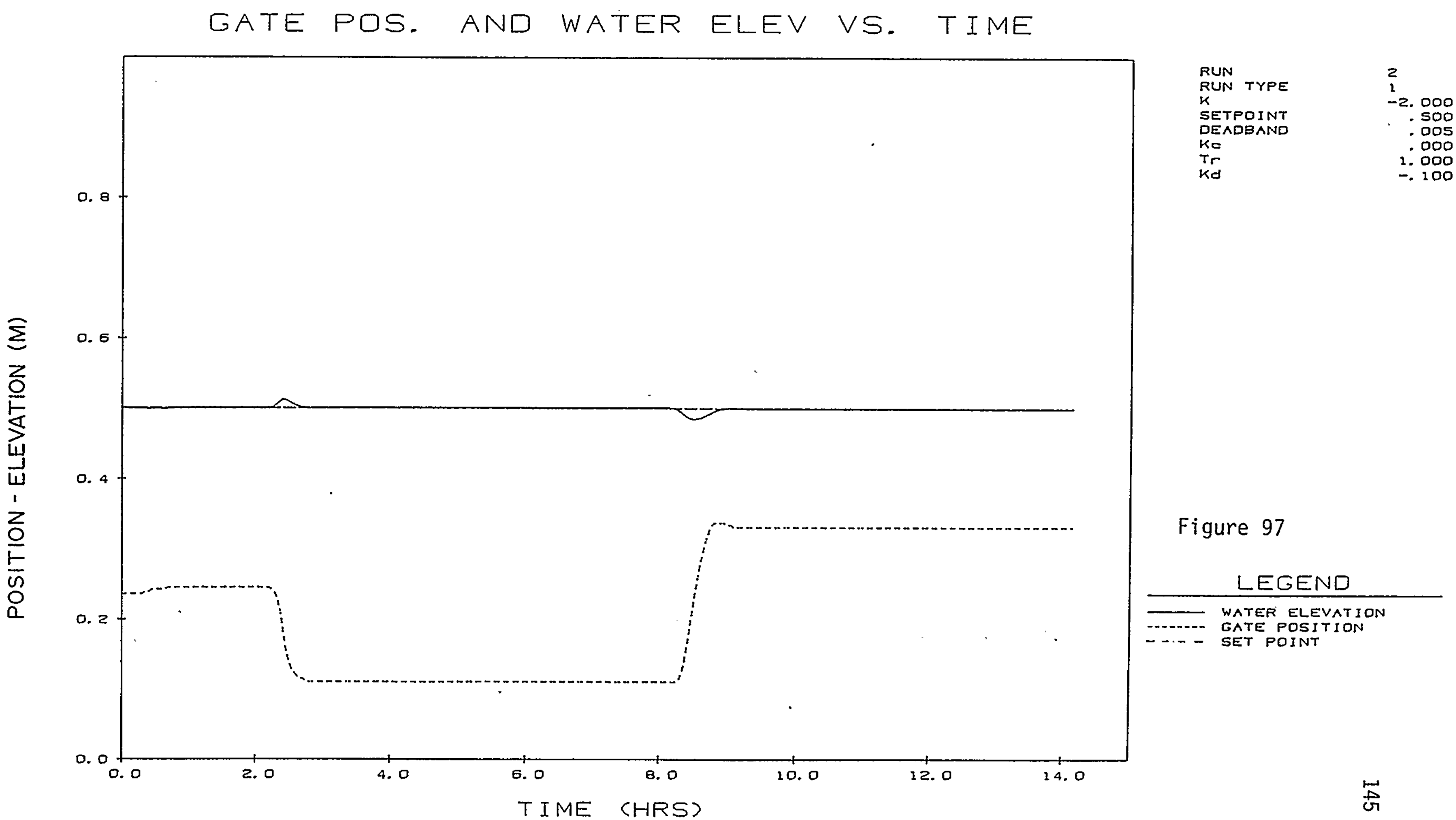
7.5 PROPORTIONAL + DIFFERENTIAL CONTROLLER

Figures 96 to 113 present the results of the numerical experiments for a type 1 inlet variation. Run numbers 1-3, 4-6 and 7-9 are identical with the exception of the deadband. Run number 10-12, 13-15 and 16-18 are also identical with the



GATE POS. AND WATER ELEV VS. TIME
POSITION - ELEVATION (M)
0.0
0.2
0.4
0.6
0.8
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
TIME (HRS)
RUN 1
RUN TYPE 1
K -2.000
SETPOINT .500
DEADBAND .005
Kc .000
Tr 1.000
Kd -.050
LEGEND
WATER ELEVATION
GATE POSITION
SET POINT

Figure 96



GATE POS. AND WATER ELEV VS. TIME
RUN 2
RUN TYPE 1
K -2.000
SETPOINT .500
DEADBAND .005
Kc .000
Tr 1.000
Kd -.100
POSITION - ELEVATION (M)
0.0
0.2
0.4
0.6
0.8
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
TIME (HRS)
LEGEND
WATER ELEVATION
GATE POSITION
SET POINT

Figure 97

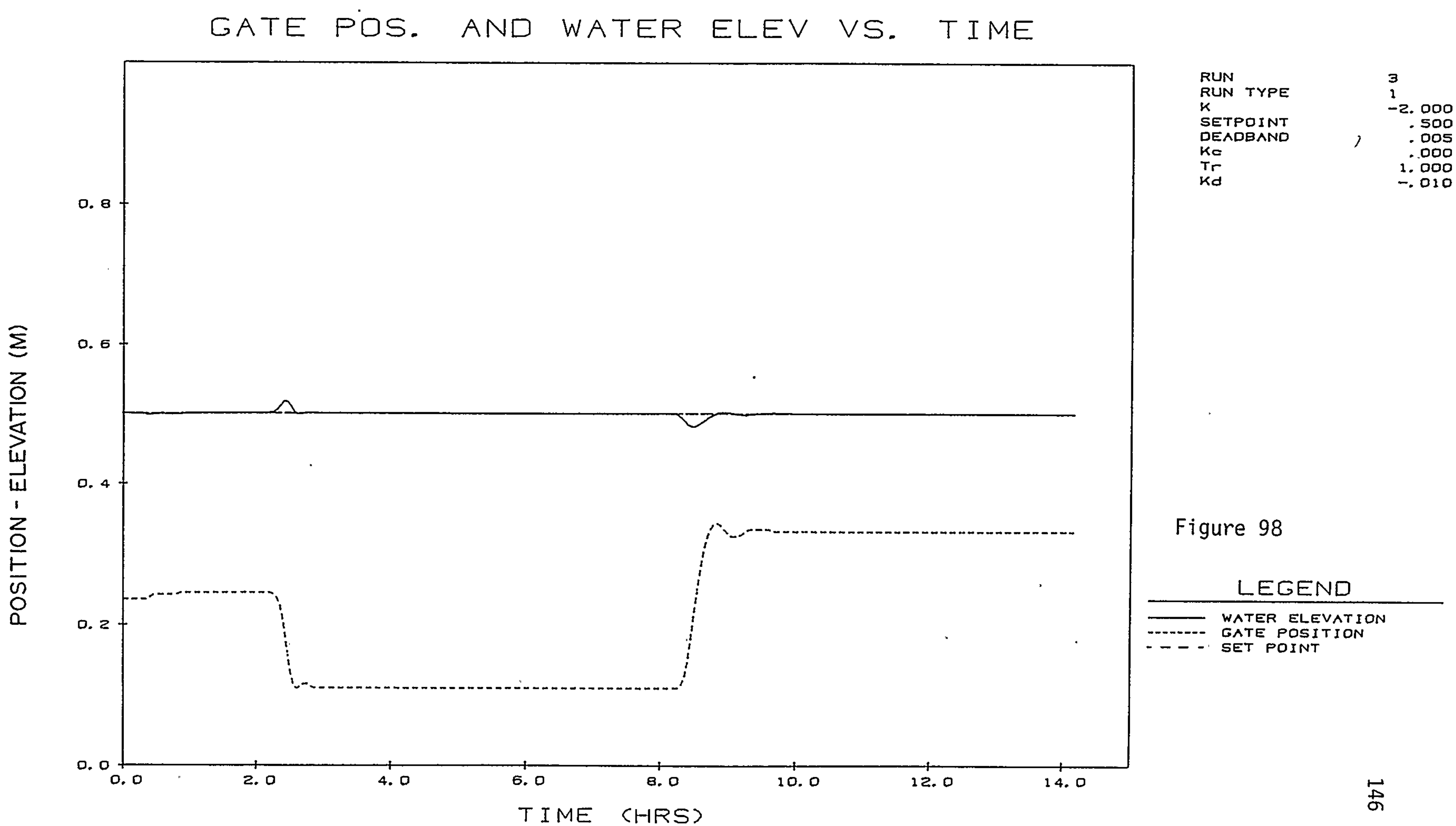

GATE POS. AND WATER ELEV VS. TIME
POSITION - ELEVATION (M)
0.0
0.2
0.4
0.6
0.8
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
TIME (HRS)
RUN 3
RUN TYPE 1
K -2.000
SETPOINT .500
DEADBAND .005
Kc .000
Tr 1.000
Kd -.010
LEGEND
WATER ELEVATION
GATE POSITION
SET POINT

Figure 98

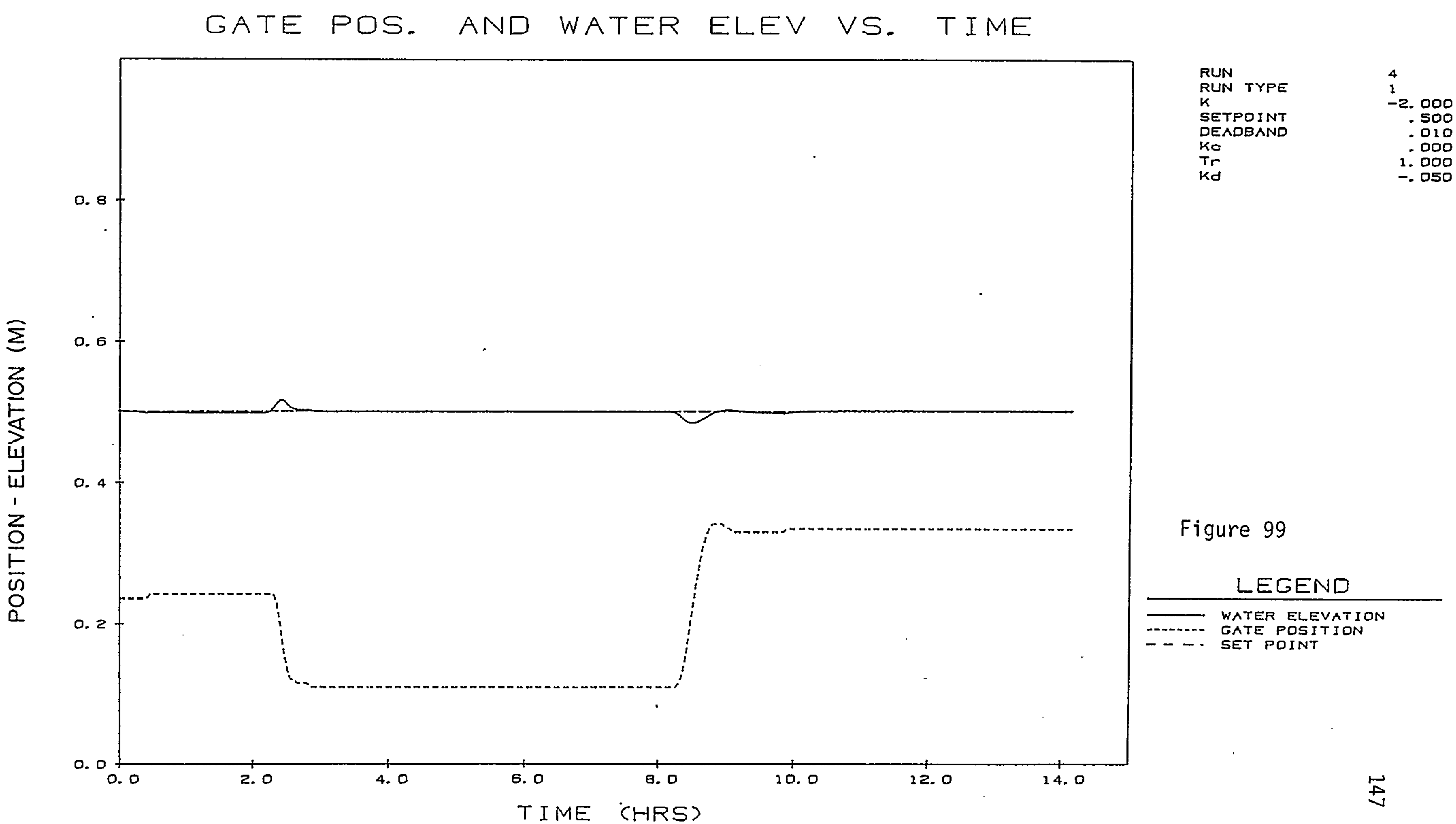

GATE POS. AND WATER ELEV VS. TIME
RUN 4
RUN TYPE 1
K -2.000
SETPOINT .500
DEADBAND .010
Kc .000
Tr 1.000
Kd -.050
POSITION - ELEVATION (M)
0.0
0.2
0.4
0.6
0.8
TIME (HRS)
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
LEGEND
WATER ELEVATION
GATE POSITION
SET POINT

Figure 99

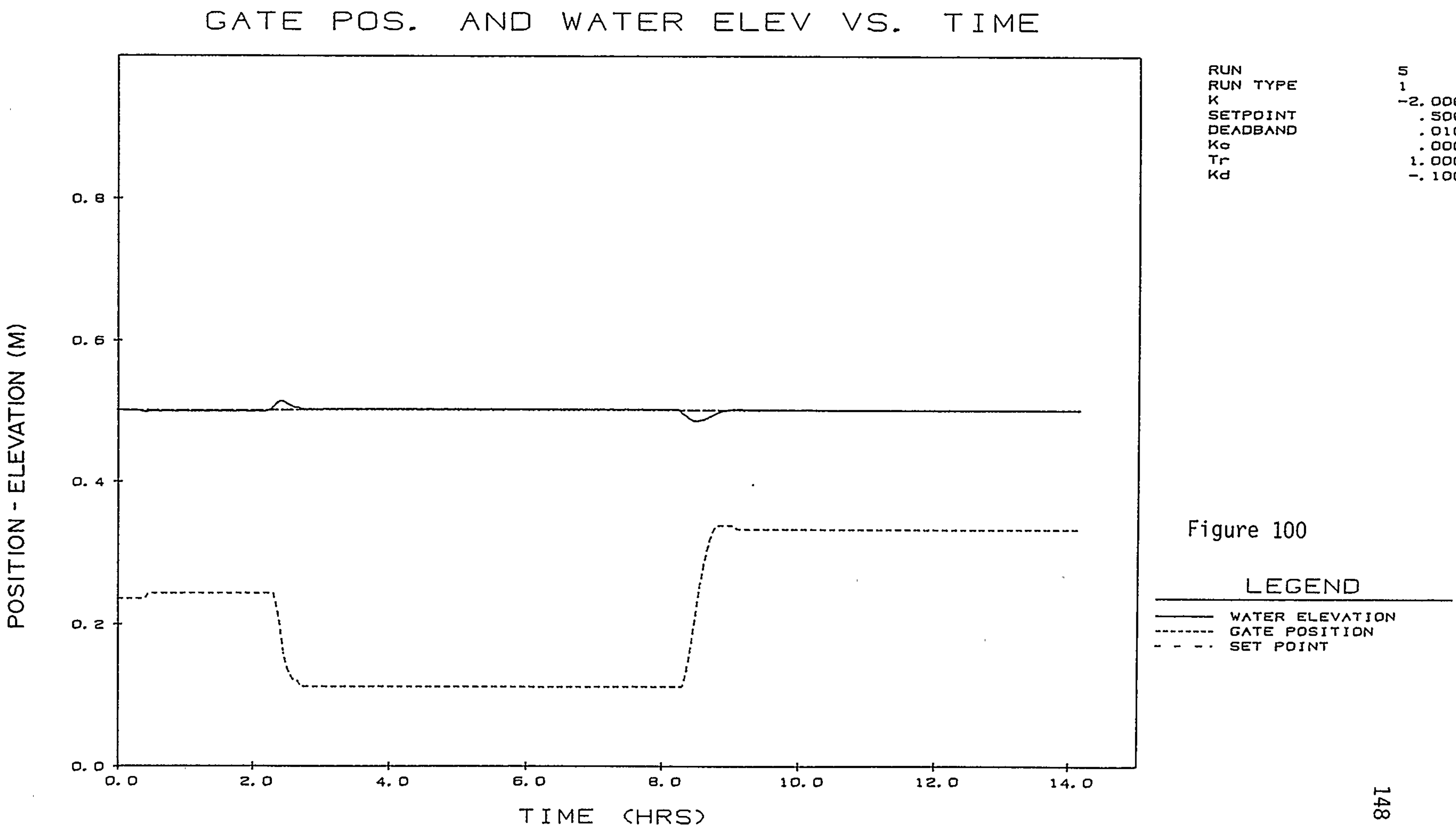

GATE POS. AND WATER ELEV VS. TIME
POSITION - ELEVATION (M)
0.0
0.2
0.4
0.6
0.8
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
TIME (HRS)
RUN 5
RUN TYPE 1
K -2.000
SETPOINT .500
DEADBAND .010
Ka .000
Tr 1.000
Kd -.100
LEGEND
WATER ELEVATION
GATE POSITION
SET POINT

Figure 100

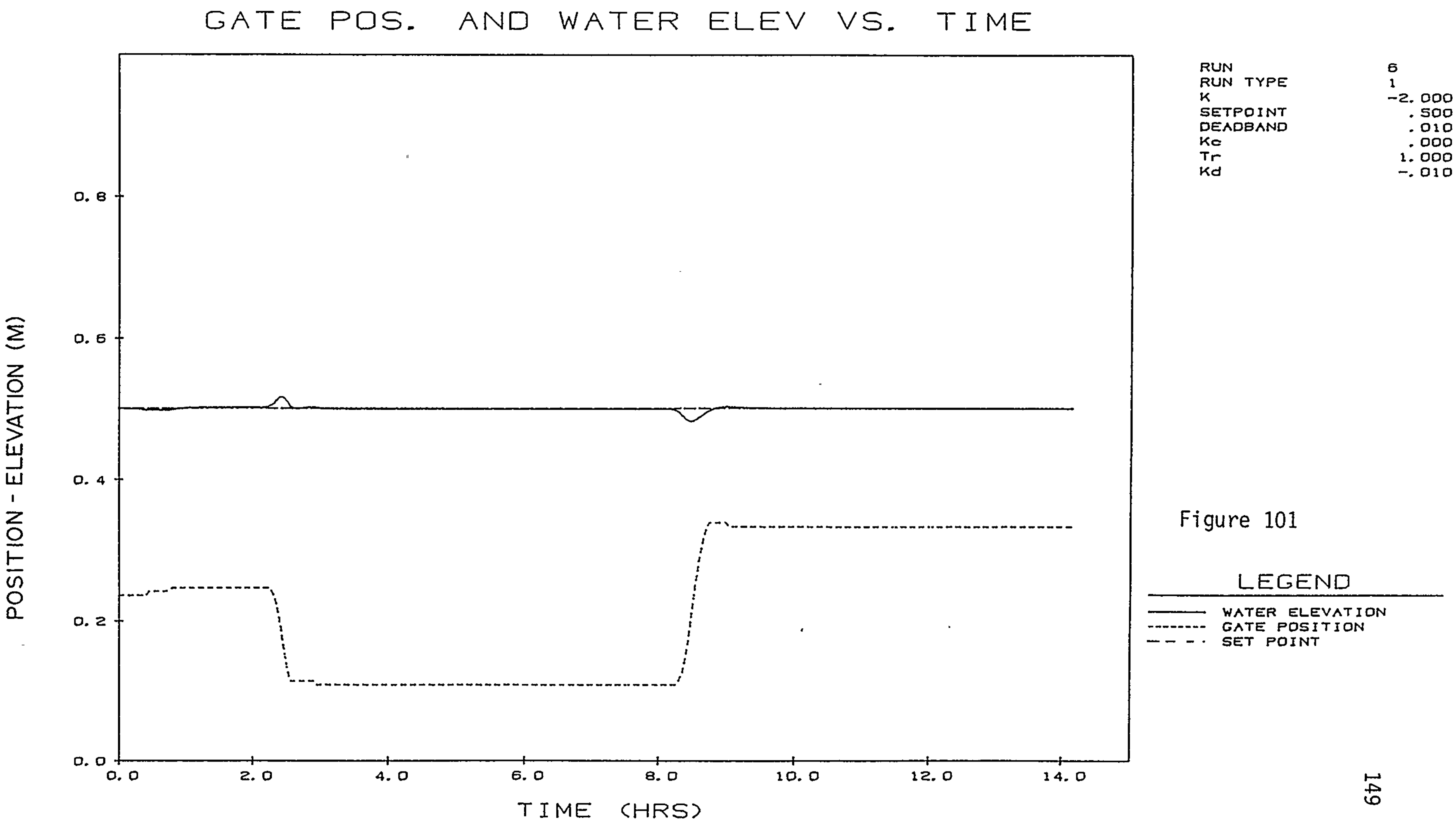
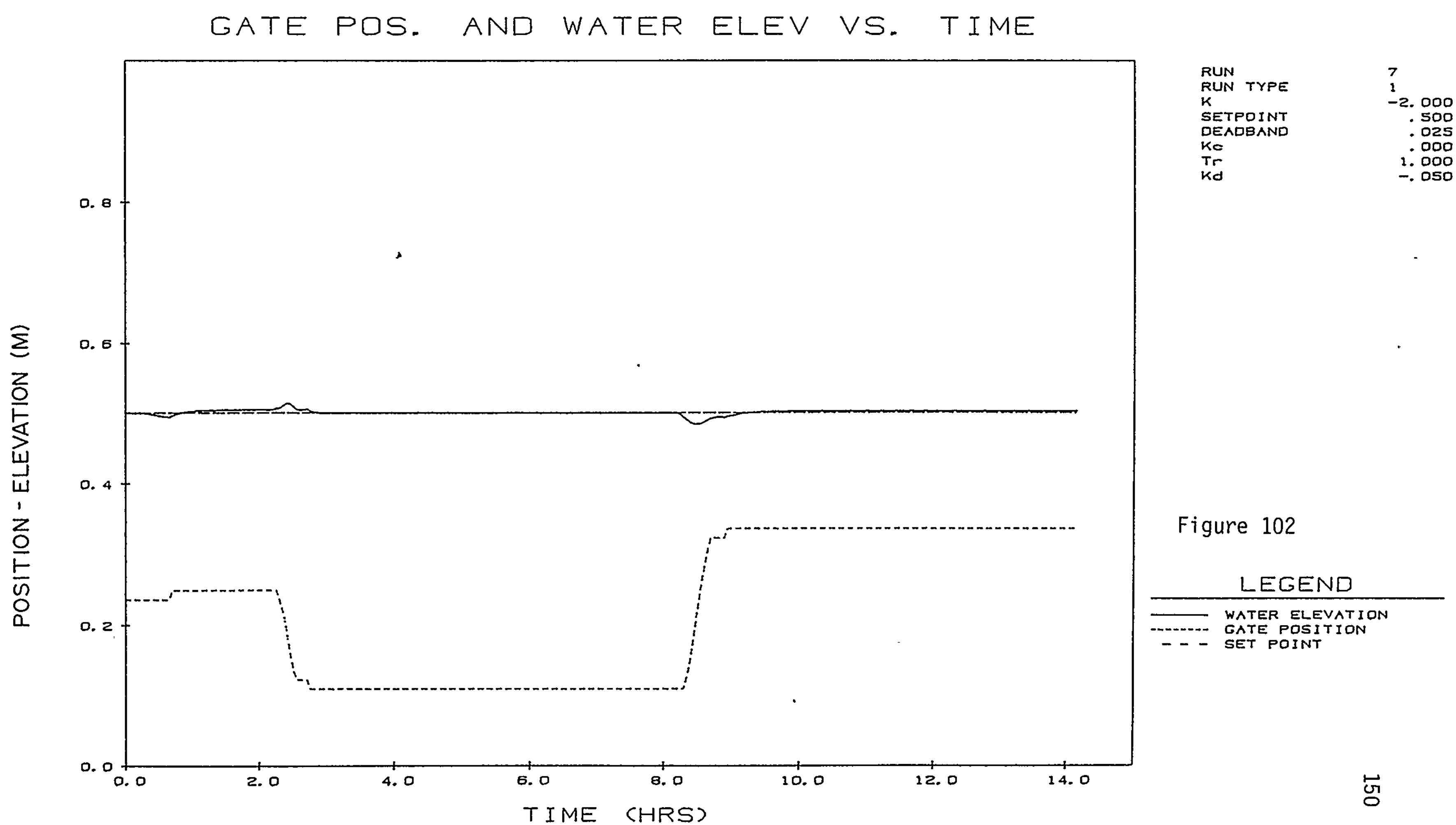

GATE POS. AND WATER ELEV VS. TIME
RUN 6
RUN TYPE 1
K -2.000
SETPOINT .500
DEADBAND .010
Kc .000
Tr 1.000
Kd -.010
POSITION - ELEVATION (M)
0.0
0.2
0.4
0.6
0.8
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
TIME (HRS)
LEGEND
WATER ELEVATION
GATE POSITION
SET POINT

Figure 101



GATE POS. AND WATER ELEV VS. TIME
POSITION - ELEVATION (M)
0.0
0.2
0.4
0.6
0.8
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
TIME (HRS)
RUN 7
RUN TYPE 1
K -2.000
SETPOINT .500
DEADBAND .025
Kc .000
Tr 1.000
Kd -.050
LEGEND
WATER ELEVATION
GATE POSITION
SET POINT

Figure 102

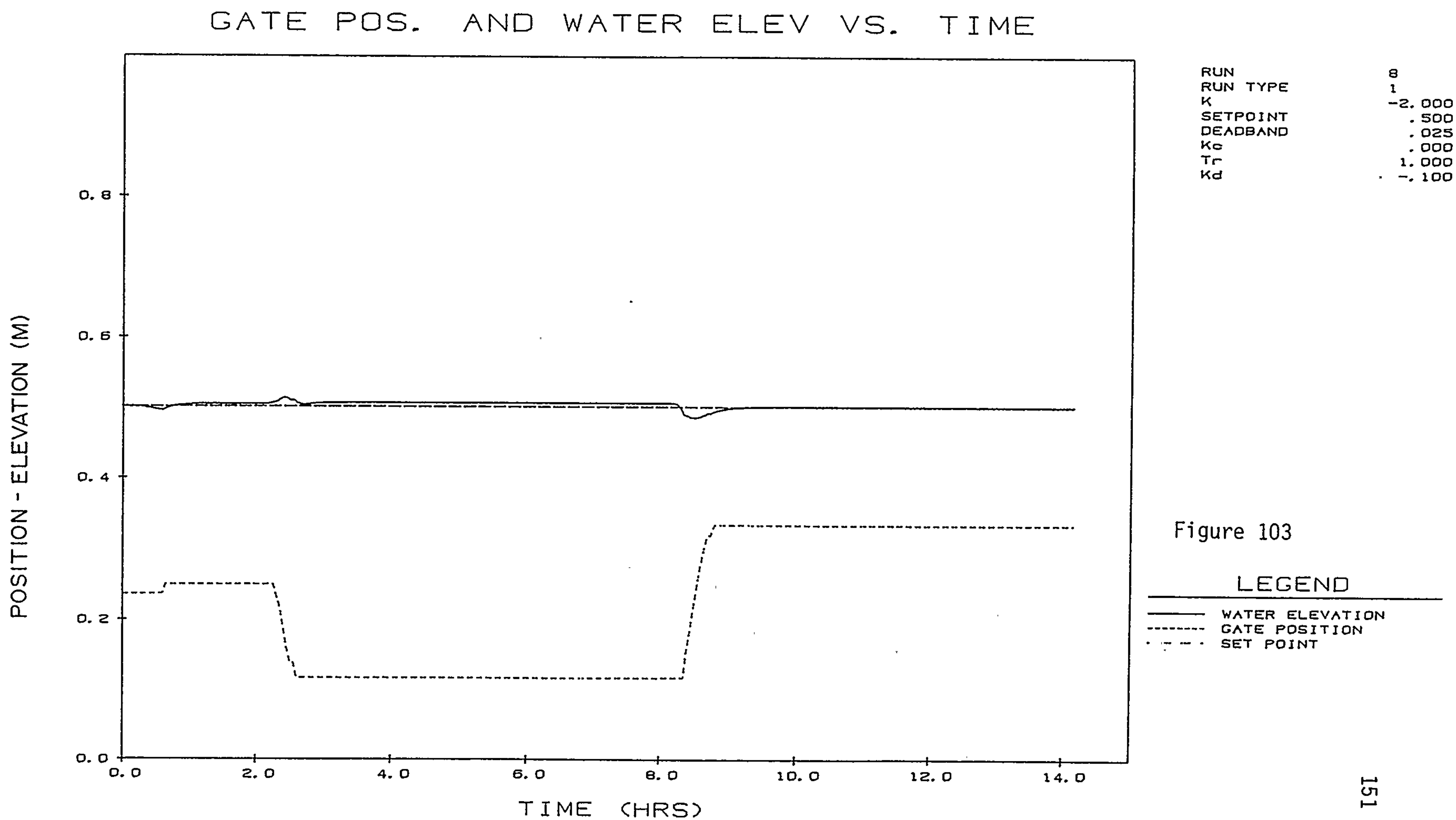
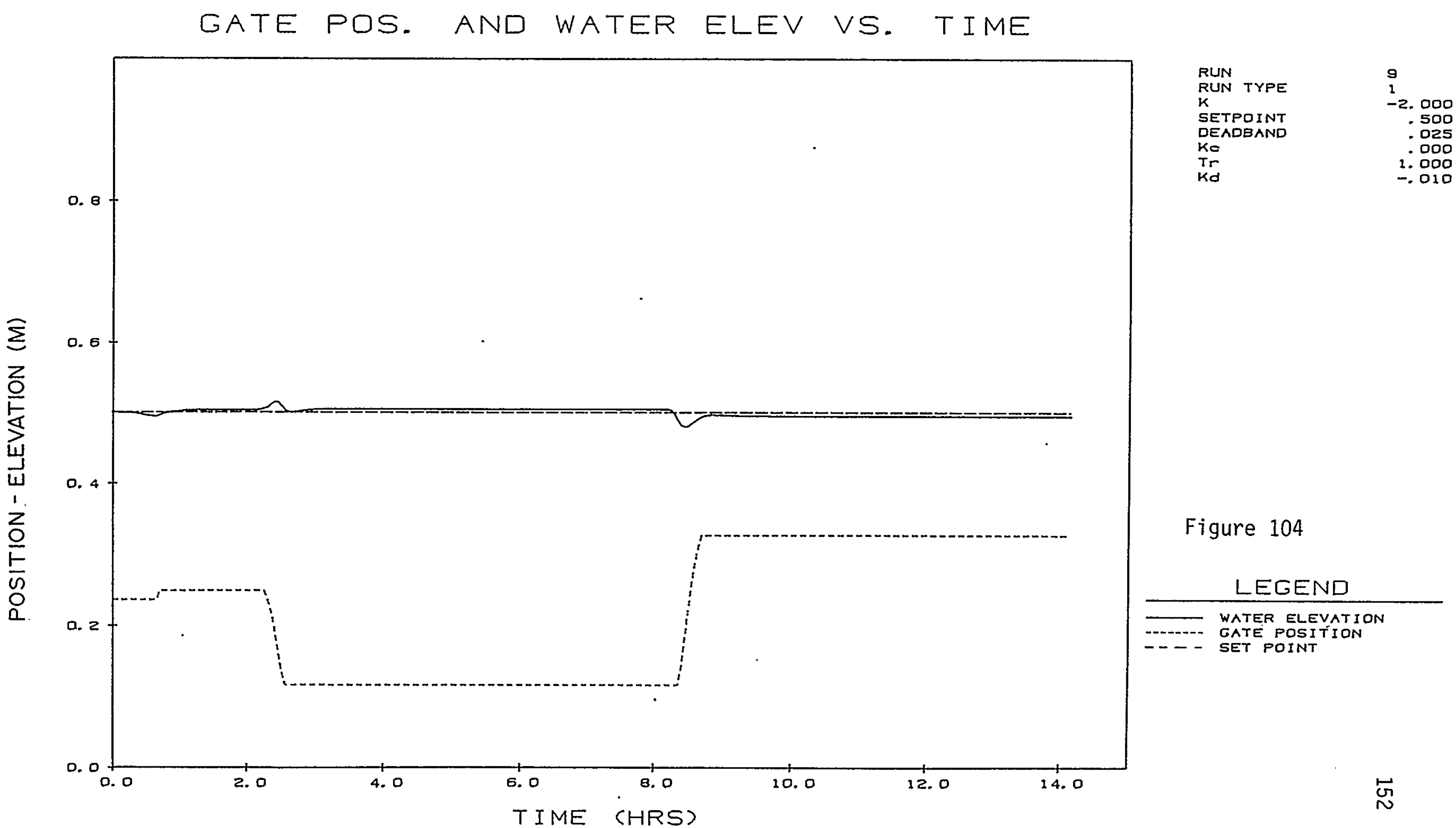

GATE POS. AND WATER ELEV VS. TIME
RUN 8
RUN TYPE 1
K -2.000
SETPOINT .500
DEADBAND .025
Kc .000
Tr 1.000
Kd -.100
POSITION - ELEVATION (M)
0.0
0.2
0.4
0.6
0.8
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
TIME (HRS)
LEGEND
WATER ELEVATION
GATE POSITION
SET POINT

Figure 103



GATE POS. AND WATER ELEV VS. TIME
RUN 9
RUN TYPE 1
K -2.000
SETPOINT .500
DEADBAND .025
Kc .000
Tr 1.000
Kd -.010
0.8
0.6
0.4
0.2
0.0
POSITION - ELEVATION (M)
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
TIME (HRS)
LEGEND
WATER ELEVATION
GATE POSITION
SET POINT

Figure 104

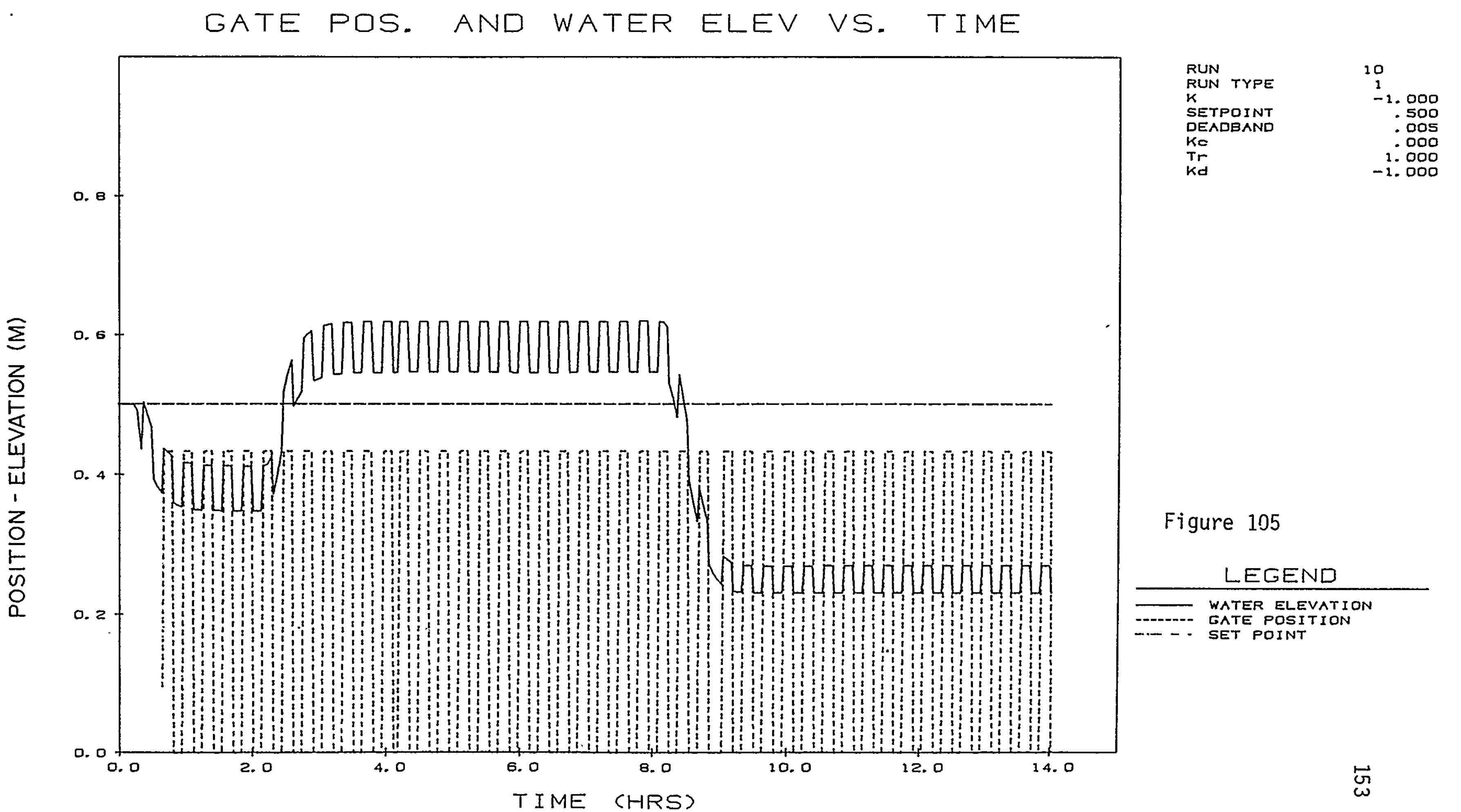

GATE POS. AND WATER ELEV VS. TIME
POSITION - ELEVATION (M)
0.0
0.2
0.4
0.6
0.8
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
TIME (HRS)
RUN 10
RUN TYPE 1
K -1.000
SETPOINT .500
DEADBAND .005
Kc .000
Tr 1.000
Kd -1.000
LEGEND
WATER ELEVATION
GATE POSITION
SET POINT

Figure 105

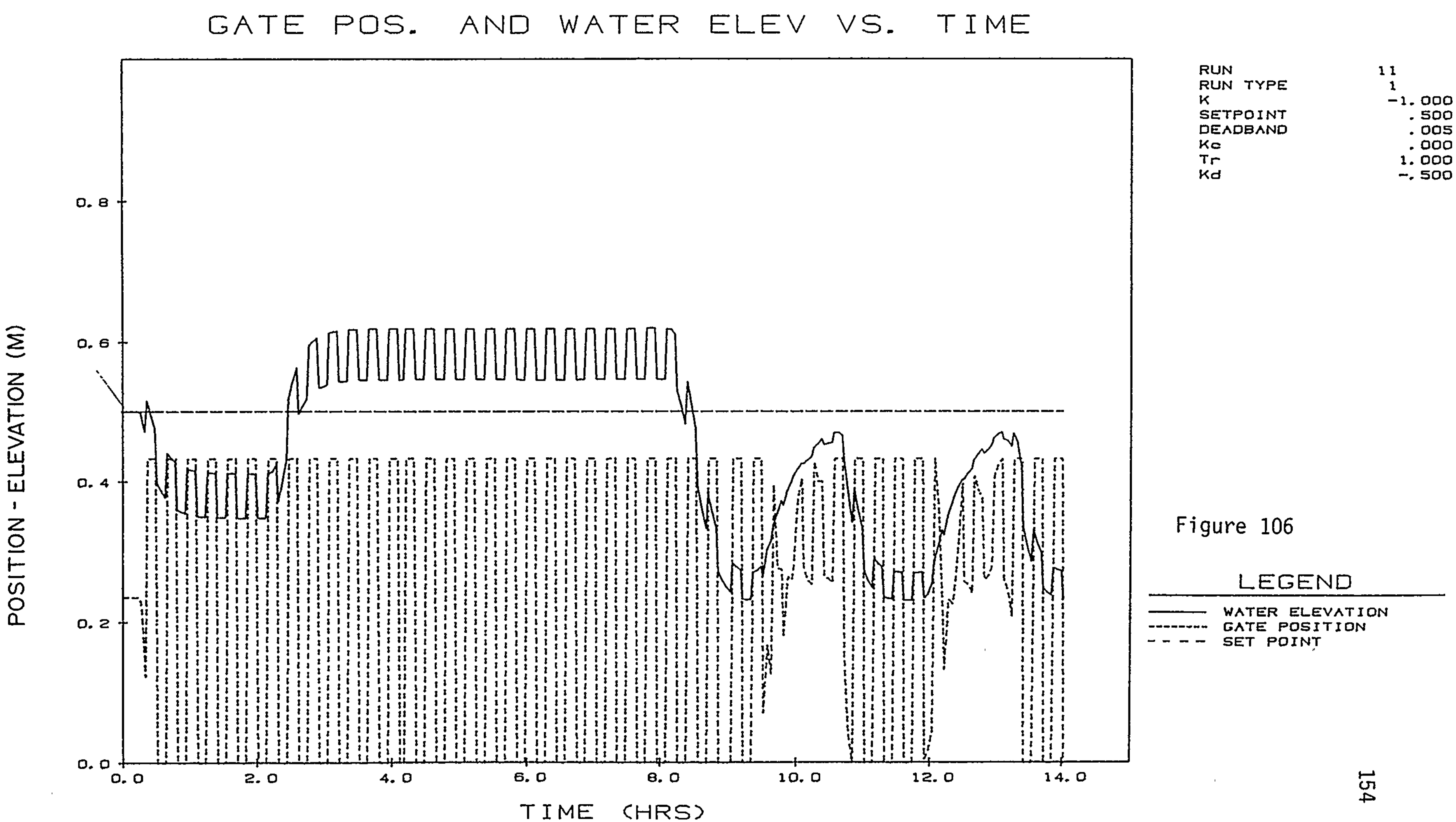
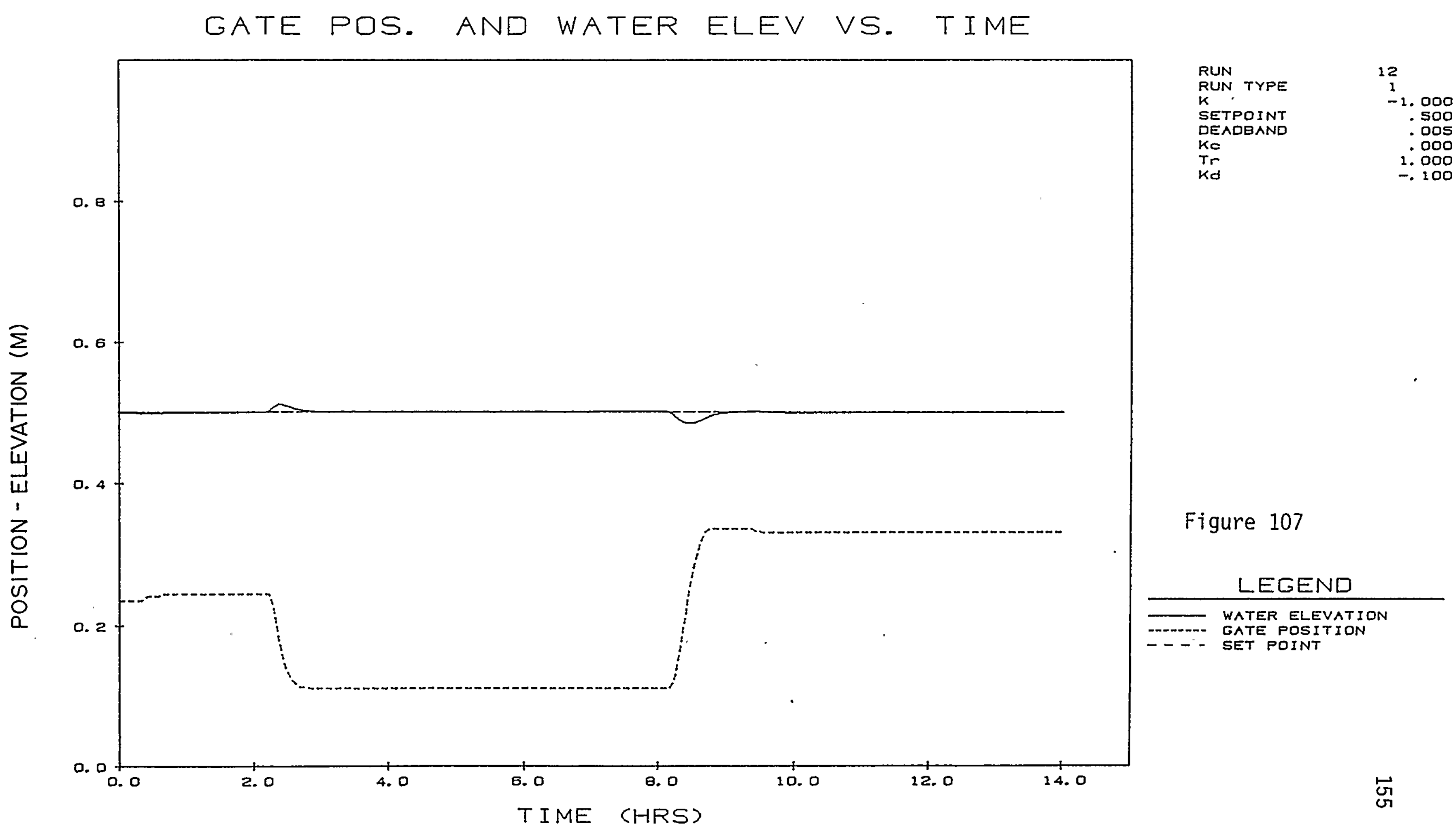

GATE POS. AND WATER ELEV VS. TIME
POSITION - ELEVATION (M)
0.0
0.2
0.4
0.6
0.8
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
TIME (HRS)
RUN 11
RUN TYPE 1
K -1.000
SETPOINT .500
DEADBAND .005
Kc .000
Tr 1.000
Kd -.500
LEGEND
WATER ELEVATION
GATE POSITION
SET POINT

Figure 106



GATE POS. AND WATER ELEV VS. TIME
POSITION - ELEVATION (M)
0.0
0.2
0.4
0.6
0.8
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
TIME (HRS)
RUN 12
RUN TYPE 1
K -1.000
SETPOINT .500
DEADBAND .005
Kc .000
Tr 1.000
Kd -.100
LEGEND
WATER ELEVATION
GATE POSITION
SET POINT

Figure 107

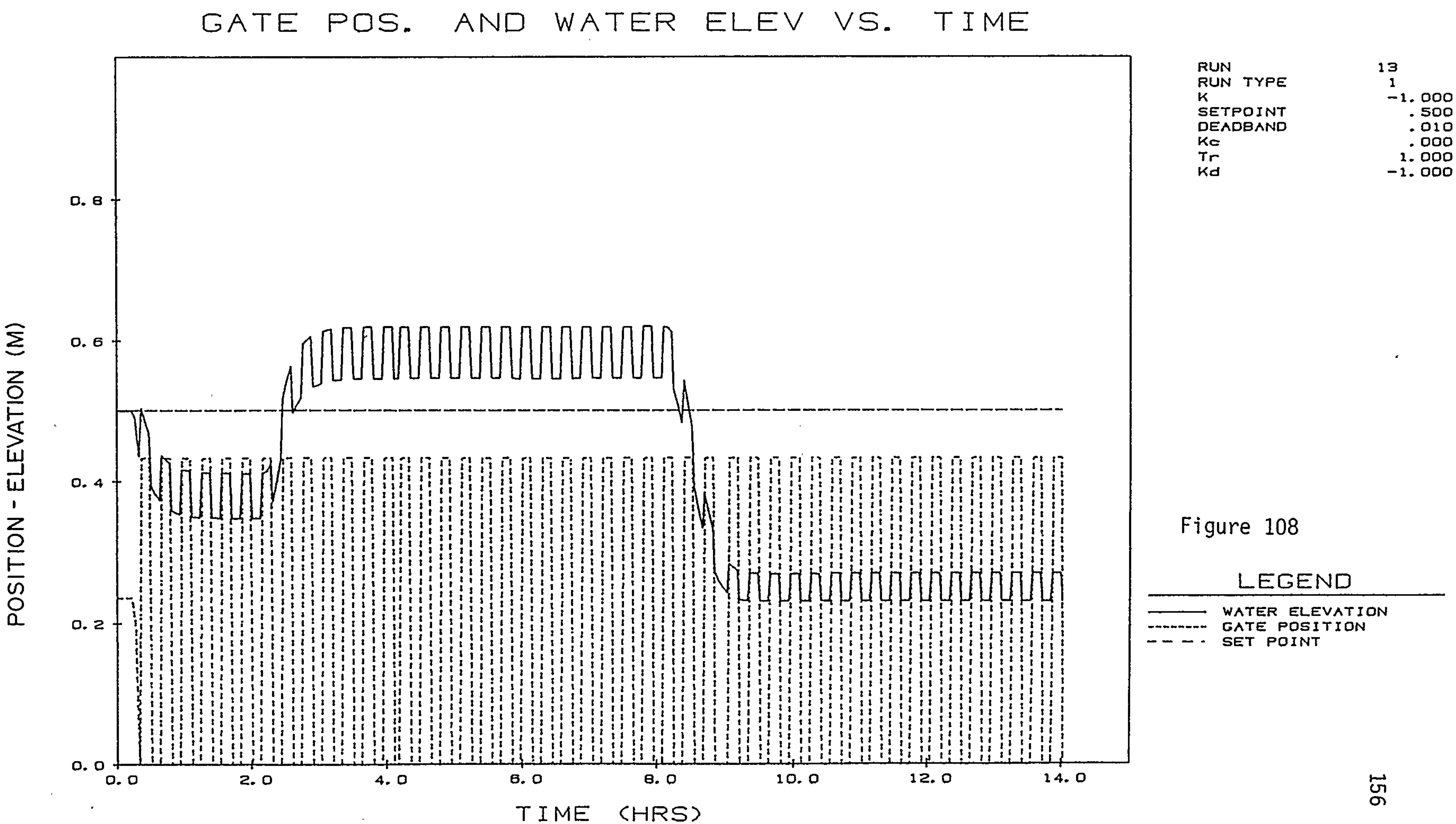

GATE POS. AND WATER ELEV VS. TIME
POSITION - ELEVATION (M)
0.0
0.2
0.4
0.6
0.8
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
TIME (HRS)
RUN 13
RUN TYPE 1
K -1.000
SETPOINT .500
DEADBAND .010
Kc .000
Tr 1.000
Kd -1.000
LEGEND
WATER ELEVATION
GATE POSITION
SET POINT

Figure 108

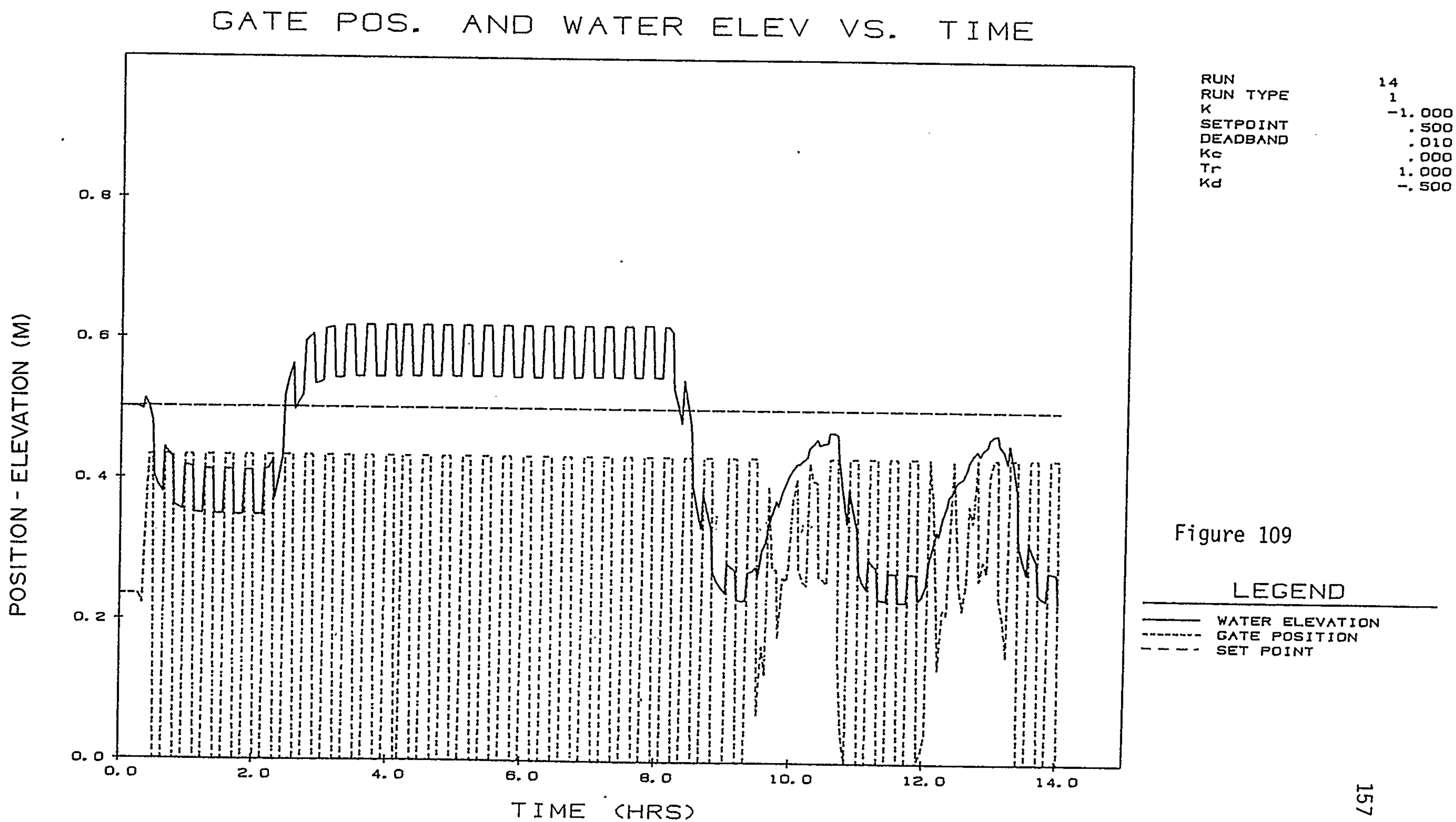

GATE POS. AND WATER ELEV VS. TIME
POSITION - ELEVATION (M)
0.0
0.2
0.4
0.6
0.8
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
TIME (HRS)
RUN 14
RUN TYPE 1
K -1.000
SETPOINT .500
DEADBAND .010
Kc .000
Tr 1.000
Kd -.500
LEGEND
WATER ELEVATION
GATE POSITION
SET POINT

Figure 109

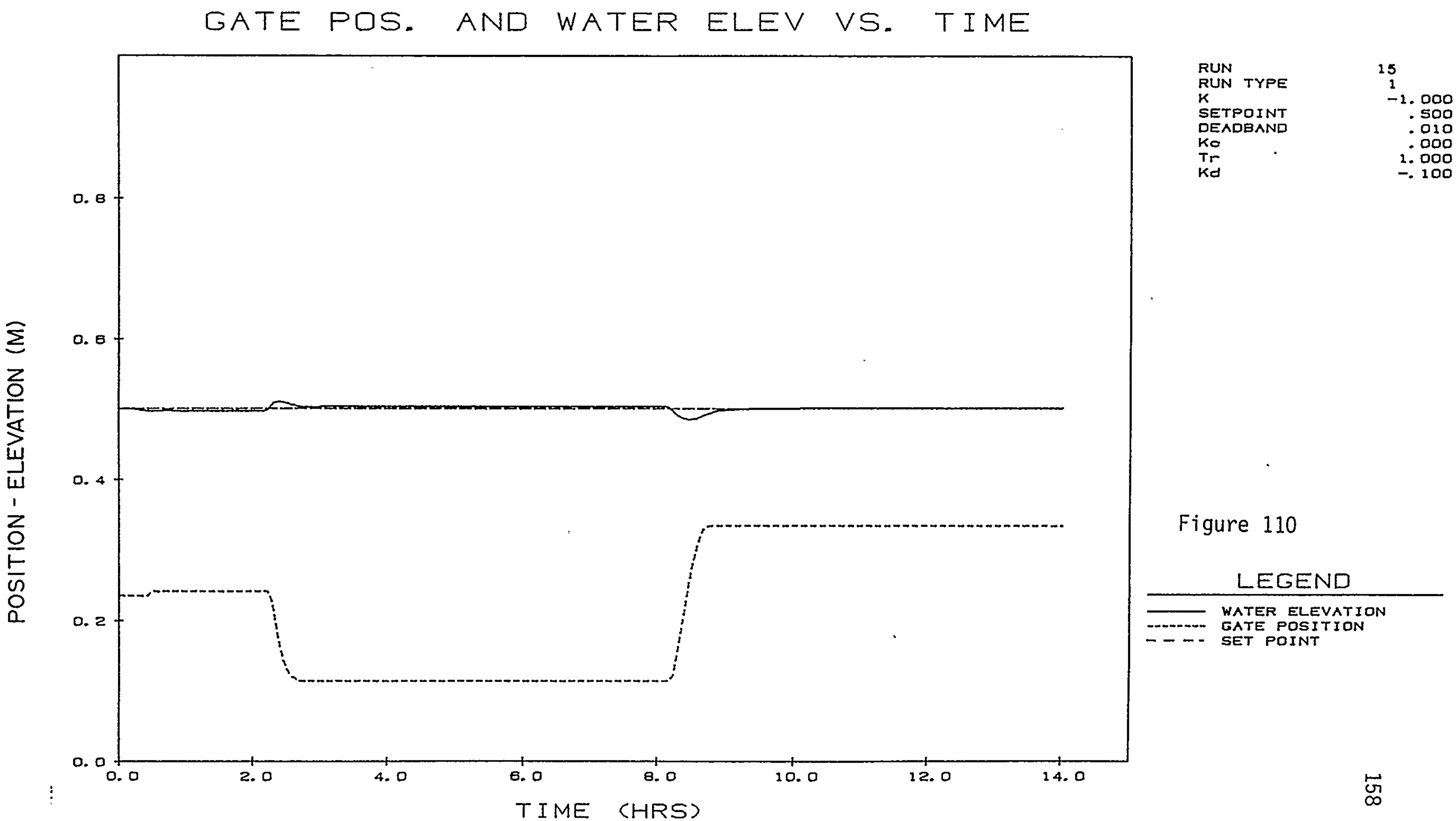

GATE POS. AND WATER ELEV VS. TIME
POSITION - ELEVATION (M)
0.0
0.2
0.4
0.6
0.8
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
TIME (HRS)
RUN 15
RUN TYPE 1
K -1.000
SETPOINT .500
DEADBAND .010
Ko .000
Tr 1.000
Kd -.100
LEGEND
WATER ELEVATION
GATE POSITION
SET POINT

Figure 110

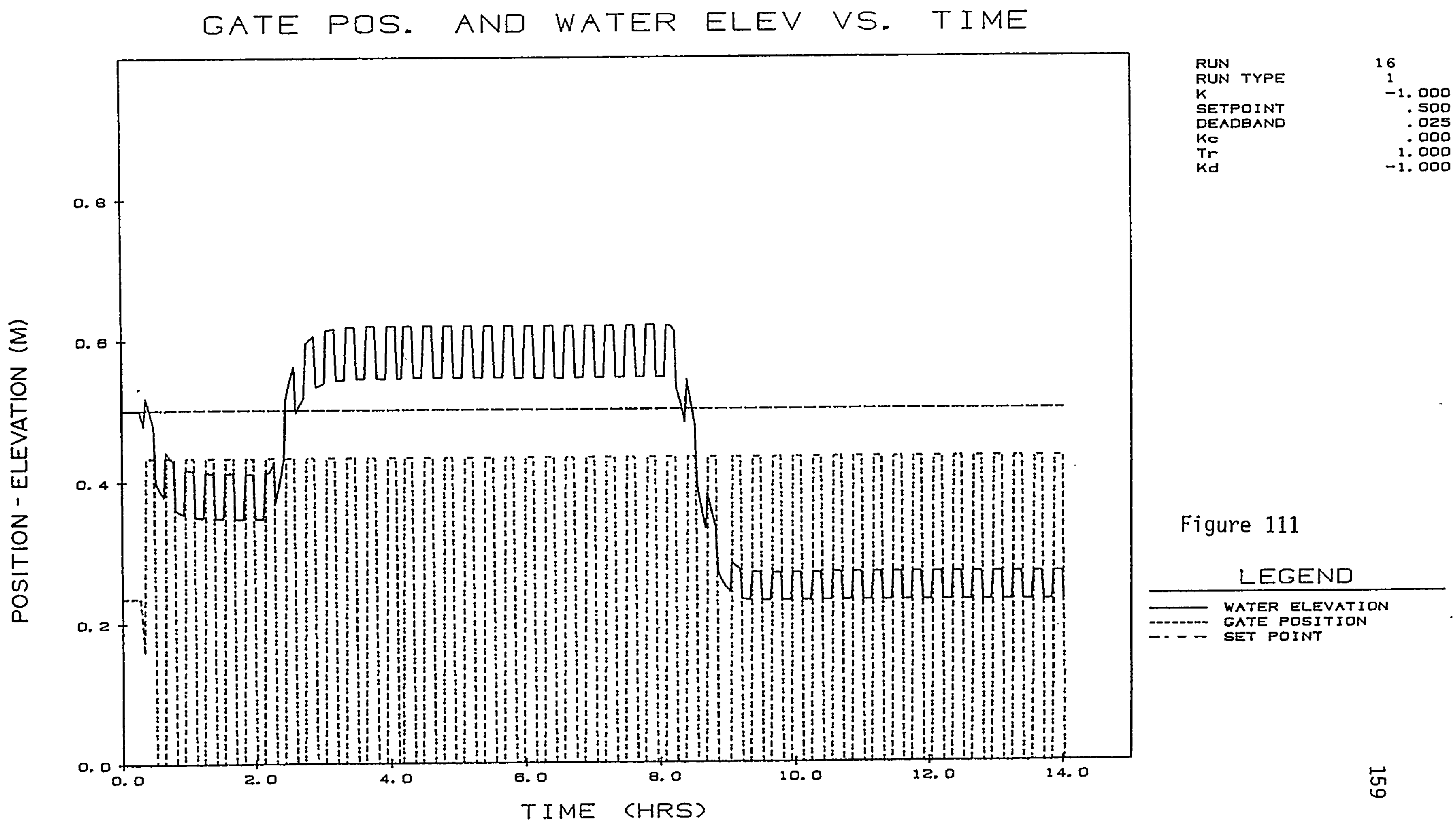

GATE POS. AND WATER ELEV VS. TIME
RUN 16
RUN TYPE 1
K -1.000
SETPOINT .500
DEADBAND .025
Kc .000
Tr 1.000
Kd -1.000
0.8
0.6
0.4
0.2
0.0
POSITION - ELEVATION (M)
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
TIME (HRS)
LEGEND
WATER ELEVATION
GATE POSITION
SET POINT

Figure 111

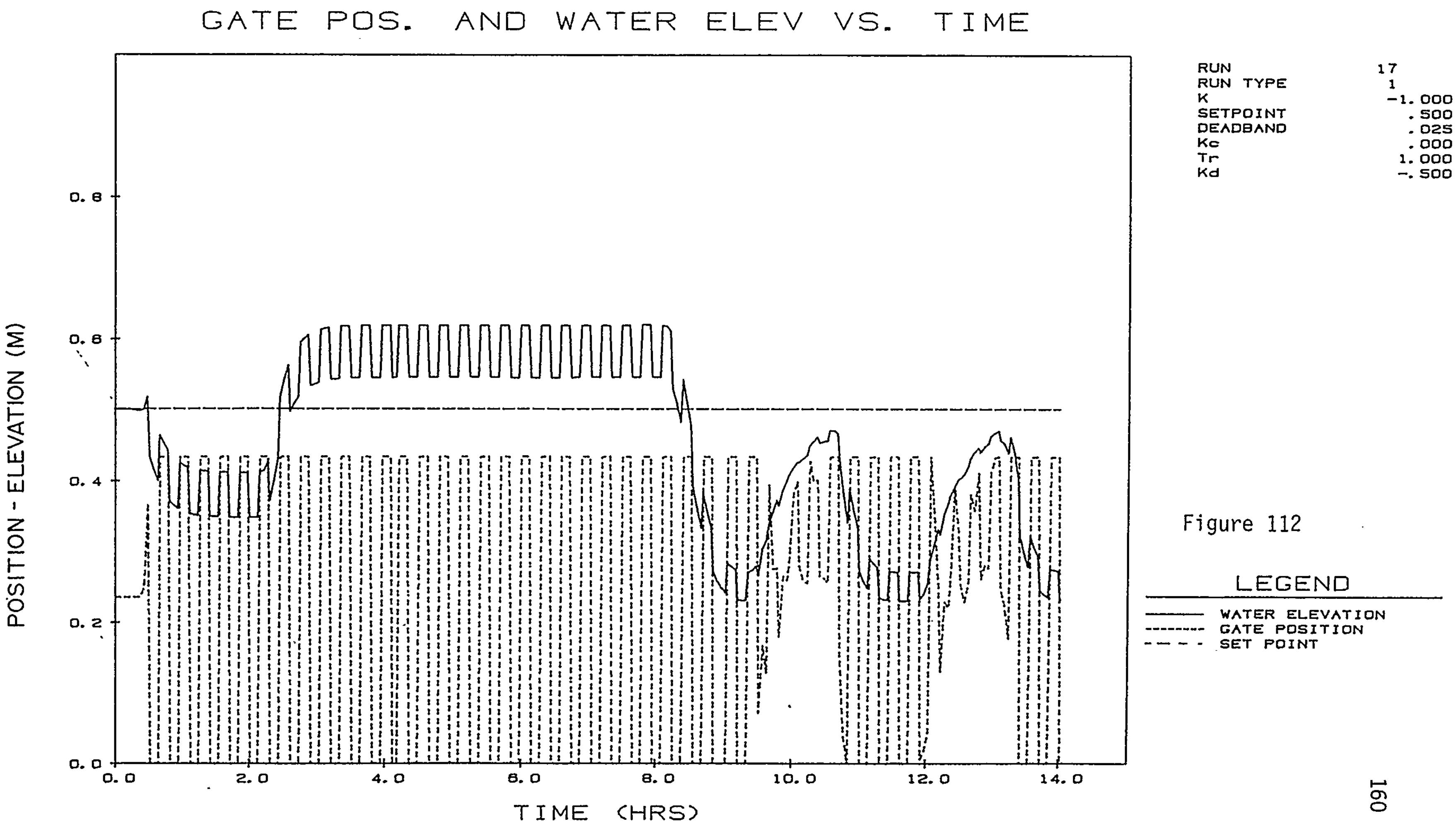

GATE POS. AND WATER ELEV VS. TIME
POSITION - ELEVATION (M)
0.0
0.2
0.4
0.6
0.8
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
TIME (HRS)
RUN 17
RUN TYPE 1
K -1.000
SETPOINT .500
DEADBAND .025
Kc .000
Tr 1.000
Kd -.500
LEGEND
WATER ELEVATION
GATE POSITION
SET POINT

Figure 112

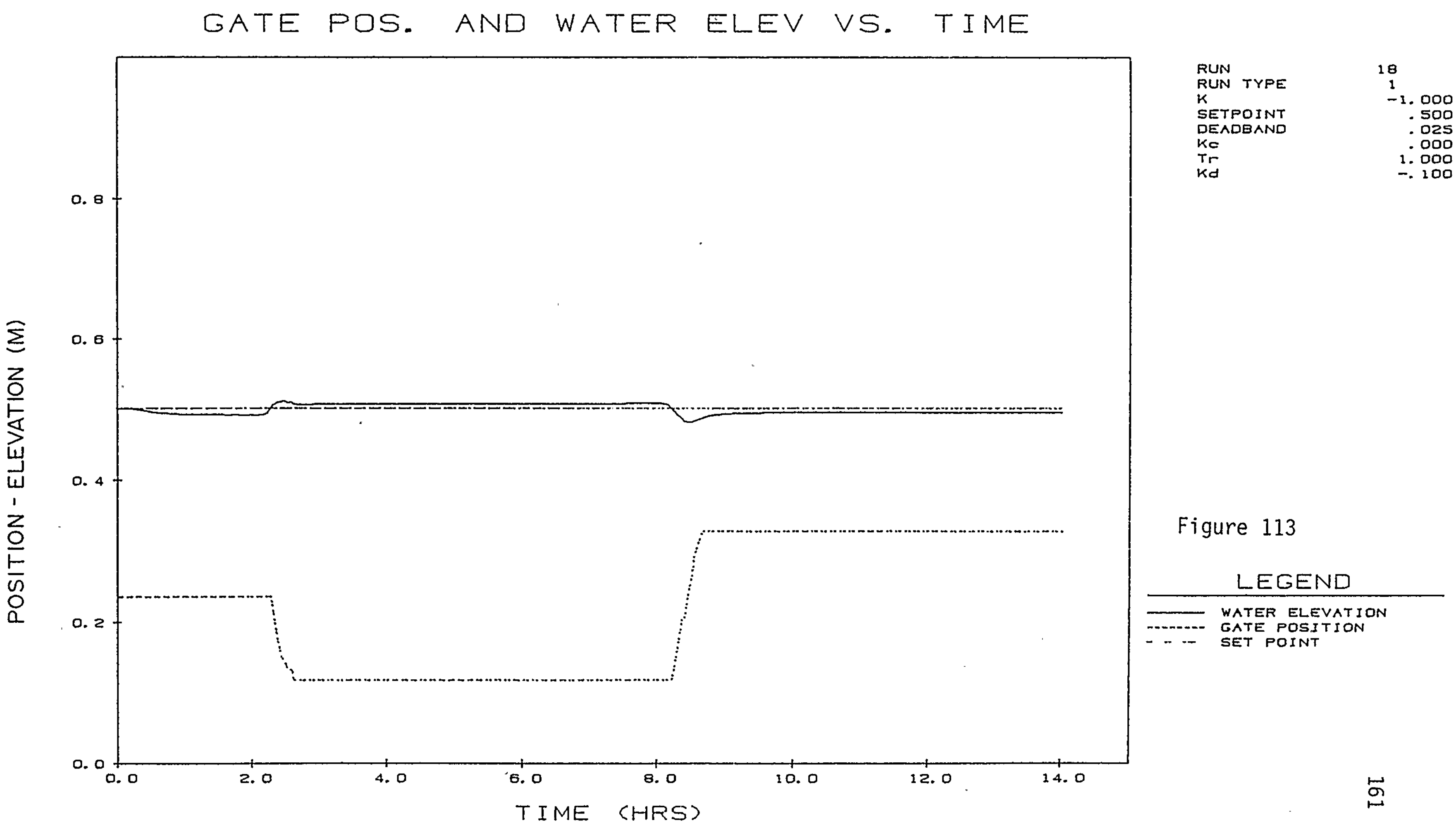
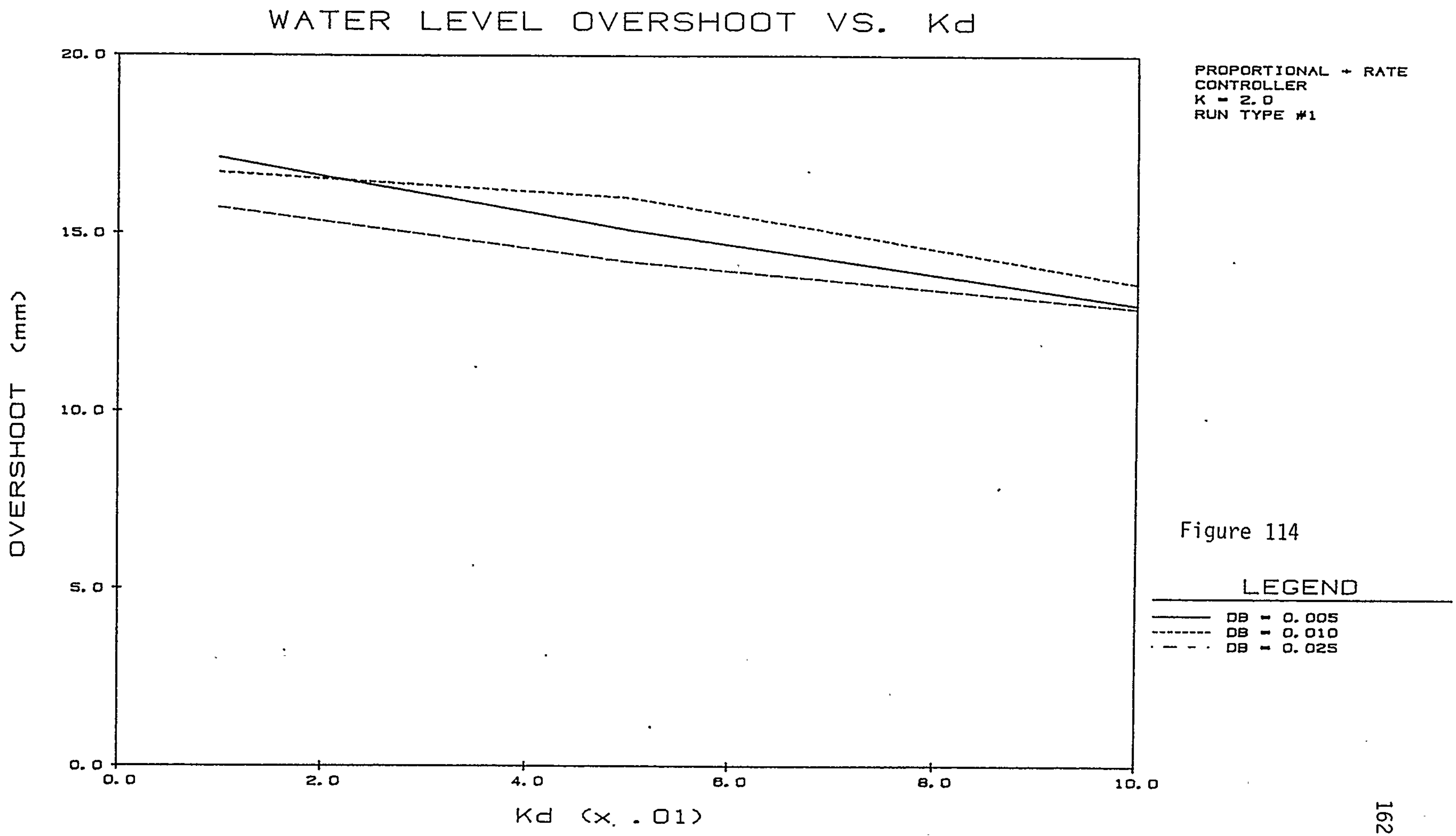

GATE POS. AND WATER ELEV VS. TIME
POSITION - ELEVATION (M)
0.0
0.2
0.4
0.6
0.8
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
TIME (HRS)
RUN 18
RUN TYPE 1
K -1.000
SETPOINT .500
DEADBAND .025
Kc .000
Tr 1.000
Kd -.100
LEGEND
WATER ELEVATION
GATE POSITION
SET POINT

Figure 113



WATER LEVEL OVERSHOOT VS. Kd
20.0
15.0
10.0
5.0
0.0
0.0
2.0
4.0
6.0
8.0
10.0
OVERSHOOT (mm)
Kd (x .01)
PROPORTIONAL + RATE
CONTROLLER
K = 2.0
RUN TYPE #1
LEGEND
DB = 0.005
DB = 0.010
DB = 0.025

Figure 114

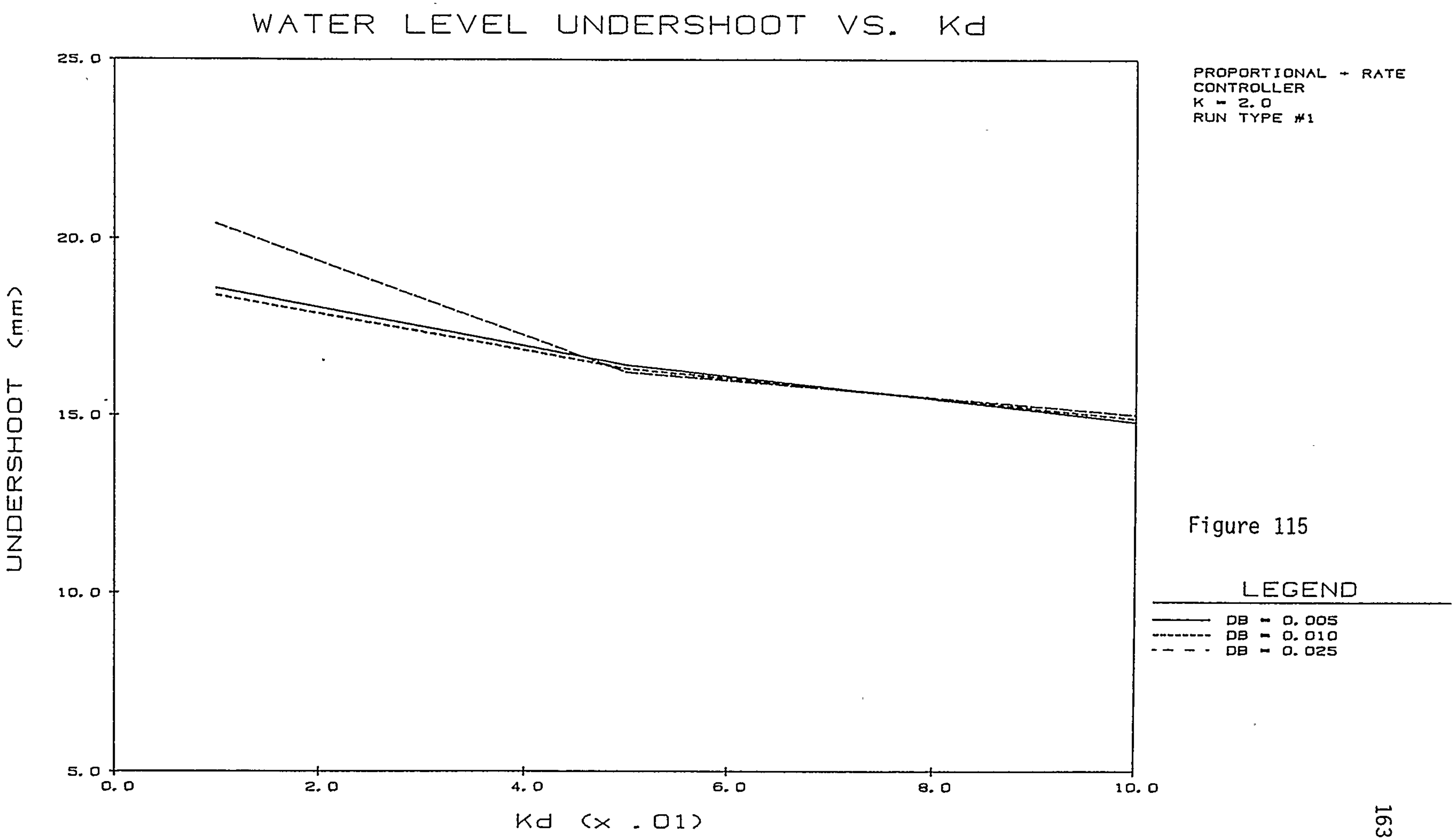
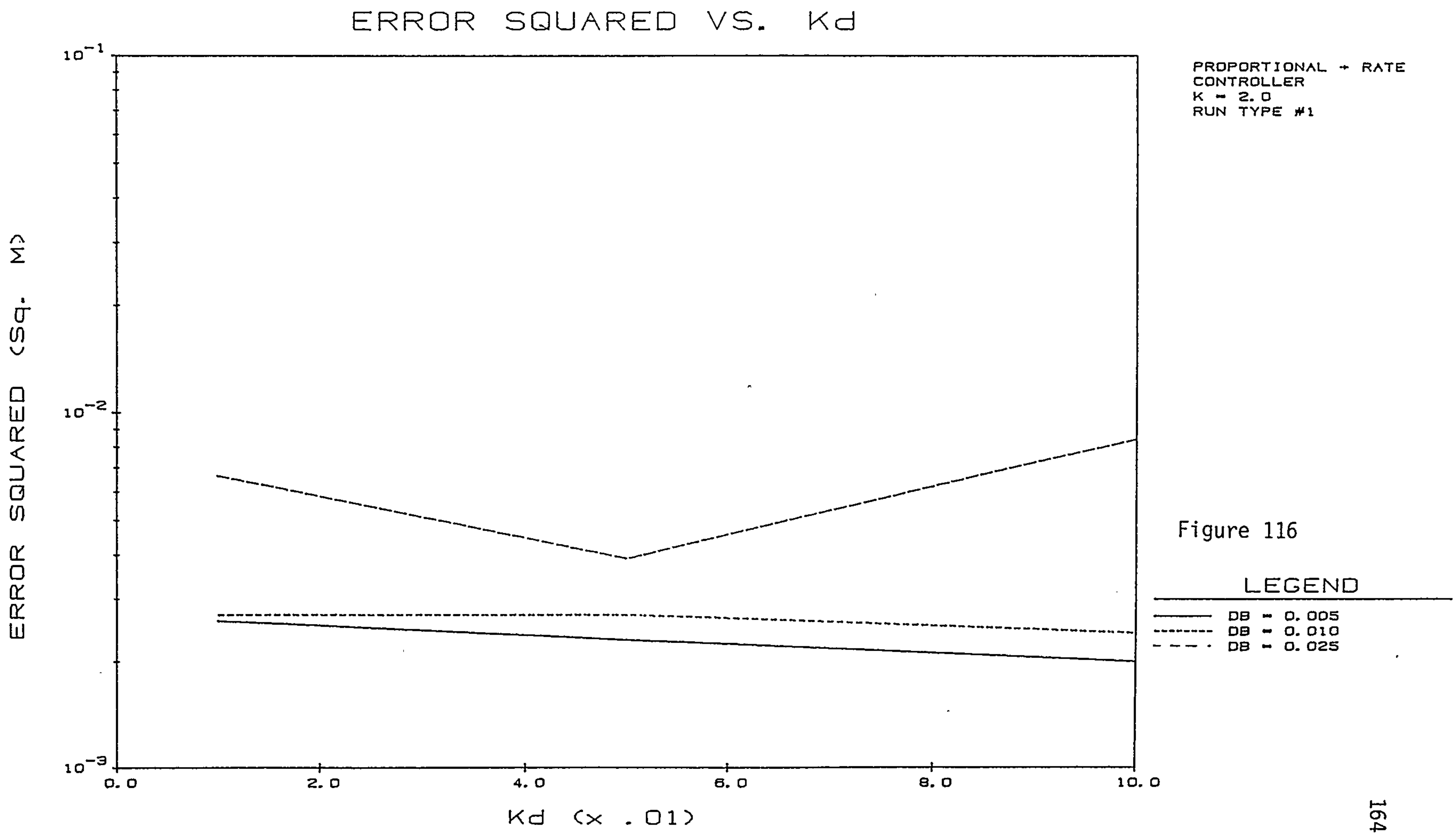

WATER LEVEL UNDERSHOOT VS. Kd
PROPORTIONAL + RATE
CONTROLLER
K = 2.0
RUN TYPE #1
UNDERSHOOT (mm)
25.0
20.0
15.0
10.0
5.0
0.0
2.0
4.0
6.0
8.0
10.0
Kd (x .01)
LEGEND
DB = 0.005
DB = 0.010
DB = 0.025

Figure 115



ERROR SQUARED VS. Kd
PROPORTIONAL + RATE
CONTROLLER
K = 2.0
RUN TYPE #1
LEGEND
DB = 0.005
DB = 0.010
DB = 0.025
ERROR SQUARED (Sq. M)
10^{-1}
10^{-2}
10^{-3}
0.0
2.0
4.0
6.0
8.0
10.0
Kd (x .01)

Figure 116

exception of the deadband. The first set of runs uses a constant K_p value of 2 and the second set a K_p value of 1.

Examining run number 1 through 3 (Figures 96-98) we do not notice any significant changes in the reaction of the controller or water levels. This may be significant as the range in which the value of K_d has been varied is between 0.010 and 0.100. This variation is a 10 fold (1000 %) increase over the minimum value used. Studying run numbers 4-6 and 7-9 (Figures 99-101 and 102-104) it may be seen that the responses are similar within each set as K_d is varied. Comparing the three sets to each other for the same value of K_d only small variations in the gate and water level responses can be seen. These differences are due to the change of deadband and may be explained similarly to sections 7.3 and 7.4.

Table 13 is a summary of maximum overshot, undershot values and summation of e^2 about the desired water level. All overshot and undershot values are below 20 mm and above 10 mm. The large range of values seen previously when parameters are changed is not seen here. The lack of change of the overshoot, undershoot and e^2 terms can be seen in Figures 114-116. All of the e_2 values are below 0.010 mm^2. The e^2 terms with a controller deadband of 0.025 M are the largest. This should be expected and is due to the coarseness of adjustment which is described in sections 6.3 and 6.4.

Run numbers 10-18 use higher values of K_d than the previous runs. The K_p value is reduced from 2 to 1. The reason for the reduction in this value is that it was found that higher values of K_d in combination with a K_p of 2 would result in the numerical model used for these experiments not to converge. This problem indicates extremely quick and large gate movements. When the value of K_p was reduced the severity of

Table 13. Proportional + Differential controller; Values of maximum overshoot, undershoot and summation of e^2 for varying controller parameter settings.

K_p	K_d	Overshoot (mm)	Undershoot (mm)	Sum of e^2 $(mm)^2$	Dead -band (m)	Run #
2.0	0.01	17.1	18.6	0.0026	0.005	3
2.0	0.05	15.1	16.4	0.0023	0.005	1
2.0	0.10	13.0	14.8	0.0020	0.005	2
2.0	0.01	16.7	18.4	0.0027	0.010	6
2.0	0.05	16.0	16.3	0.0027	0.010	4
2.0	0.10	13.6	14.9	0.0024	0.010	5
2.0	0.01	15.7	20.4	0.0084	0.025	9
2.0	0.05	14.2	16.2	0.0039	0.025	7
2.0	0.10	12.9	15.0	0.0066	0.025	8
1.0	0.10	12.0	15.0	0.0025	0.005	12
1.0	0.50	120.0	270.0	4.8964	0.005	11
1.0	1.00	120.0	270.0	8.0796	0.005	10
1.0	0.10	11.0	15.0	0.0044	0.010	15
1.0	0.50	120.0	270.0	4.9556	0.010	14
1.0	1.00	120.0	270.0	8.0796	0.010	13
1.0	0.10	12.0	19.0	0.0135	0.025	18
1.0	0.50	120.0	270.0	4.8956	0.025	17
1.0	1.00	120.0	270.0	8.0671	0.025	16

the gate movements could be reduced. It may be seen, however, by reviewing run numbers 10 to 12 (Figures 105-107) that values of K_d higher than 0.100 causes the controller to become very unstable. Run 10, with a K_d value of 1.0 is inconsolable regardless of the water level. Run 11, with a K_d value of 0.50 m is unstable, similar to run 10 from 0 to approximately 9 hours. The form of the instability changes repeatedly driving the water level towards the setpoint, then breaking down into uncontrolled oscillations from 9 to 14 hours. Similarly run numbers 13 to 15 and 16 to 18 (Figures 108-110 and 111-113) show the same responses for varying values of the deadband.

The summary table of overshoot, undershoot and e^2 values also give an indication of the instability which occurs when K_d is greater than 0.100. The e^2 values jump approximately 2000 times when instability is encountered as opposed to when the controller is stable. The overshoot and undershoot also jump 10 to 20 times that of the stable controller.

7.6 FARM TURNOUT DELIVERY QUALITY

These numerical experiments were conducted using canal type 2. The controller used to control the gate was the PID controller with only the proportional and integral parts active. Controller parameters were held constant and the inlet flow was varied by using inlet flow types 2 through 7.

The first set of experiments, run numbers 1 - 6 (Figures 117-122, Farm turnout responses Figures 129-134) were designed to show the effects on farm water delivery using the high checking technique. This technique involves setting the water level higher than required, thus creating additional storage in the canal system.

The first three runs in this series are based on small changes (0.05 - 0.10 cms) in inlet flow. Reviewing Figures 117 to 119 we notice very little change in the response of the actual water level from one inlet condition to the next. The gate adjustments, however, are different and adjust in the proper direction to bring the actual water level to the desired water level. Figures 129 to 131 show the flow response at the farm turnout. The flow from the upstream turnout is regulated superbly.

Run numbers 4 to 6 (Figures 120-122) show the response of the gate and water level to large inflow disturbances (0.15 to 0.20 cms). Figure 120 illustrates the response of the controller when a large increase in flow (0.20 cms) is encountered. Water level fluctuations are pronounced just after 2.0 hours and 6.0 hours, corresponding to the inflow fluctuations. Run numbers 5 and 6 (Figures 121-122) do not

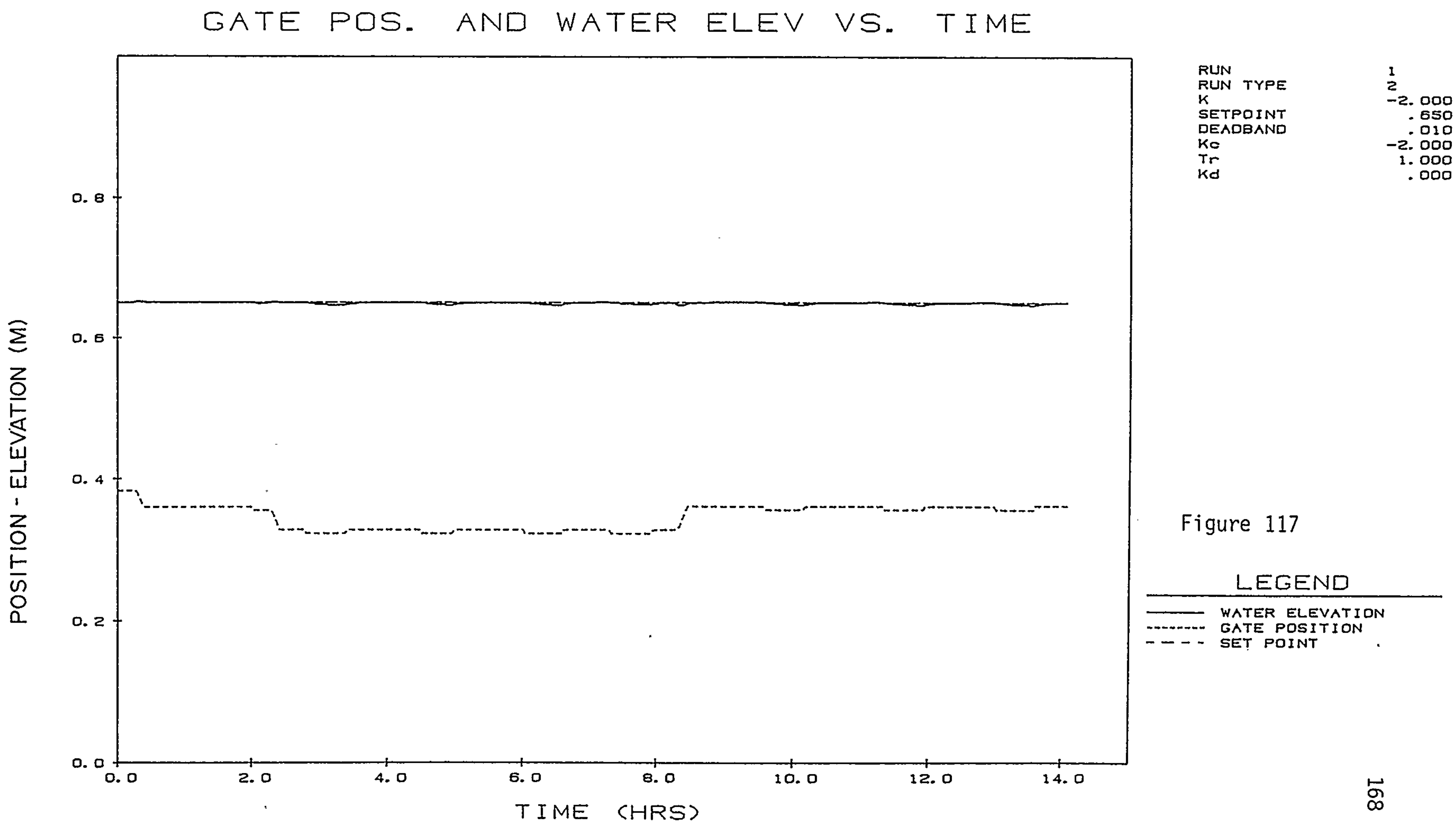
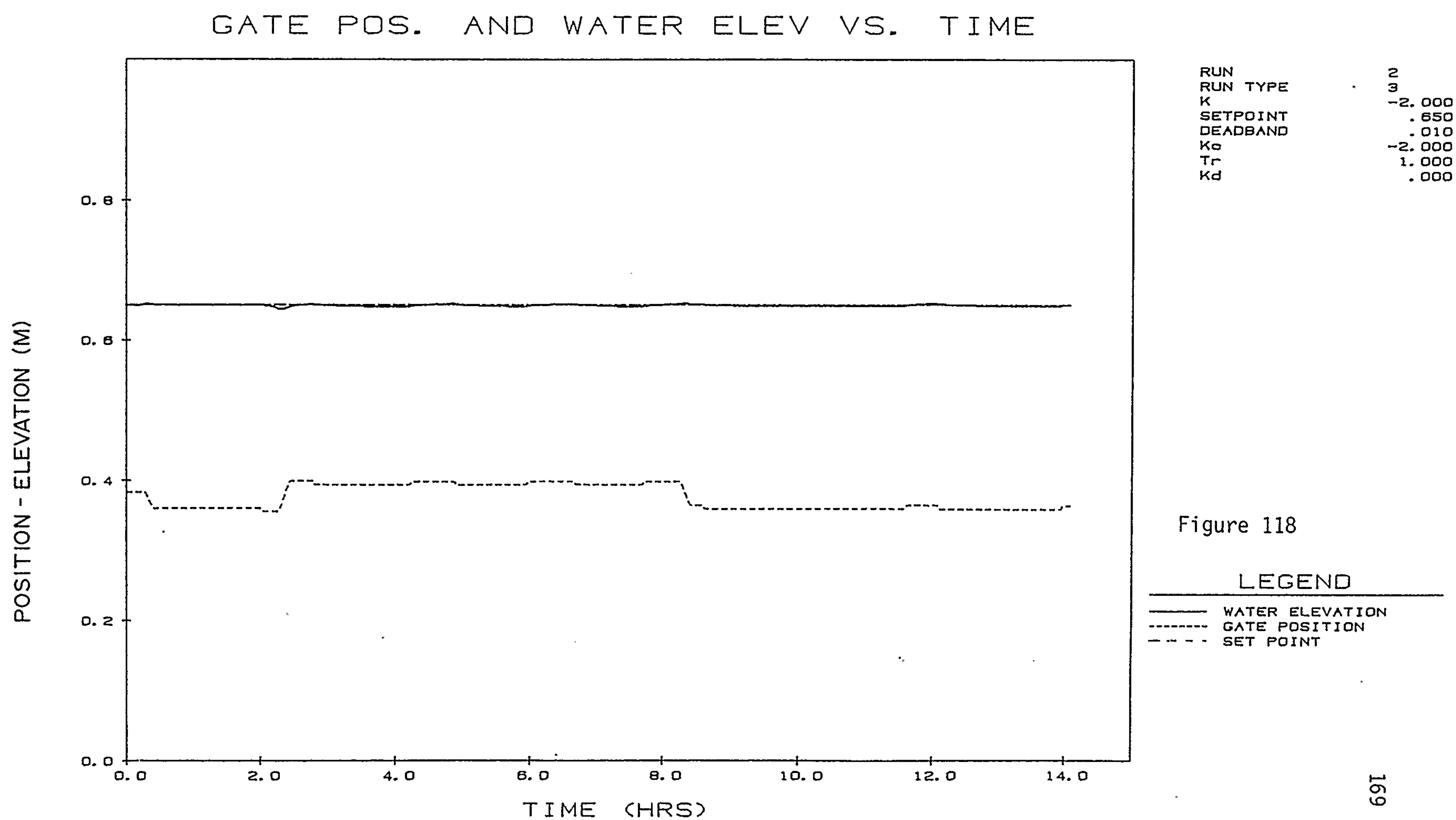
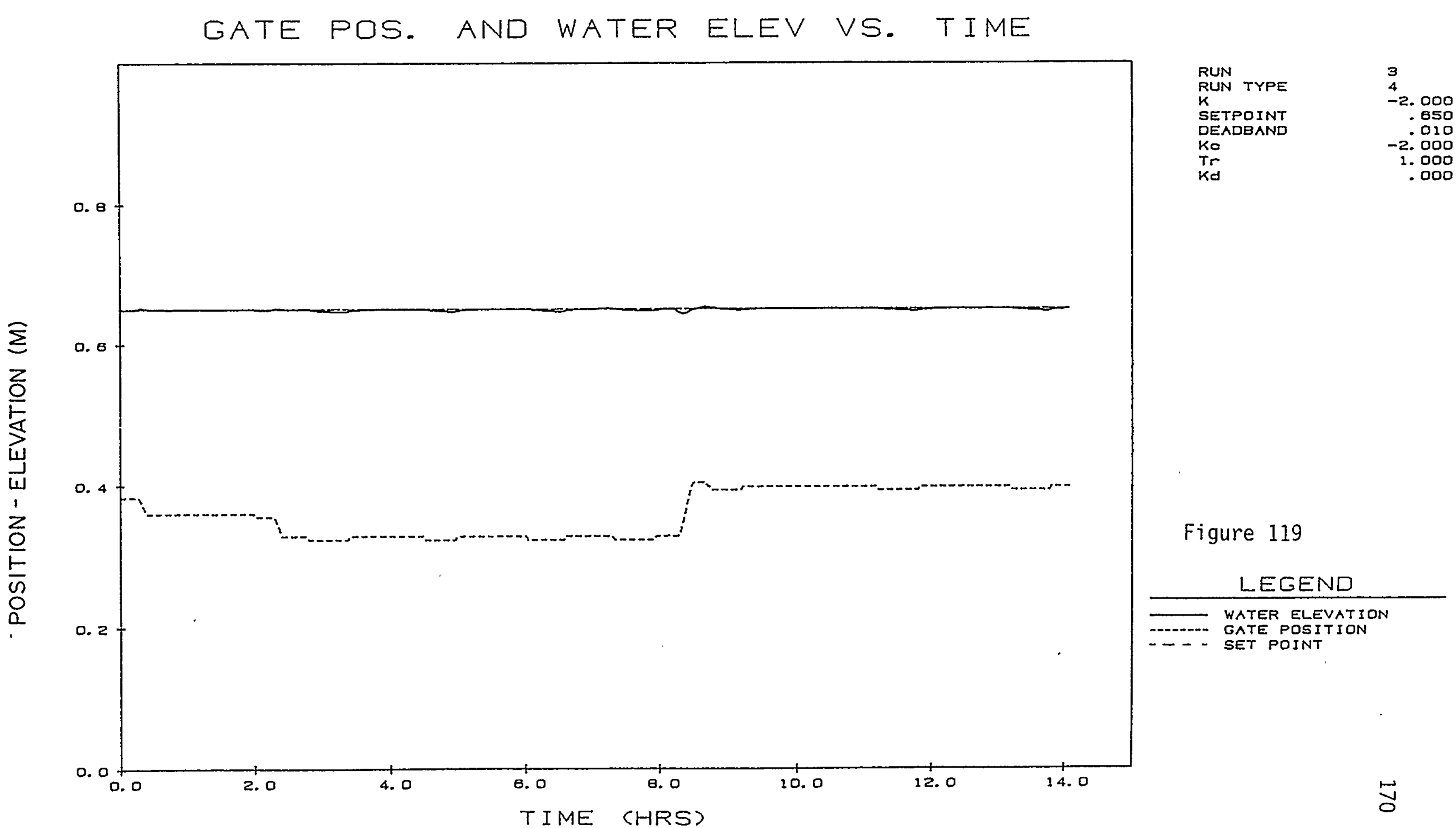

GATE POS. AND WATER ELEV VS. TIME
RUN 1
RUN TYPE 2
K -2.000
SETPOINT .650
DEADBAND .010
Kc -2.000
Tr 1.000
Kd .000
POSITION - ELEVATION (M)
0.0
0.2
0.4
0.6
0.8
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
TIME (HRS)
LEGEND
WATER ELEVATION
GATE POSITION
SET POINT

Figure 117



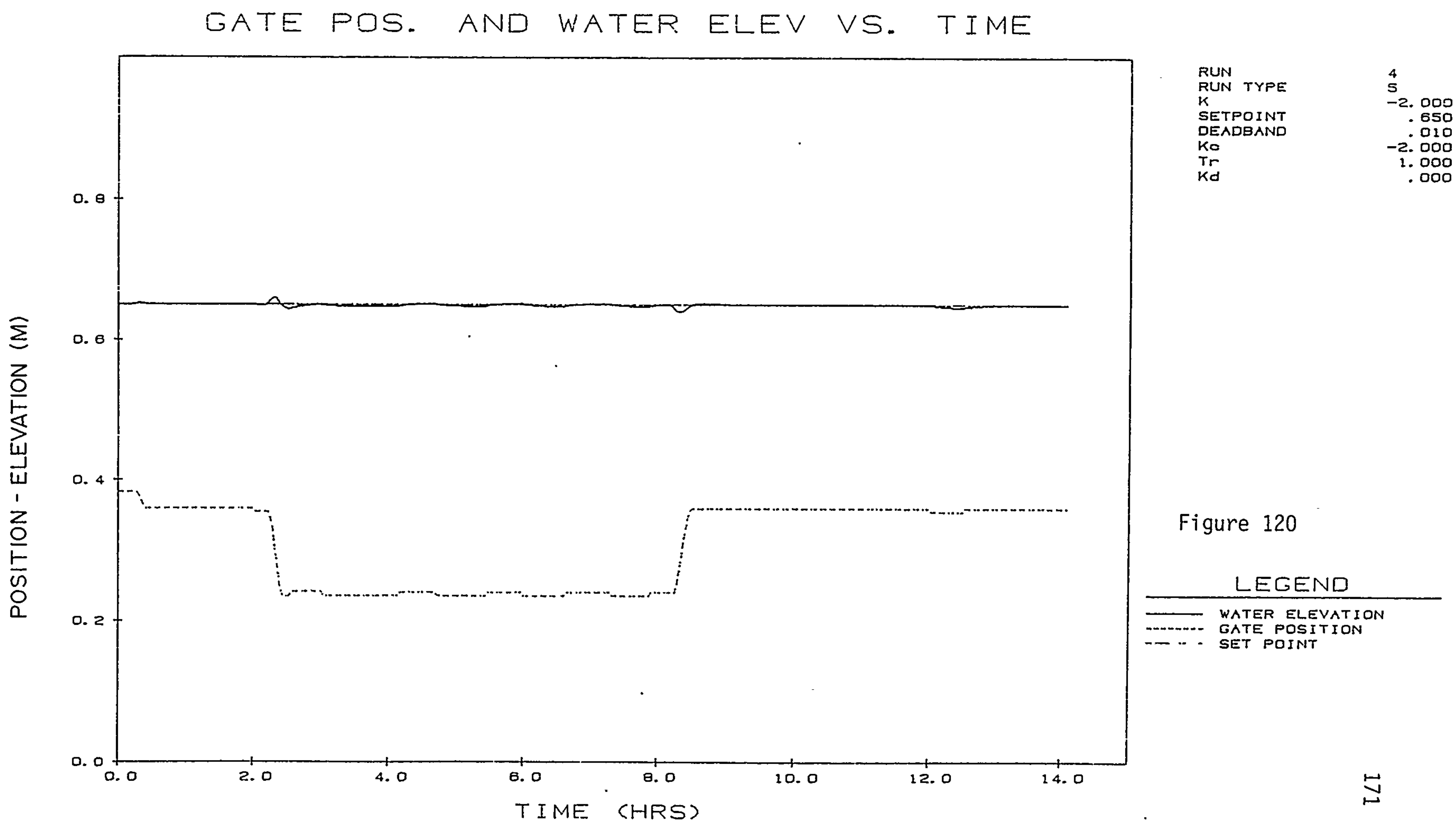
GATE POS. AND WATER ELEV VS. TIME
POSITION - ELEVATION (M)
0.0
0.2
0.4
0.6
0.8
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
TIME (HRS)
RUN 2
RUN TYPE 3
K -2.000
SETPOINT .650
DEADBAND .010
Ko -2.000
Tr 1.000
Kd .000
LEGEND
WATER ELEVATION
GATE POSITION
SET POINT

Figure 118



GATE POS. AND WATER ELEV VS. TIME
POSITION - ELEVATION (M)
0.0
0.2
0.4
0.6
0.8
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
TIME (HRS)
RUN 3
RUN TYPE 4
K -2.000
SETPOINT .650
DEADBAND .010
Kc -2.000
Tr 1.000
Kd .000
LEGEND
WATER ELEVATION
GATE POSITION
SET POINT

Figure 119


GATE POS. AND WATER ELEV VS. TIME
POSITION - ELEVATION (M)
0.8
0.6
0.4
0.2
0.0
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
TIME (HRS)
RUN 4
RUN TYPE S
K -2.000
SETPOINT .650
DEADBAND .010
Ko -2.000
Tr 1.000
Kd .000
LEGEND
WATER ELEVATION
GATE POSITION
SET POINT
Figure 120

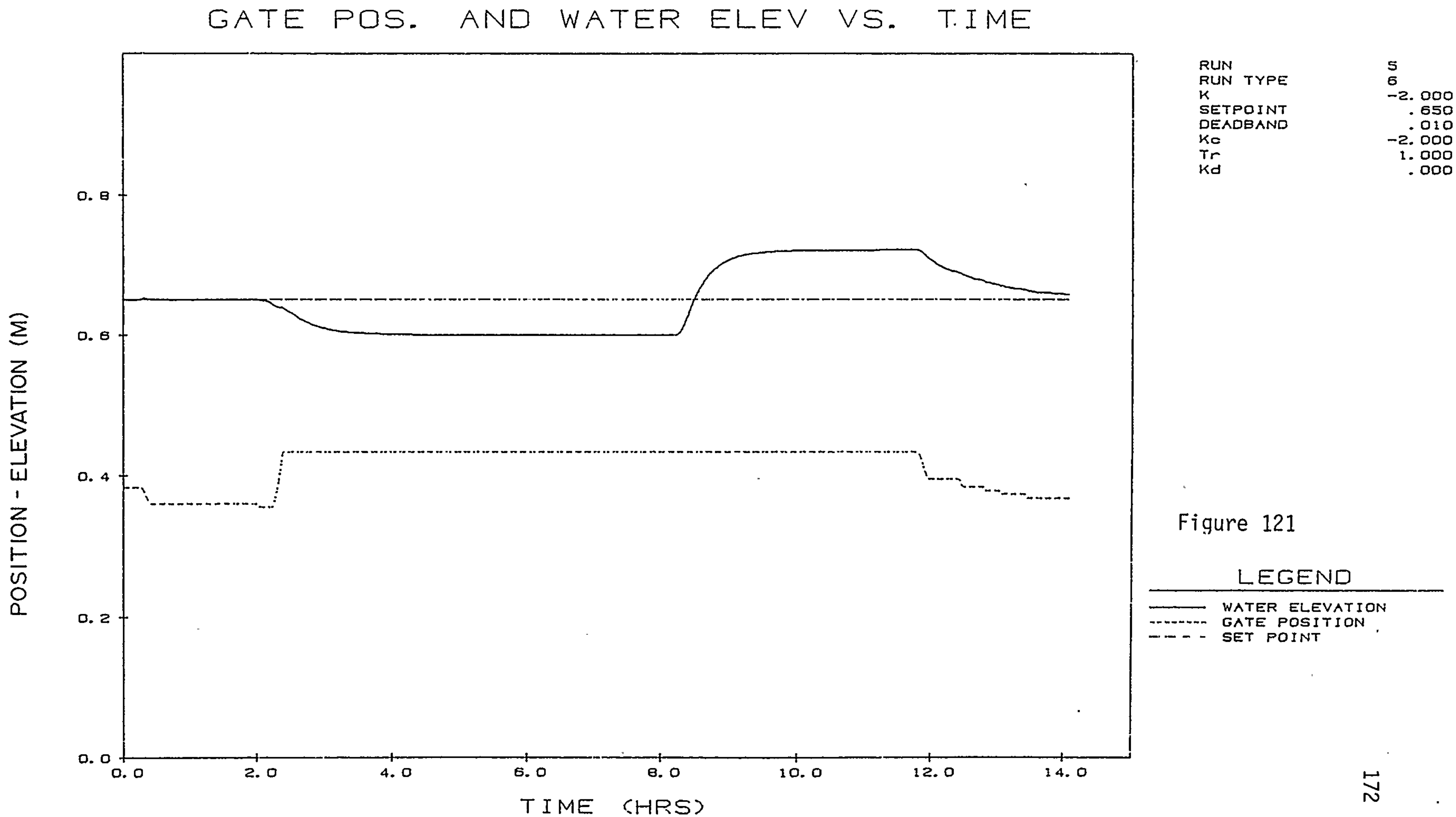
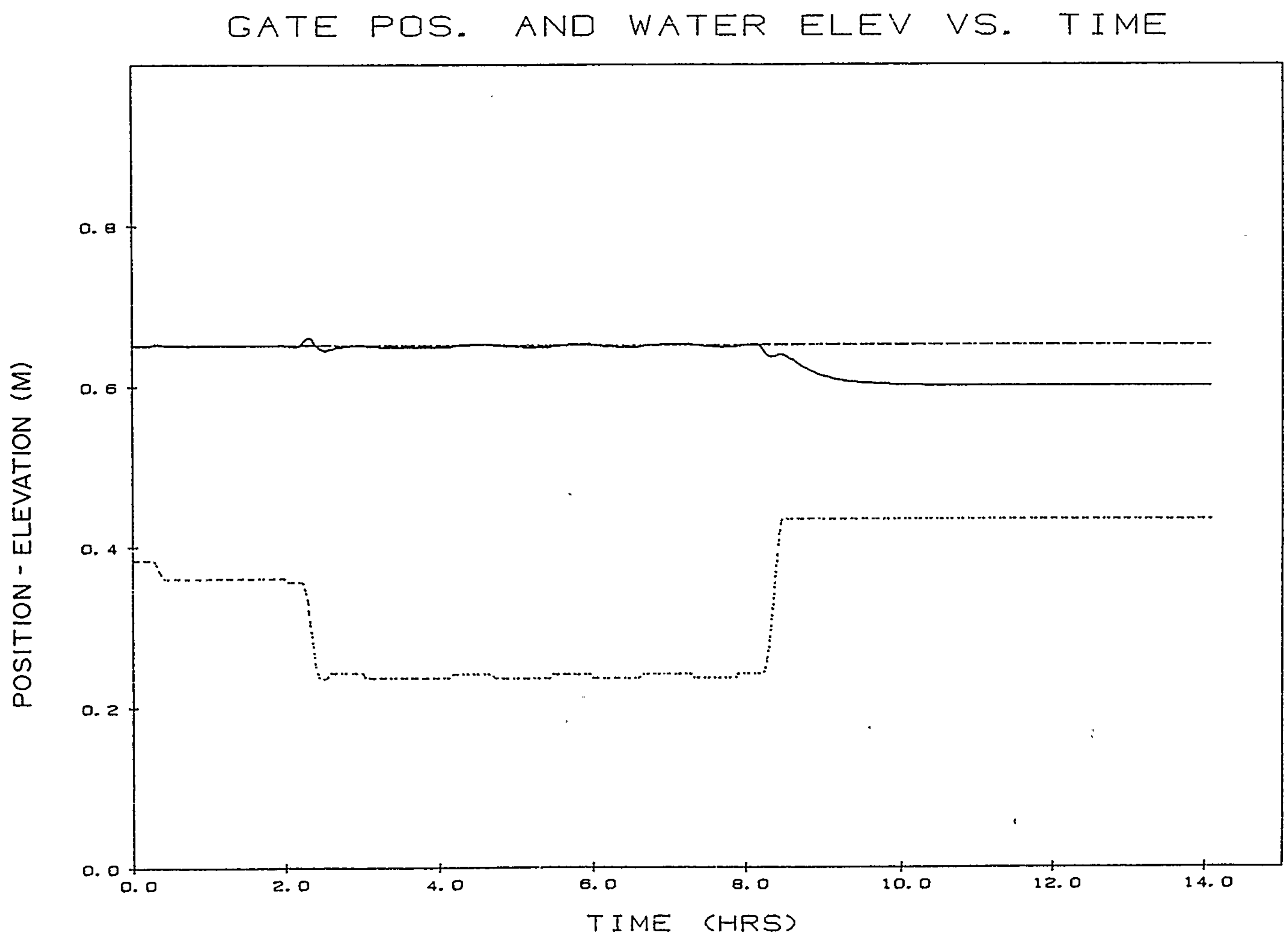

GATE POS. AND WATER ELEV VS. TIME
POSITION - ELEVATION (M)
TIME (HRS)
0.0
0.2
0.4
0.6
0.8
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
RUN 5
RUN TYPE 6
K -2.000
SETPOINT .650
DEADBAND .010
Kc -2.000
Tr 1.000
Kd .000
LEGEND
WATER ELEVATION
GATE POSITION
SET POINT

Figure 121



RUN	6
RUN TYPE	7
K	-2.000
SETPOINT	.650
DEADBAND	.010
Kc	-2.000
Tr	1.000
Kd	.000

Figure 122

LEGEND

——— WATER ELEVATION
-------- GATE POSITION
— - — SET POINT

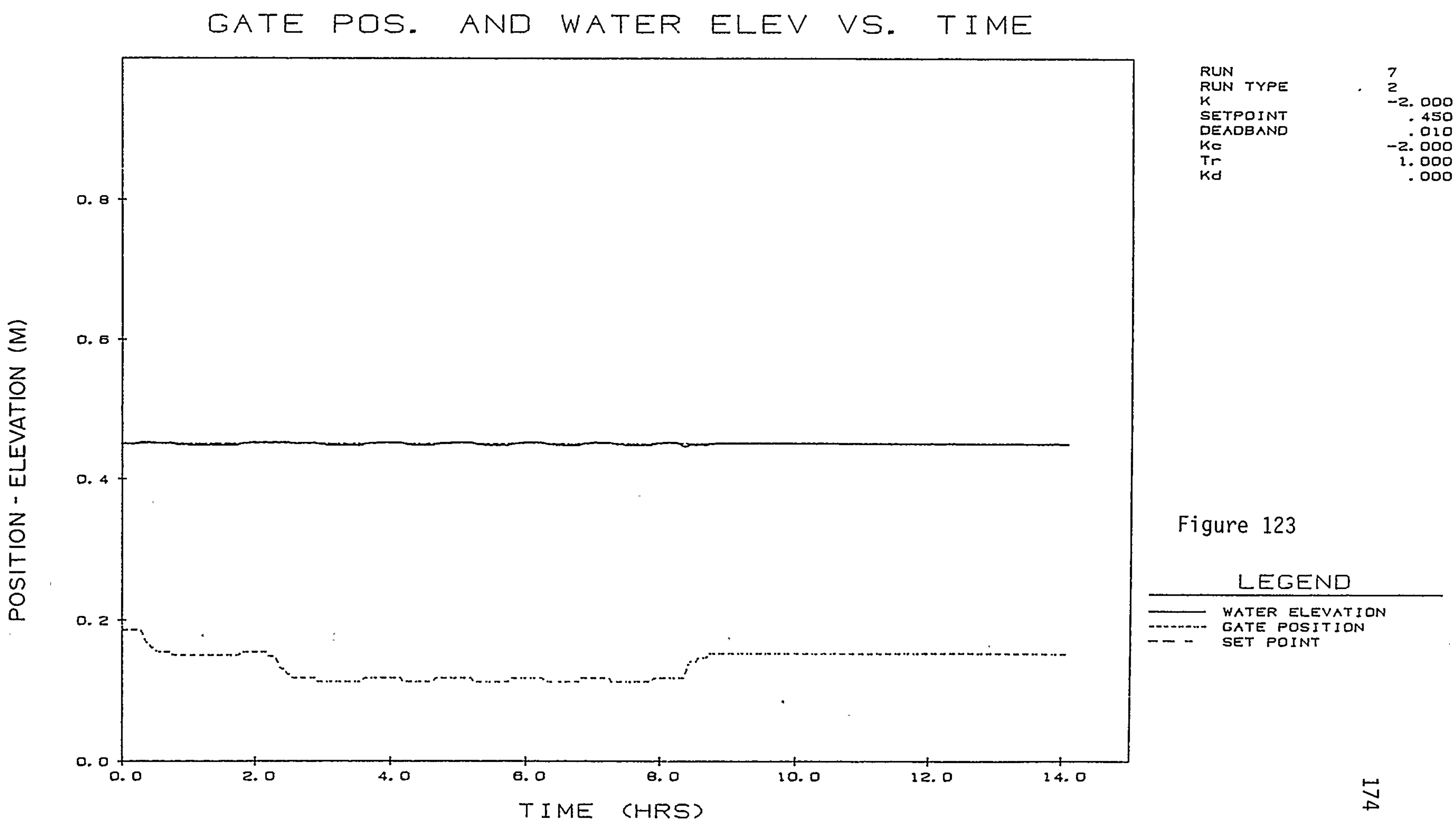

GATE POS. AND WATER ELEV VS. TIME
RUN 7
RUN TYPE 2
K -2.000
SETPOINT .450
DEADBAND .010
Kc -2.000
Tr 1.000
Kd .000
POSITION - ELEVATION (M)
0.0
0.2
0.4
0.6
0.8
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
TIME (HRS)
LEGEND
WATER ELEVATION
GATE POSITION
SET POINT

Figure 123

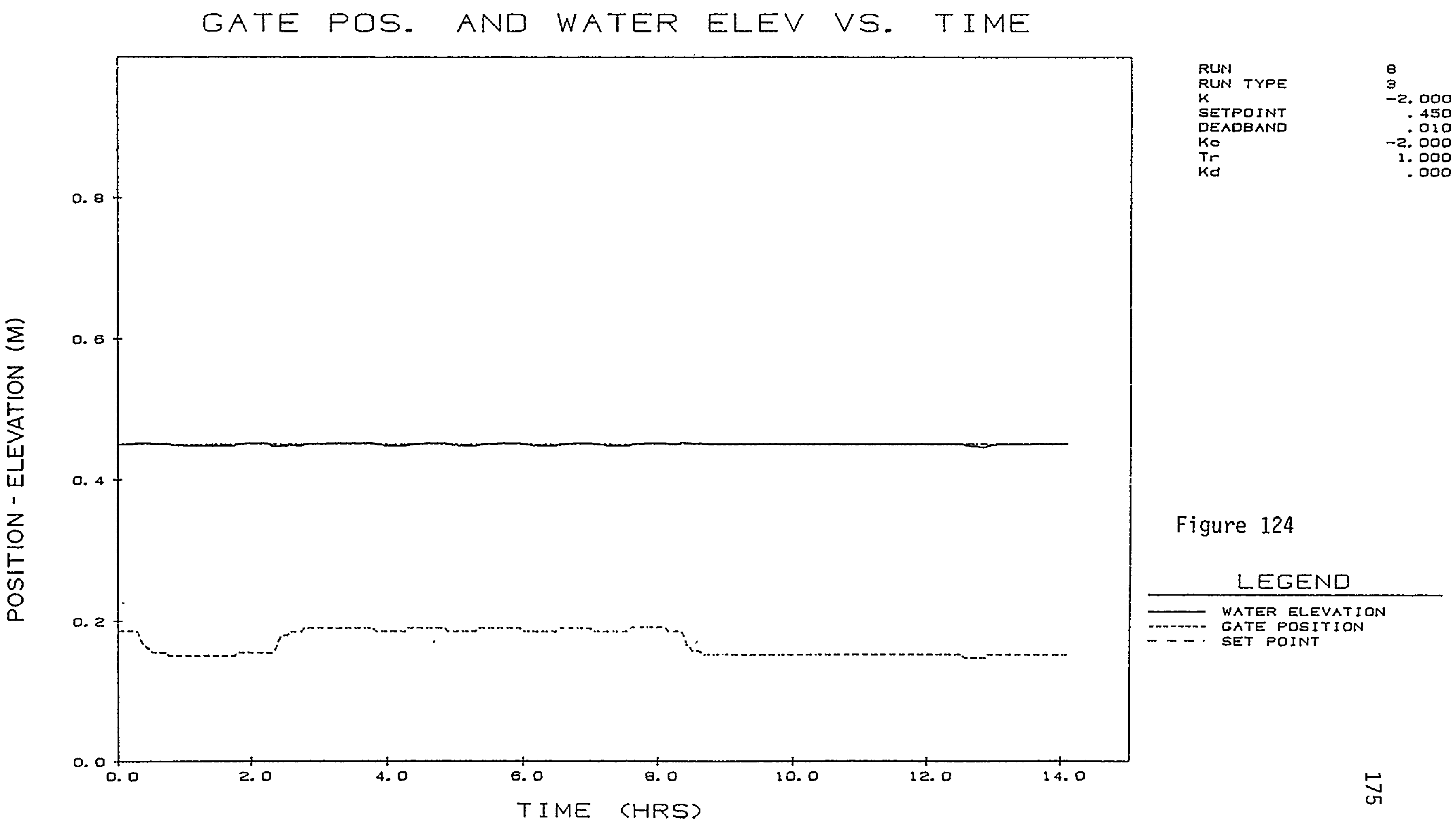

GATE POS. AND WATER ELEV VS. TIME
POSITION - ELEVATION (M)
0.0
0.2
0.4
0.6
0.8
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
TIME (HRS)
RUN 8
RUN TYPE 3
K -2.000
SETPOINT .450
DEADBAND .010
Kc -2.000
Tr 1.000
Kd .000
LEGEND
WATER ELEVATION
GATE POSITION
SET POINT

Figure 124

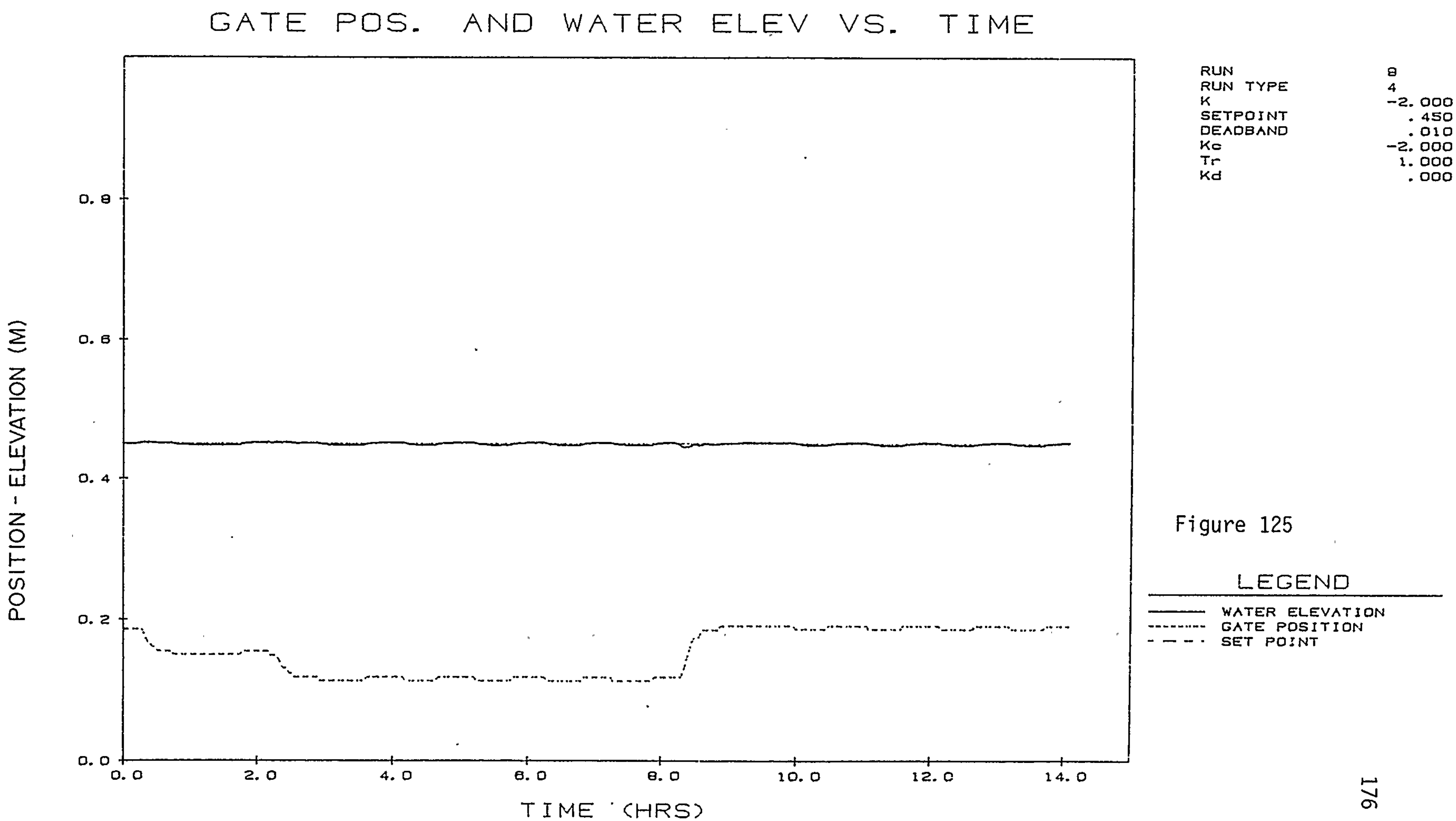

GATE POS. AND WATER ELEV VS. TIME
POSITION - ELEVATION (M)
0.0
0.2
0.4
0.6
0.8
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
TIME (HRS)
RUN 8
RUN TYPE 4
K -2.000
SETPOINT .450
DEADBAND .010
Kc -2.000
Tr 1.000
Kd .000
LEGEND
WATER ELEVATION
GATE POSITION
SET POINT

Figure 125

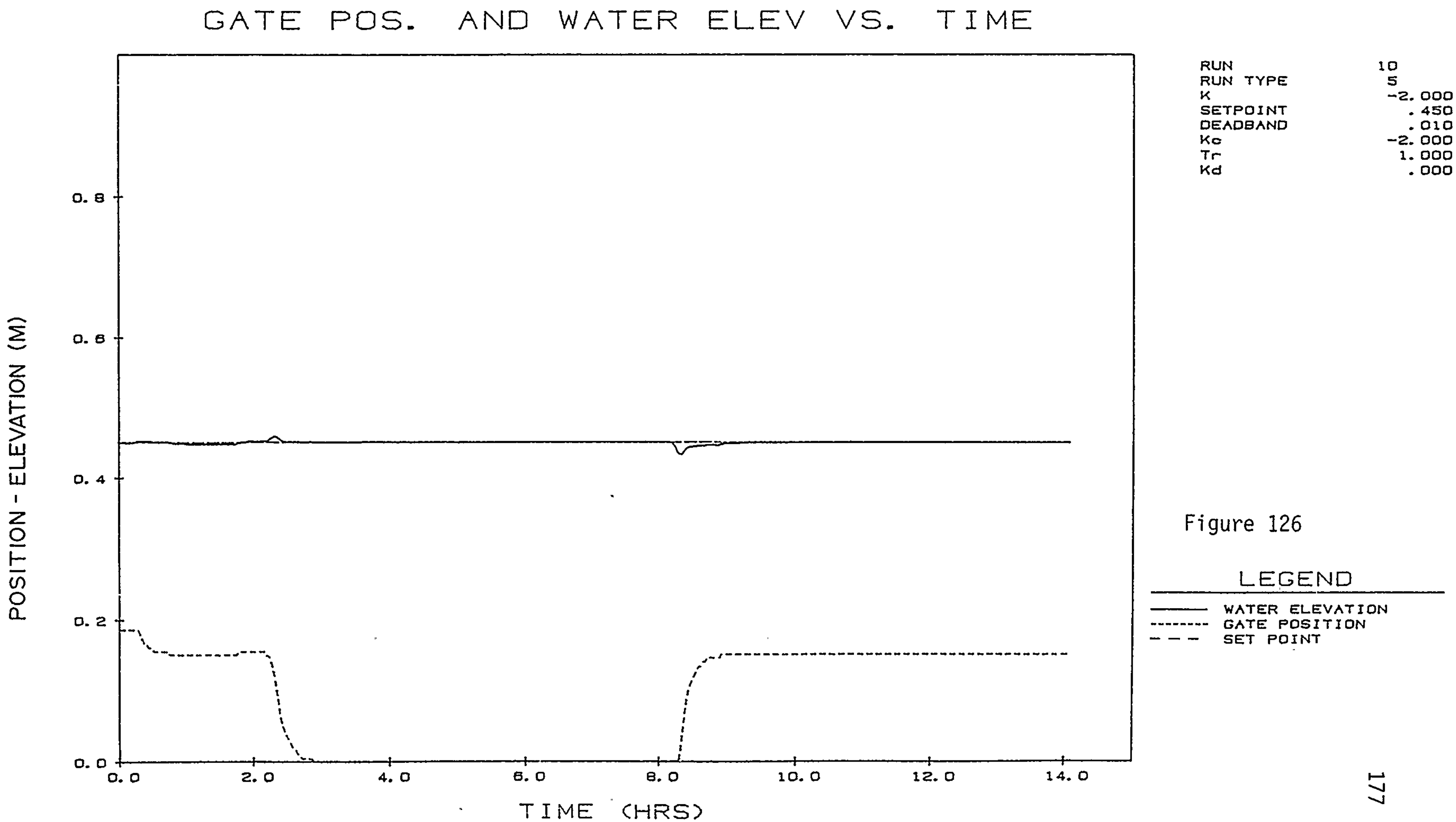

GATE POS. AND WATER ELEV VS. TIME
POSITION - ELEVATION (M)
0.8
0.6
0.4
0.2
0.0
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
TIME (HRS)
RUN 10
RUN TYPE 5
K -2.000
SETPOINT .450
DEADBAND .010
Kc -2.000
Tr 1.000
Kd .000
LEGEND
WATER ELEVATION
GATE POSITION
SET POINT

Figure 126

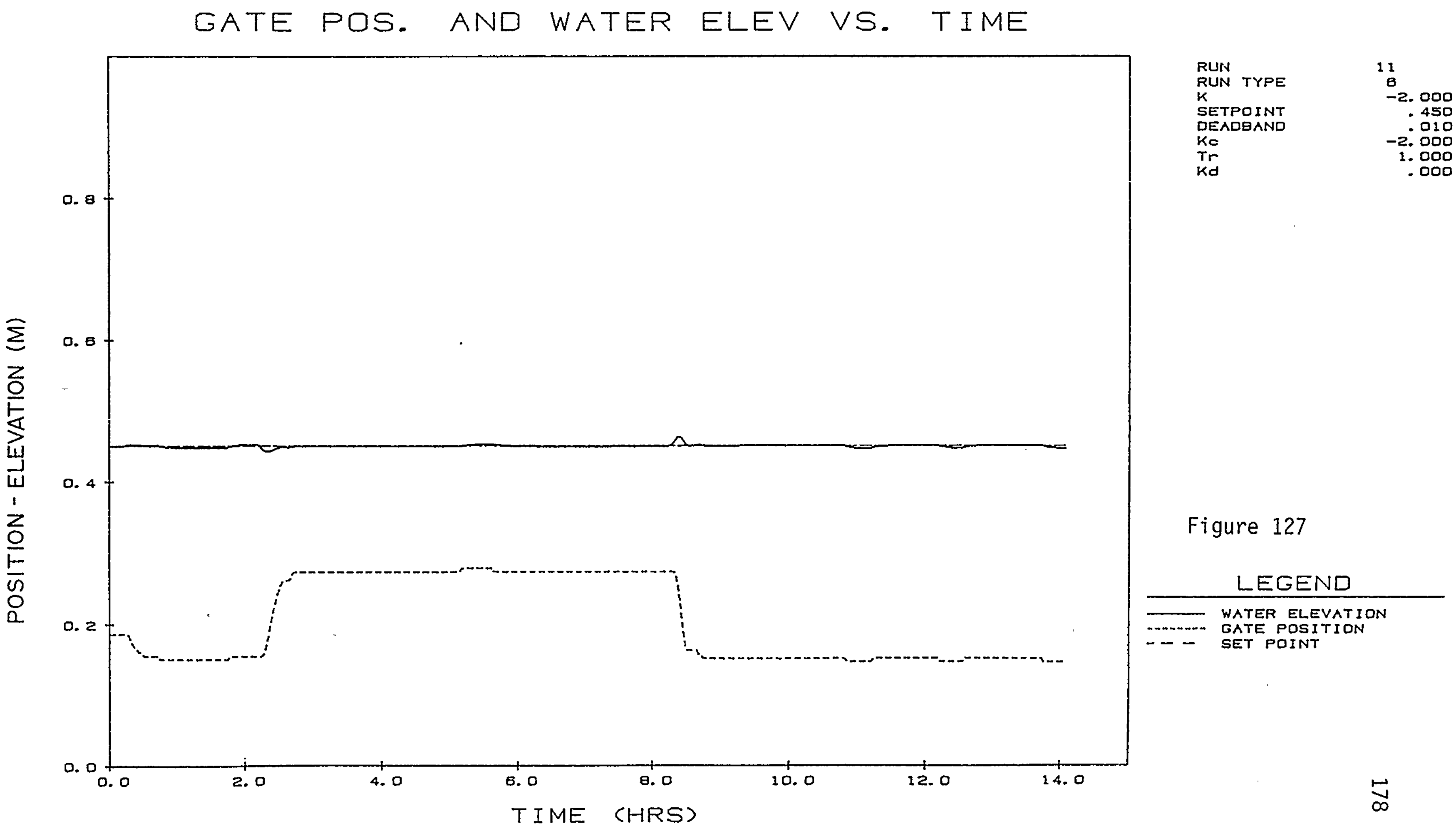

GATE POS. AND WATER ELEV VS. TIME
RUN 11
RUN TYPE 8
K -2.000
SETPOINT .450
DEADBAND .010
Kc -2.000
Tr 1.000
Kd .000
POSITION - ELEVATION (M)
0.0
0.2
0.4
0.6
0.8
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
TIME (HRS)
LEGEND
WATER ELEVATION
GATE POSITION
SET POINT

Figure 127

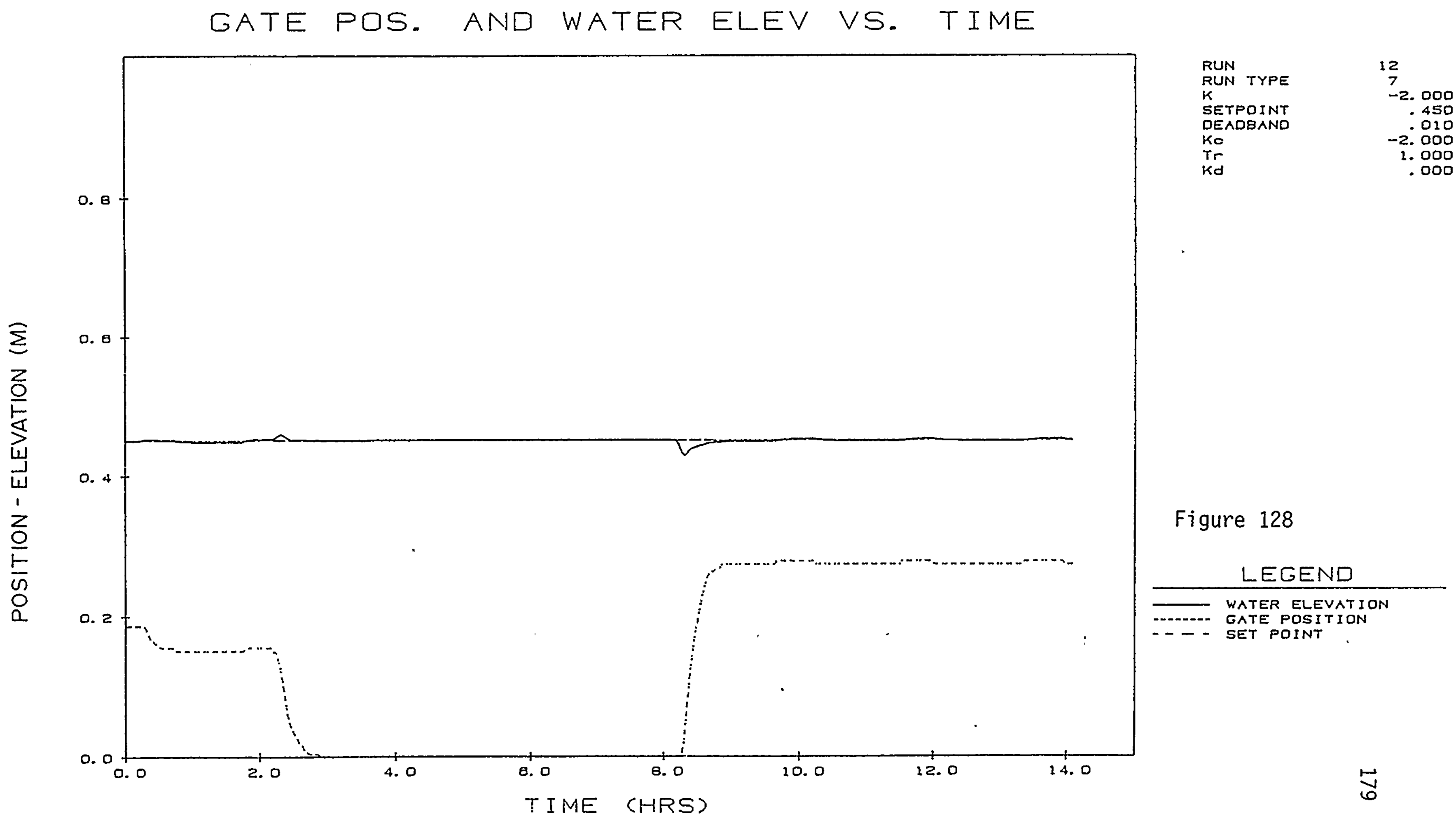

GATE POS. AND WATER ELEV VS. TIME
RUN 12
RUN TYPE 7
K -2.000
SETPOINT .450
DEADBAND .010
Kc -2.000
Tr 1.000
Kd .000
0.8
0.6
0.4
0.2
0.0
POSITION - ELEVATION (M)
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
TIME (HRS)
LEGEND
WATER ELEVATION
GATE POSITION
SET POINT

Figure 128

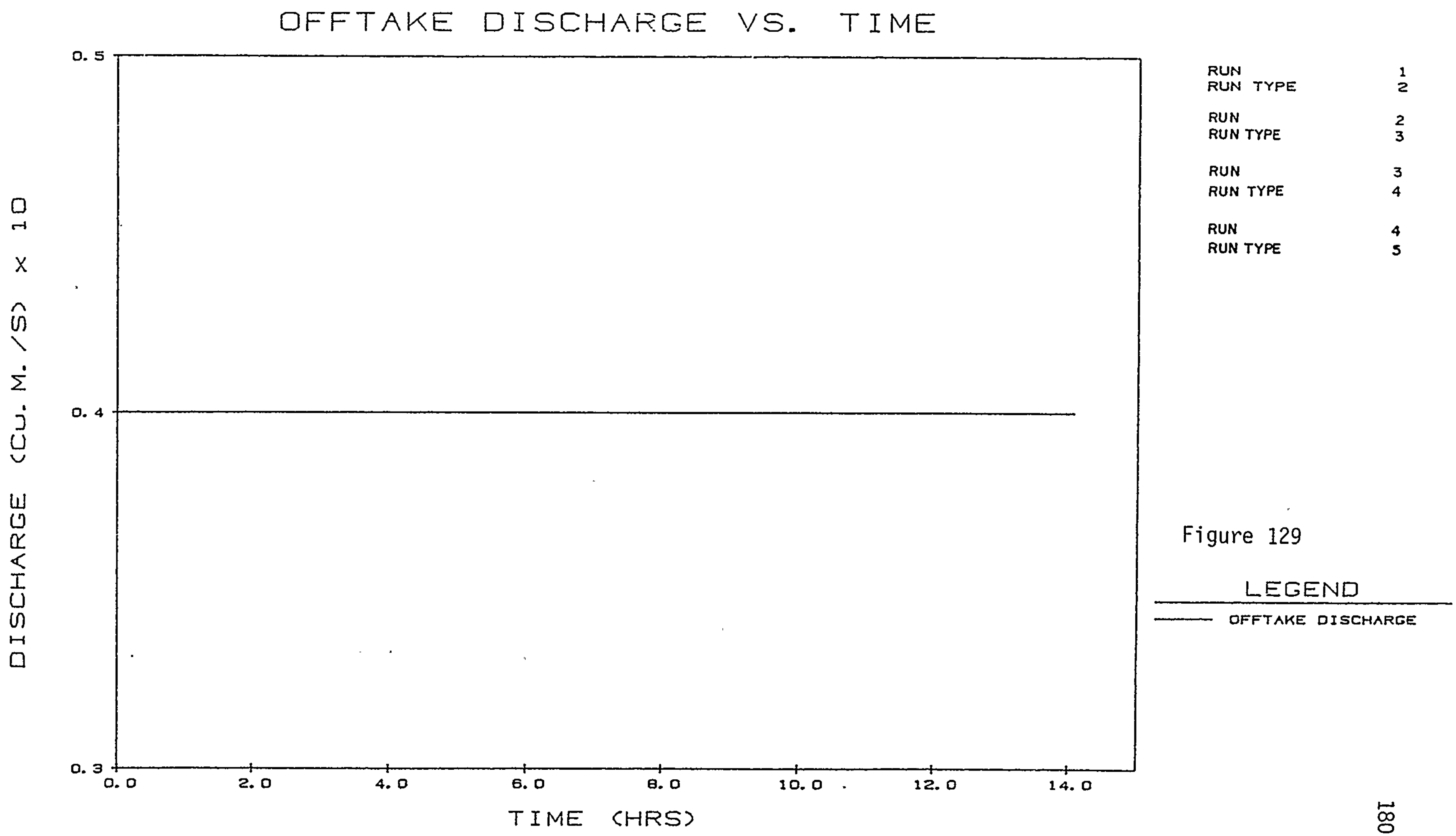
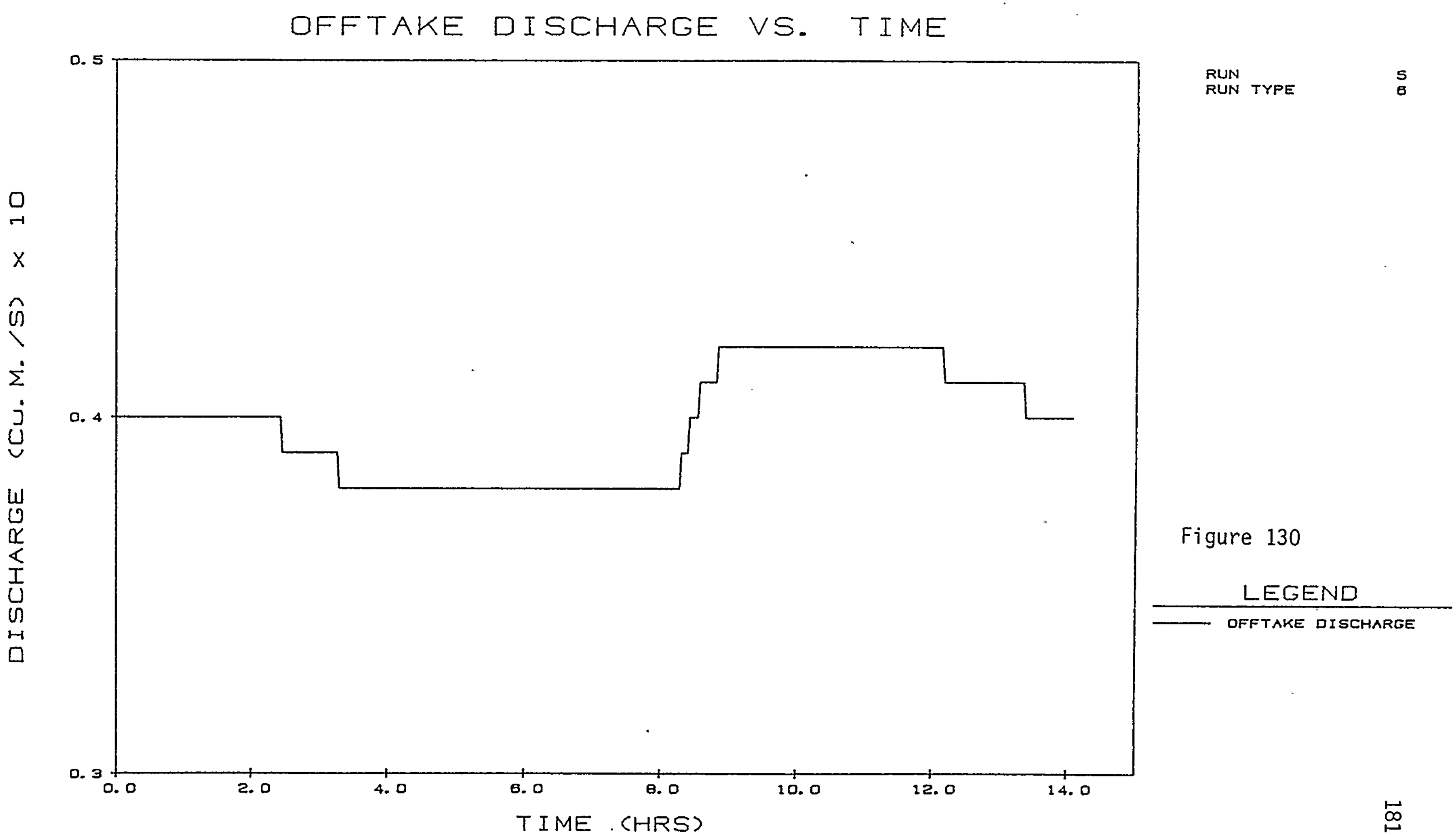

OFFTAKE DISCHARGE VS. TIME
DISCHARGE (CU. M. /S) X 10
0.5
0.4
0.3
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
TIME (HRS)
RUN 1
RUN TYPE 2
RUN 2
RUN TYPE 3
RUN 3
RUN TYPE 4
RUN 4
RUN TYPE 5
LEGEND
OFFTAKE DISCHARGE

Figure 129



OFFTAKE DISCHARGE VS. TIME
0.5
0.4
0.3
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
TIME (HRS)
DISCHARGE (CU. M. /S) x 10
RUN S
RUN TYPE 6
LEGEND
OFFTAKE DISCHARGE

Figure 130

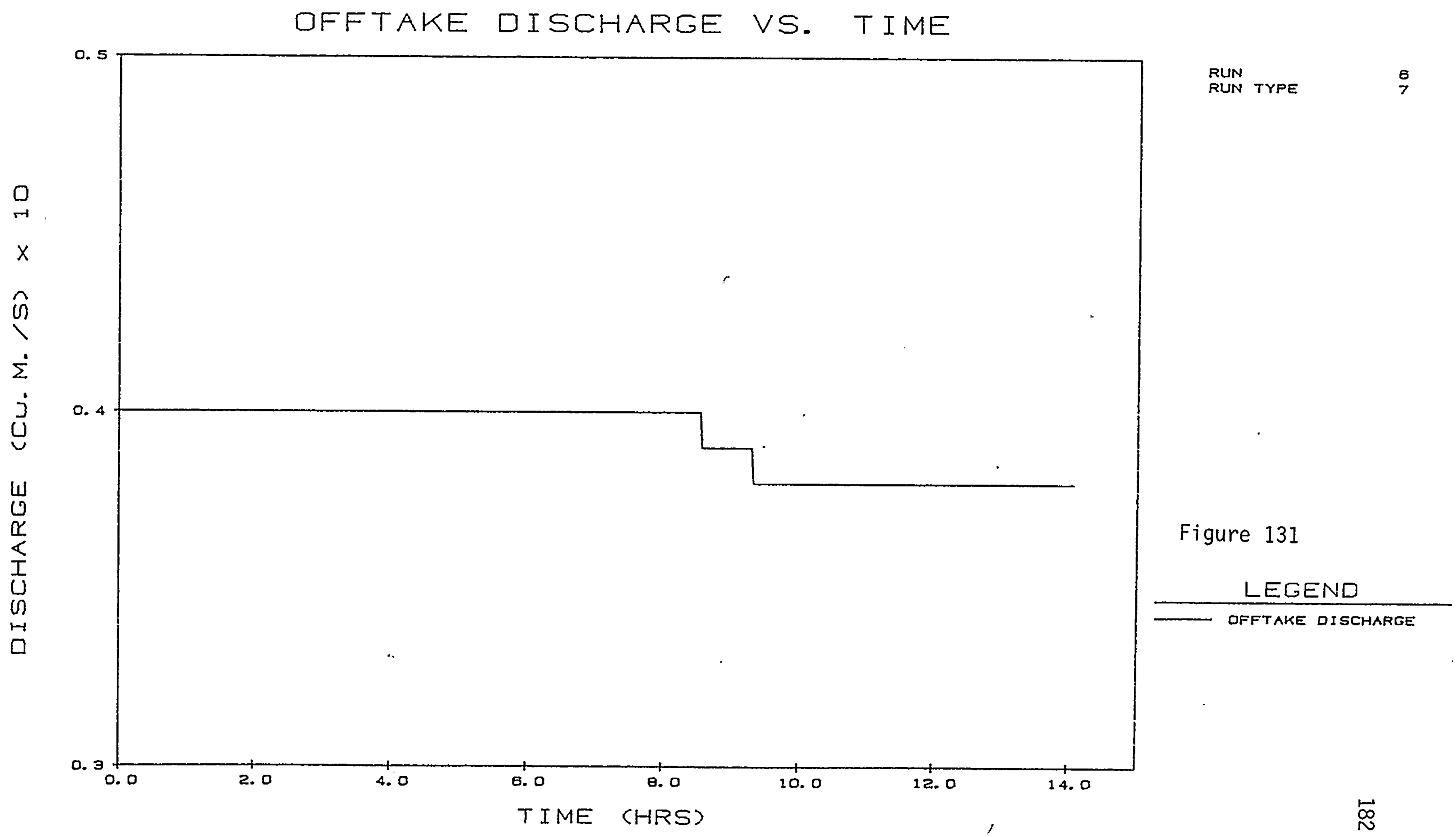

OFFTAKE DISCHARGE VS. TIME
DISCHARGE (CU. M. /S) X 10
0.5
0.4
0.3
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
TIME (HRS)
RUN 6
RUN TYPE 7
LEGEND
OFFTAKE DISCHARGE

Figure 131

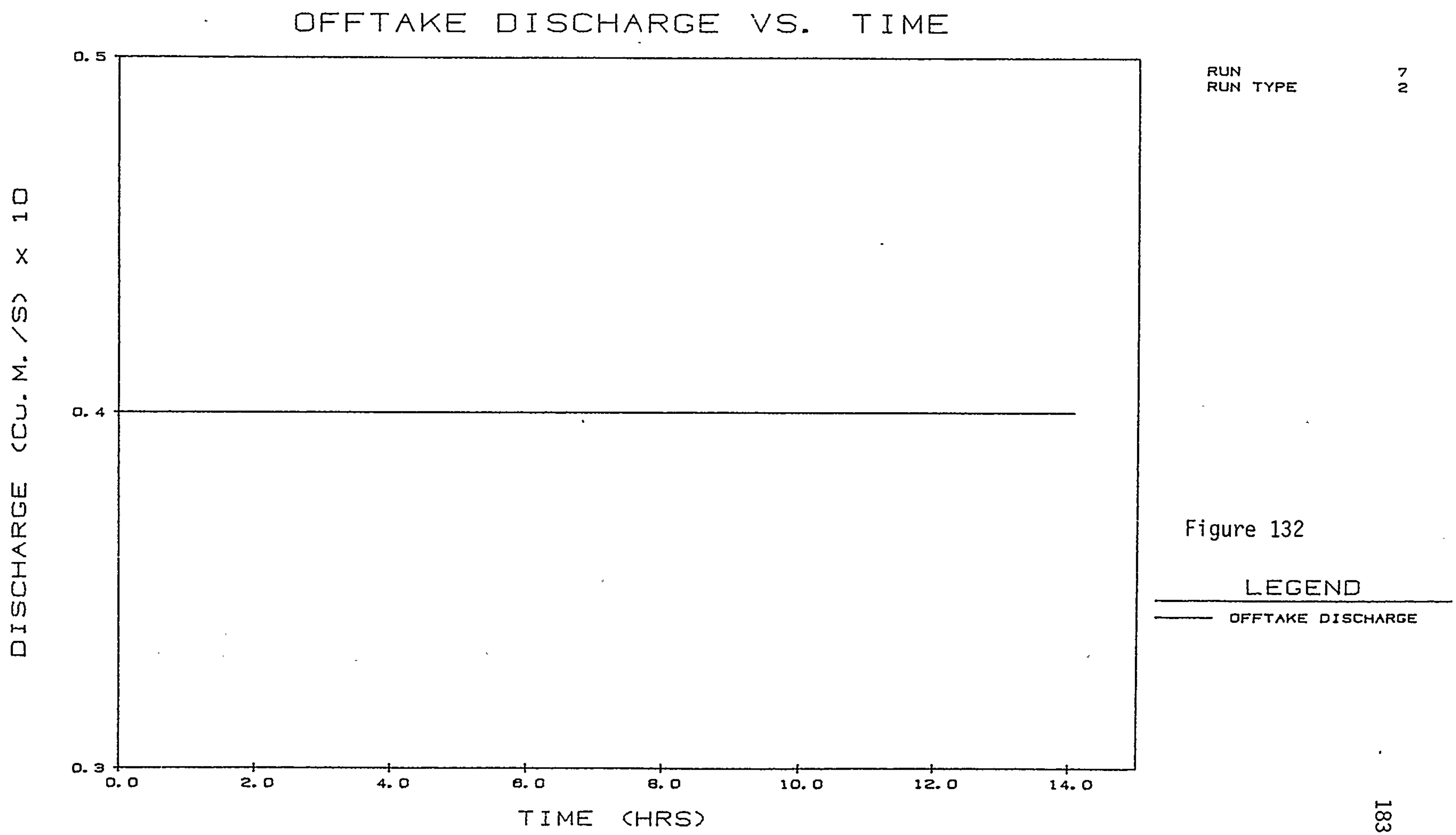
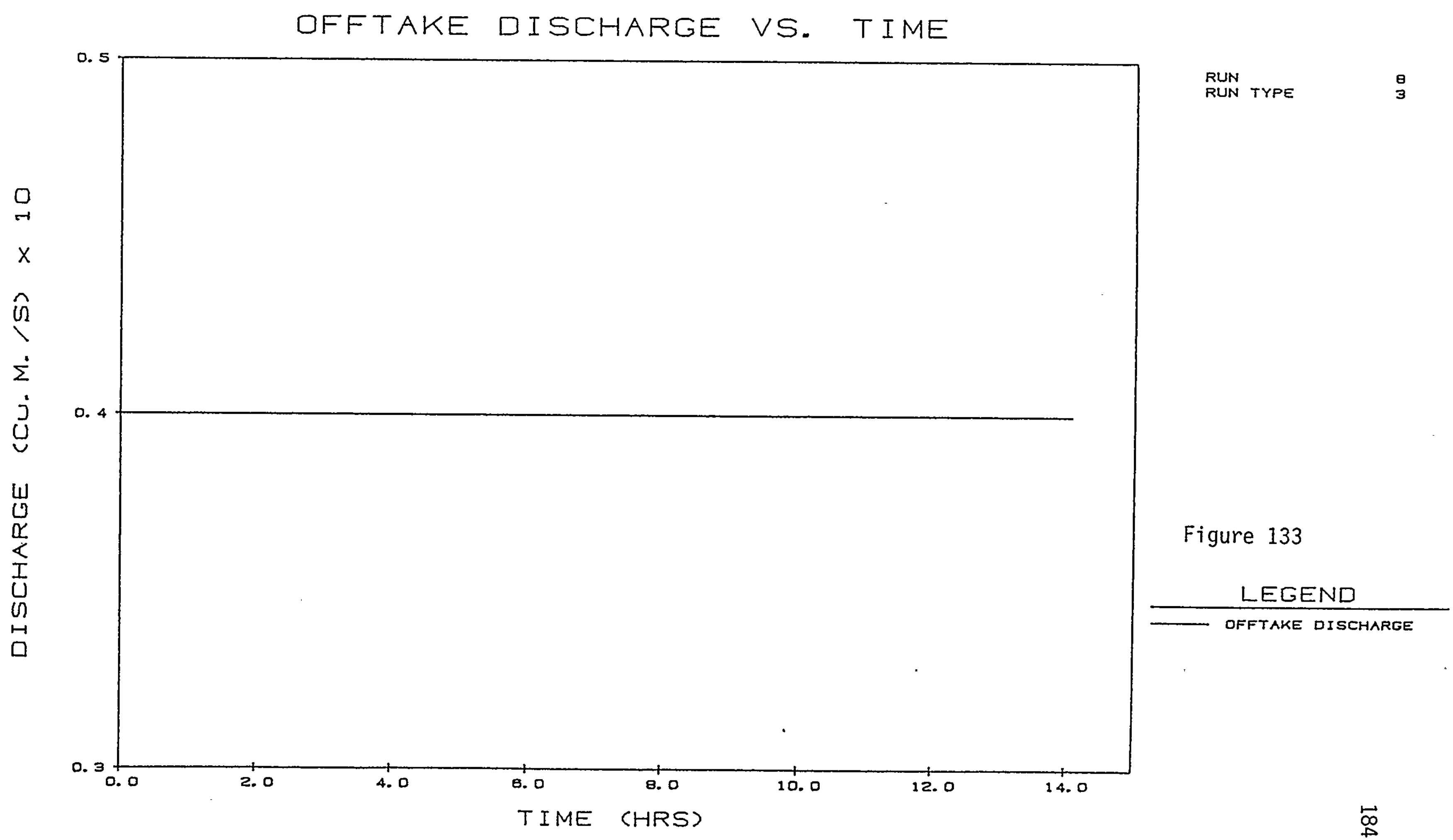

OFFTAKE DISCHARGE VS. TIME
RUN 7
RUN TYPE 2
DISCHARGE (CU. M. /S) x 10
0.5
0.4
0.3
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
TIME (HRS)
LEGEND
OFFTAKE DISCHARGE

Figure 132



OFFTAKE DISCHARGE VS. TIME
0.5
0.4
0.3
DISCHARGE (CU. M. /S) X 10
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
TIME (HRS)
RUN 8
RUN TYPE 3
LEGEND
OFFTAKE DISCHARGE

Figure 133

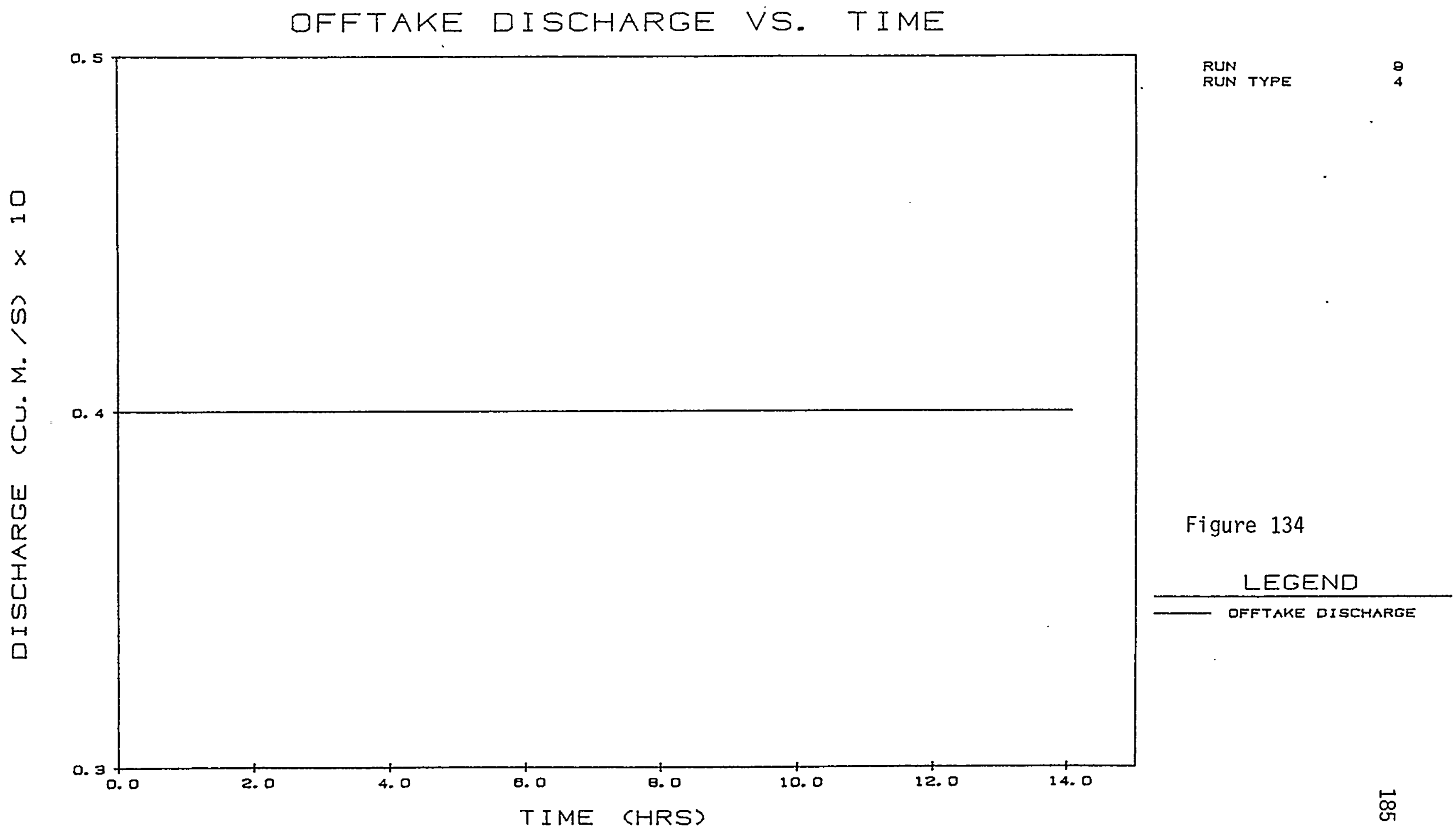
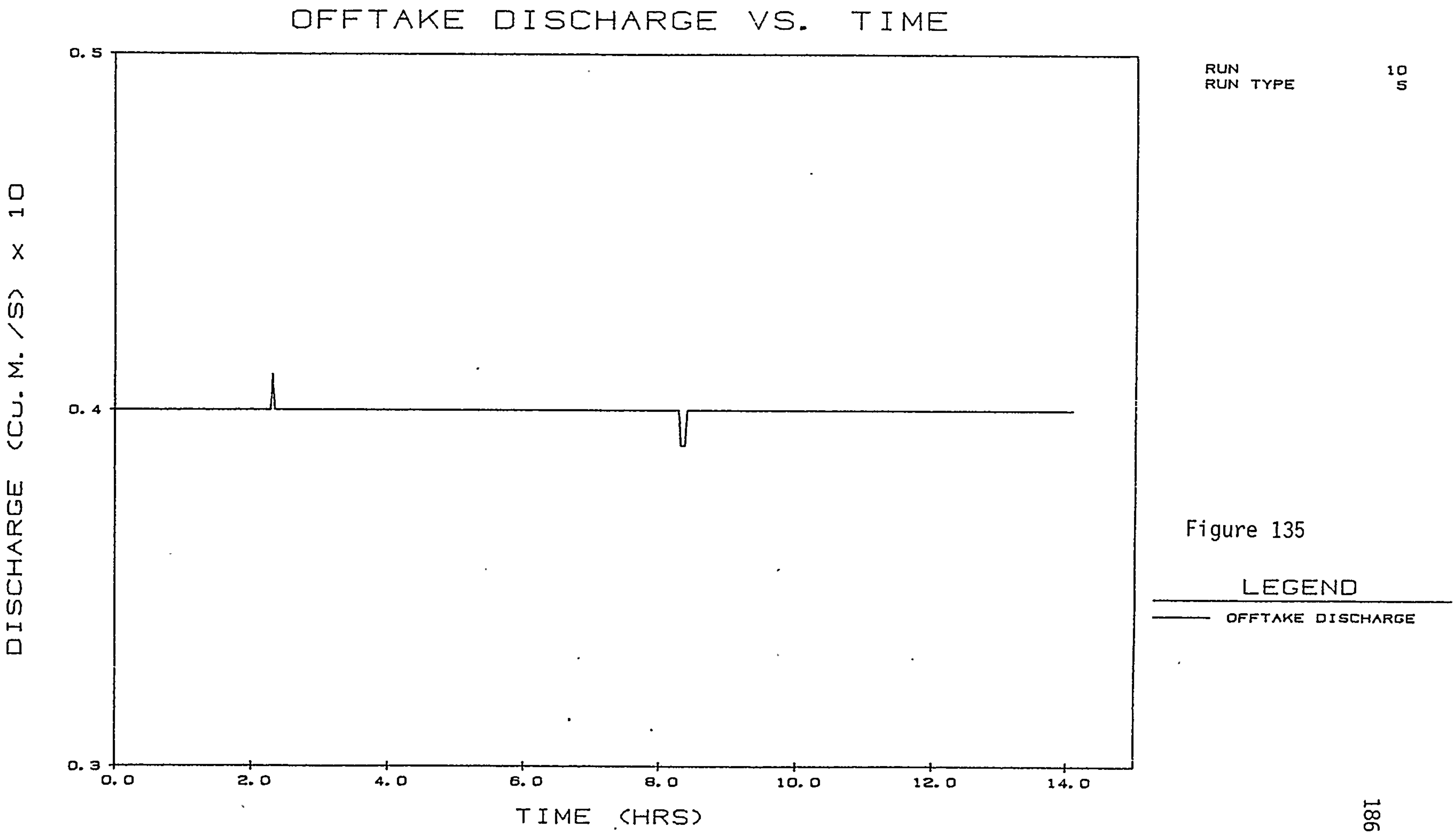

OFFTAKE DISCHARGE VS. TIME
DISCHARGE (CU. M. /S) x 10
0.5
0.4
0.3
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
TIME (HRS)
RUN 9
RUN TYPE 4
LEGEND
OFFTAKE DISCHARGE

Figure 134



OFFTAKE DISCHARGE VS. TIME
DISCHARGE (CU. M. /S) x 10
0.5
0.4
0.3
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
TIME (HRS)
RUN 10
RUN TYPE 5
LEGEND
OFFTAKE DISCHARGE

Figure 135

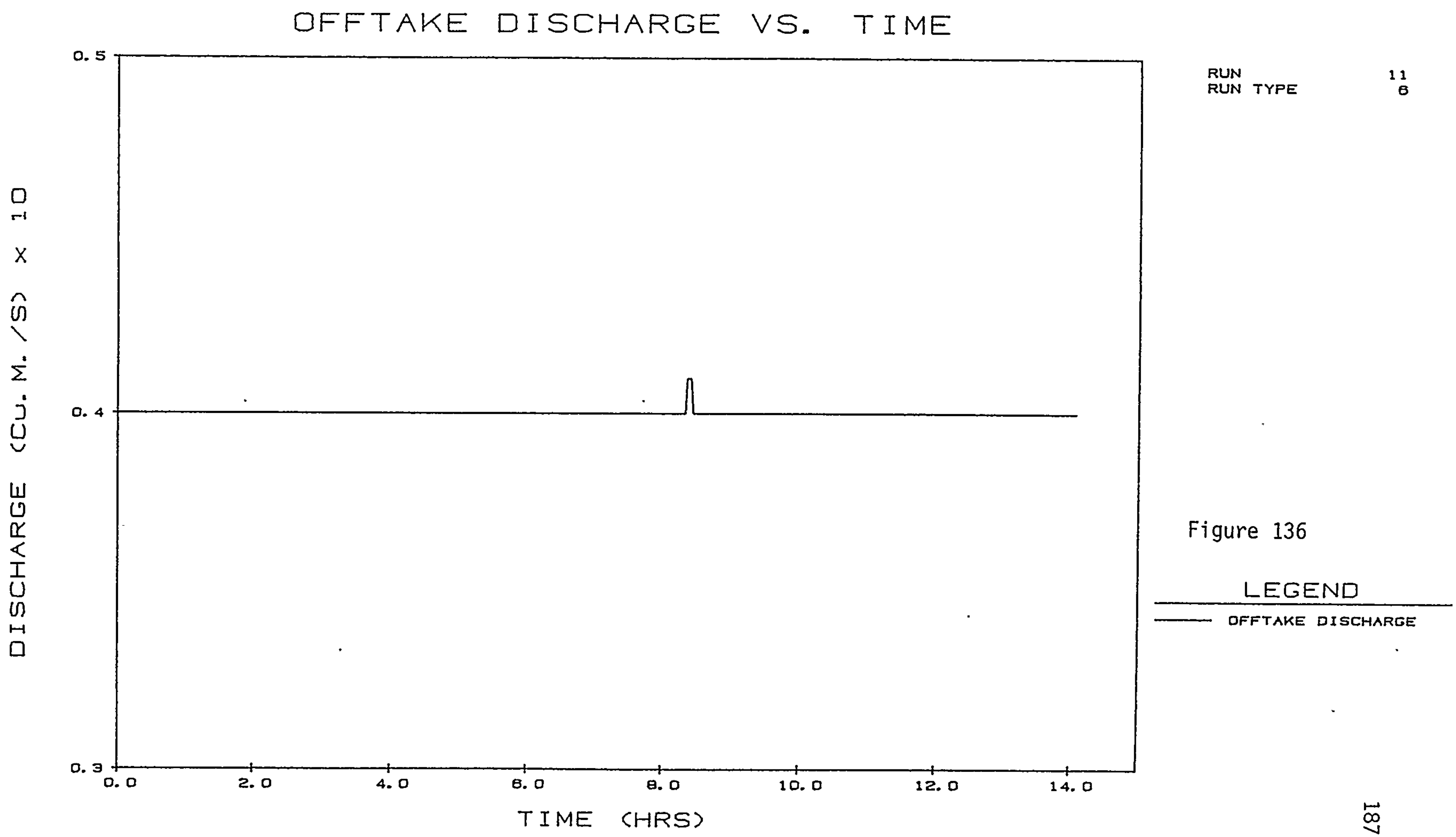

OFFTAKE DISCHARGE VS. TIME
RUN 11
RUN TYPE 6
DISCHARGE (CU. M. /S) x 10
0.5
0.4
0.3
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
TIME (HRS)
LEGEND
OFFTAKE DISCHARGE

Figure 136

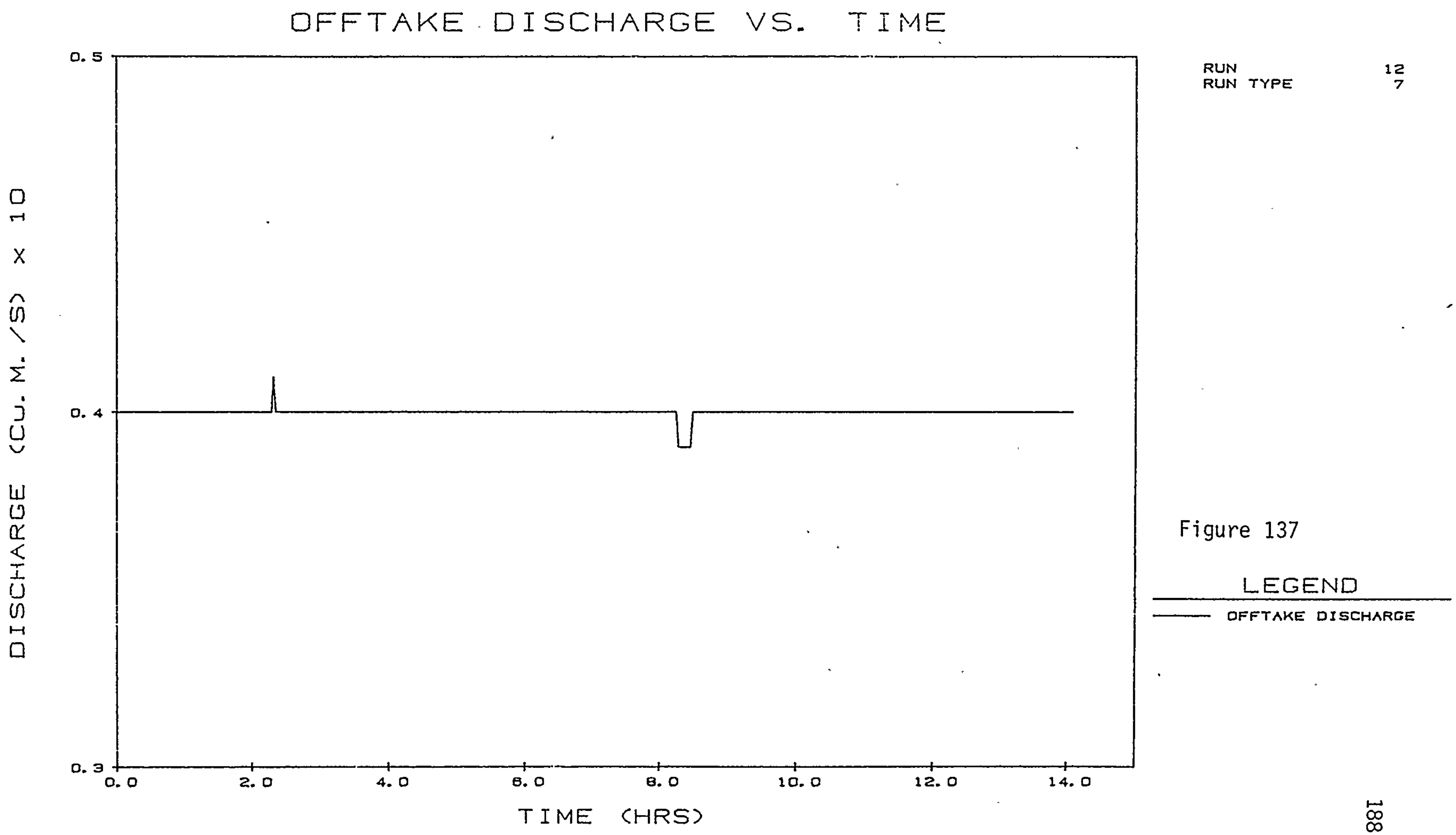

OFFTAKE DISCHARGE VS. TIME
0.5
0.4
0.3
DISCHARGE (CU. M./S) x 10
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
TIME (HRS)
RUN 12
RUN TYPE 7
LEGEND
OFFTAKE DISCHARGE

Figure 137

seem to regulate the water level as well as is expected. This is not the fault of the controller. All hydraulic control structures have physical limits. The physical height limit for the overshot pivoting weir has been reached just after the two hour mark an no more upward adjustments may be made. The maximum height adjustment of the overshot pivoting weir is not sufficient to bring the water level to the desired water level. During this time the controller is accumulating the error from the desired water level within the integral term. When the flow is once again reduced (at 8.0 hours) the water level increases, yet the controller seems not to react. In fact the controller is operating and is simply reducing the error within the integral term to a point where adjustments may be made once again by the controller. The controller response is seen at hour 12 of the simulation. A similar response happens after hour 8 of the simulation of run 6 (Figure 122).

Figures 129 to 131 show the effects this controller has on the flow through the turnout. The flow through the turnout in run 4 (Figure 129) is very good. The flow through the turnout in run numbers 5 and 6 (Figures 130-131) show changes in the flow rate. These changes are a direct result of the problems encountered as discussed previously.

Run numbers 7 to 12 (Figures 123-128), Farm turnout responses Figures 132-137) are numerical experiments which test the effects of low checking. Using this method of checking the water level is kept fairly low. This means that less storage is available as compared to the high checking method.

Run numbers 7 to 9 (Figures 123-125) show the response of the controller to small changes in inflow (0.05 - 0.10 cms). The water level in all three cases is controlled very well. As expected the flow through the turnouts is constant (Figures

132-134).

Run numbers 10 to 12 (Figures 126-128) show the response of the controller when large (0.15-0.20 cms) flow variations are encountered. At time 2.0 hours and 8.0 hours small deviations in the actual water level and the desired water level may be noted. These deviations are similar to those encountered during run number 4 (Figure 120). Examining the turnout flow response (Figures 135-137) to these changes flow peaks and valleys are seen which correspond with those in Figures 125-127. Although the same water level deviations are noted in run 4, the turnout flow (Figure 129) has no indication that these small disturbances have occurred.

8.0 DISCUSSION OF ANALYSIS

This section is intended as an evaluation and summary of the numerical experiments presented in section 7.0. The discussion will consists of five sections pertaining to the Littleman, EL-FLO, Proportional, Proportional + Integral and Proportional + Differential controllers. These sections are as follows:

1. General description of controller characteristics.

2. Controller parameter adjustment sensitivity

3. Quality of water level control.

4. Range of water level control.

5. Effect of deadband on controller.

The farm turnout delivery quality experiments will be discussed in the final section. The performance of the controller will be discussed based on the consistency of farm water deliveries for a range of different flow conditions using both high and low checking techniques.

8.1 GENERAL DESCRIPTION OF CONTROLLER CHARACTERISTICS

The Littleman controller was found to cycle wildly about the desired water level (setpoint). By modifying the operation of the controller to slow the gate movement it was found that the length of each cycle was increased. The amplitude of the controller also decreased with slower gate speeds. When the antihunt device was activated the controller became stable as near to the setpoint as the deadband allowed. This offset from the setpoint is never corrected during the operation of the controller.

Using the EL-FLO controller, regulation of the upstream water level was always stable. However, large offsets from the setpoint occur when the value of K_p are very small or very large (<2.0 or > 3.0). The large offset which occurs with small values of K_p is a result of the controllers inability to respond even with large error values(Figure 33). Offsets which occur when the value of K_p is large is a result of the controller becoming too sensitive and becoming unable to respond even with very small error values (Figure 36). Thus it may be surmised that an optimal value of K_p must be selected in order for the controller to operate correctly. In all cases, without the use of the reset function, actual water level arrived at is offset from the desired water level.

The operation of the EL-FLO controller with the reset function provides the ability to correct this offset. Small values of K_i provide for slow rates of correction. (Figure 38) Larger values of K_i provide for much improved rates of offset correction. (Figure 41).

Evaluation of the Proportional controller shows small offsets as compared to the EL-FLO controller. Small values of K_p simply make for a slower response time, as opposed to a very large offset value as seen in the EL-FLO method. The actual water level approximates the desired water level in all cases. Larger values of K_p approximate the desired water level closer than smaller values. However, if K_p becomes too large the automatic controller will become unstable. Illustrations of small, large and unstable values of K_p are shown in Figures 52, 55 and 56 respectively. Values of K_p are 0.10, 2.0, 5.0. The unstable operations at high values of K_p are expected as outlined in section 2.3.6. This controller may be optimized by increasing the value of K_p until instability is encountered. The value should then be decreased until satisfactorily stable operations are encountered.

The proportional + integral controller acts in very much the same way as the proportional controller. Differences between the two controllers, however, are evident. Firstly, the offsets encountered using the proportional controller are still present, but due to the presence of the integral term converge towards the setpoint at a rate dependent on the K_i term. This action may be seen by comparing Figures 52 and 73. Both Figures show the response of the gate and water level for identical parameter settings and flow changes with only the addition of a integral constant K_i in Figure 73.

The integral term of the proportional + integral controller also adds to the initial response of the system. This combination tends to create more cycling about the setpoint than the proportional controller. Comparing Figures 49 and 70, again identical in every respect except for the addition of the integral constant, shows the additional cycling which may occur. The initial response at 2.0 hours is very similar. The response of the controller to the second disturbance at 8.0 hours however are different. The proportional controller in Figure 49 requires 1 1/2 cycles to become stable, while the proportional + integral controller requires 2 1/2 cycles to become stable.

Holding K_p constant and varying K_i indirectly (actually varying T_r, see section 6.4) no significant change in operation is seen. The only exception to this is when K_i is increased (T_r is reduced) the controller will eventually become unstable.

Optimization of the proportional + integral controller would be similar to that of the proportional controller.

The proportional + differential controller behaves in a very similar manner to the proportional controller. Changing the values of K_d within a certain range (< 0.10) has very little effect on the performance of the controller. Beyond a certain value (>0.10) the controller becomes wildly unstable. As the performance of the controller does not change a great deal with adjustment of K_d, optimization of this controller becomes a moot exercise. The only guideline which should be adhered to when configuring this controller is to find where the controller becomes unstable, and decrease the value of K_d to well within the stable region.

8.2 CONTROLLER PARAMETER ADJUSTMENT SENSITIVITY

The change of speed of the motor used to control the gate of the Littleman controller directly affects the amplitude and the wavelength of the oscillations about the setpoint. With the addition of the antihunting device the improvement in controller stability is evident.

The sensitivity to parameter adjustments for the remaining controllers are evaluated based on the amount of change of the parameter with respect to the amount of change to the e^2 value as reported in the preceding section. An example calculation is shown below:

EL-FLO controller values:

$K_1 = 0.1$ $\qquad$ ${e^2}_1 = 27.2410$

$K_2 = 1.0$ $\qquad$ ${e^2}_2 = 17.4967$

The relative change in K may be defined as:

$$K_x = K_2 \;/\; K_1$$
$$K_x = 1.0 \;/\; 0.1$$
$$K_x = 10$$

The relative change in e^2 may be defined as:

$$e^2{}_x = (e^2{}_1 - e^2{}_2) \;/\; e^2{}_1$$
$$e^2{}_x = (27.2410 - 17.4967) \;/\; 27.2410$$
$$e^2{}_x = 0.36$$

The relative change in e^2 per unit increase in K is calculated as:

$$e^2{}_u = e^2{}_x \;/\; K_x$$
$$e^2{}_u = 0.36 \;/\; 10$$
$$e^2{}_u = 0.036 \text{ per K}$$

The results of these calculations on the EL-FLO, Proportional, Proportional + Reset and Proportional + Differential controller types are presented in Tables 14 to 19.

A value of zero indicates that the controller is not sensitive to changes in K. Increasing values of $e^2{}_u$ indicate increasing sensitivity. Negative values indicate that the e^2 term actually got worse between two succeeding K values. A value of one (1) indicates that a unit change in K value effects a unit change in error values as defined previously. The sensitivity of the controller may be judged as extreme if the $e^2{}_u$ term is greater than one (1).

Table 14. EL-FLO controller, Parameter adjustment sensitivity.

K_i = constant = 0.0

K_p	K_x	e^2	$e^2{}_x$	$e^2{}_u$
0.1		27.2410		
	10		0.358	0.036
1.0		17.4967		
	2		0.540	0.270
2.0		8.0407		
	1.5		0.426	0.280
3.0		4.6161		
	1.66		-23.410	-14.100
5.0		112.6772		

Table 15. EL-FLO controller, Parameter sensitivity of reset portion of controller.

K_p = constant = 3.0

K_i	K_x	e^2	$e^2{}_x$	$e^2{}_u$
0.1		3.4525		
	5.0		0.576	0.115
0.5		1.4652		
	2.0		0.470	0.235
1.0		0.7764		
	2.0		0.487	0.244
2.0		0.3986		

Table 16. Proportional Controller, Parameter change sensitivity.

K_p	K_x	e^2	$e^2{}_x$	$e^2{}_u$	Deadband
0.1		0.2787			0.005
	5		0.898	0.180	
0.5		0.0284			0.005
	2		0.585	0.293	
1.0		0.0118			0.005
	2		0.763	0.382	
2.0		0.0028			0.005
5.0		UNSTABLE			0.005
0.1		0.4160			0.010
	5		0.869	0.174	
0.5		0.0546			0.010
	2		0.773	0.387	
1.0		0.0124			0.010
	1.5		0.540	0.360	
1.5		0.0057			0.010
	1.33		0.439	0.330	
2.0		0.0032			0.010
	1.5		0.563	0.375	
3.0		0.0014			0.010
4.0		UNSTABLE			0.010
5.0		UNSTABLE			0.010
0.1		2.3845			0.025
	5		0.957	0.191	
0.5		0.1022			0.025
	2		0.651	0.326	
1.0		0.0357			0.025
	2		0.810	0.405	
2.0		0.0068			0.025
5.0		UNSTABLE			0.025

Table 17. Proportional + Integral Controller, Parameter change sensitivity.

K_p	K_i	K_x	e^2	$e^2{}_x$	$e^2{}_u$	Deadband
0.1	0.1		0.3932			0.005
		5		0.878	0.176	
0.5	0.5		0.0478			0.005
		2		0.745	0.373	
1.0	1.0		0.0122			0.005
		2		0.795	0.398	
2.0	2.0		0.0025			0.005
5.0	5.0		UNSTABLE			0.005
0.1	0.1		0.4034			0.010
		5		0.876	0.175	
0.5	0.5		0.0498			0.010
		2		0.719	0.359	
1.0	1.0		0.0140			0.010
		1.5		0.593	0.395	
1.5	1.5		0.0057			0.010
		1.3		0.526	0.404	
2.0	2.0		0.0027			0.010
3.0	3.0		UNSTABLE			0.010
4.0	4.0		UNSTABLE			0.010
5.0	5.0		UNSTABLE			0.010
0.1	0.1		0.6579			0.025
		5		0.922	0.184	
0.5	0.5		0.0514			0.025
		2		0.654	0.327	
1.0	1.0		0.0178			0.025
		2		0.781	0.391	
2.0	2.0		0.0039			0.025

Table 18. Proportional + Integral Control, Parameter (T_r) sensitivity

K_p	K_i	T_r	K_x	e^2	$e^2{}_x$	$e^2{}_u$	Deadband
2.0	2.0	2.0	2	0.0027	0.074	0.037	0.005
2.0	2.0	1.0		0.0025			0.005
2.0	2.0	0.5		UNSTABLE			0.005
2.0	2.0	2.0	2	0.0028	0.036	0.018	0.010
2.0	2.0	1.0		0.0027			0.010
2.0	2.0	0.5		UNSTABLE			0.010
2.0	2.0	2.0	2	0.0027	-0.444	-0.222	0.025
2.0	2.0	1.0		0.0039			0.025
2.0	2.0	0.5		UNSTABLE			0.025

The sensitivity to changes in K ($e^2{}_u$) for the EL-FLO controller increases until $K_p = 3.0$. At this point $e^2{}_u$ becomes negative indicating a degradation of the error term between $K_p = 3$ and $K_p = 5$. These values of $e^2{}_u$ indicate that the controller becomes more sensitive as the values of K_p increase. Until at some point the controller becomes too sensitive as indicated by the large error value for $K_p = 5.0$ and the large negative change in $e^2{}_u$ between $K_p = 3.0$ and 5.0. Table 15 lists the controller sensitivity based on changes in the integral constant K_i only. The sensitivity increases with an increasing K_i, but is less drastic than with changes in K_p.

The change in sensitivity as measured by the $e^2{}_u$ value for the proportional and proportional + integral controllers are more uniform as can be seen from Tables 16 and 17. Values of $e^2{}_u$ were evaluated only when the controller was operating in a

Table 19. Proportional + Differential Controller, Parameter sensitivity.

K_p = constant = 2.0

K_d	K_x	e^2	$e^2{}_x$	$e^2{}_u$	Deadband
0.01		0.0026			0.005
	5		0.115	0.001	
0.05		0.0023			0.005
	2		0.130	0.065	
0.10		0.0020			0.005
0.01		0.0027			0.010
	5		0.000	0.000	
0.05		0.0027			0.010
	2		0.111	0.055	
0.10		0.0024			0.010
0.01		0.0084			0.025
	5		0.536	0.107	
0.05		0.0039			0.025
	2		-0.692	-0.346	
0.10		0.0066			0.025

stable mode. The sensitivity to K_p based on the $e^2{}_u$ values is very low for all runs between $K_p = 0.1$ and $K_p = 0.5$.

As the integral term in the proportional + integral controller enhances the operation of the controller initially and later to continually seek the desired water level, it would be expected that the rate of decrease of error per unit increase in K_p should increase. Comparing the $e^2{}_u$ values for the proportional and proportional + integral controller it can be seen that generally this is the case.

The effects of adjusting the K_i (T_r) constant alone are tabulated in Table 18. This analysis indicates that the integral controller is not sensitive to adjustments in the integral constant (K_i).

The proportional + differential controller is insensitive to changes in K_d. This is indicated by the low values of $e^2{}_u$ ranging from 0.001 to 0.107.

8.3 QUALITY OF CONTROL

The quality of control for the controllers investigated can be measured quantitatively by comparing values of e^2 terms. A qualitative evaluation of the controllers quality may be ascertained by reviewing the plots of each individual numerical experiment.

As the change in gate position is slowed for the Littleman controller the e^2 term increases. The quality of control from a quantitative standpoint becomes even worse when the antihunt device is put into operation. The primary reason for this seeming decrease in controller quality. This decrease in controller quality is a direct result of the length of time away from the setpoint increasing. The increase in time is a result of slowing the rate of change in gate position and thus lengthening the oscillations. This can be seen be reviewing Figures 27 to 29. Finally when the antihunt device is added, oscillations stop (Figure 30) and the error is allowed to accumulate.

Even though a high e^2 value is encountered for the Littleman controller with the antihunt device activated, this turns out to be the best mode of control. The upstream water level is stable, albeit not at the desired level. Changes in the inflow into the canal force the controller to adjust and the water level becomes stable at another level.

The EL-FLO typically contains values of e^2 much higher than that of the Littleman controller. All parameters, however, produce a stable water level. Unless optimum values of K_p are chosen, the stable water level may be quite far away from the desired water level. By enabling the reset term we find the controller quality increases substantially, until the e^2 term is lower than that of the Littleman controller operating in a stable state.

In the case of the EL-FLO controller the quantitative analysis seems to tell the complete story about the controller quality. Comparing Figures 33 to 41 to their respective e^2 values show a correspondence between the quantitative (e^2 term) and the qualitative (visual analysis) quality of control.

The quality of the proportional controller increases as K_p increases. Values of e^2 lower than either the Littleman or EL-FLO controller may be obtained without effort with the Proportional controller. High values of K_p (>1, <5) produce very low e_2 terms (< 0.05 m^2) over the entire simulation. However, unlike the EL-FLO controllers it is impossible to have the complete picture using quantitative analysis alone. Reviewing Figures 46, 51, 56 and 59 it can be seen that even though low values of e^2 are reported (0.0004, 0.0008, 0.0014 and 0.0008 m^2 respectively) the operation of the controller has become unstable. This mode of operation is unacceptable and a quantitative analysis may not be regarded as definitive.

The Proportional + Integral controller is very similar to the Proportional control. The quality of control also increase as K_p and K_i increase. Comparison of the e^2 terms between the Proportional and Proportional + Integral controllers show that the quantitative measure of control has not changed dramatically. Again the measure of the quality of control can not be purely a quantitative one. Review of Figures 62, 67, 72, 79 and 80 show the unstable nature of the controller even though reported values of e^2 are low (.0004, .0004, .0024, .0013 and .0007 m^2 respectively).

The effect of the Integral term warrants some additional investigation. Changing the reset time constant T_r (equivalent to the reciprocal of K_i) does not change the quantitative evaluation of quality significantly (See Table 12 and Section 8.2). Qualitatively, however, one must take care in the selection of an integral constant (K_i). To large a selection may cause the controller to become unstable as demonstrated in Figures 81, 84 and 87.

The Proportional + Integral controller does enhance the quality of control by the fact that it continually seeks to adjust the actual water level to the desired water level by virtue of the integral term of the controller.

The Proportional + Differential controller again acts very similarly to the Proportional controller. The level controller quality is not affected drastically by adjusting the differential control constant (K_d). Error squared values for this controller type compare favourably to the Proportional controller.

The Proportional + Differential controller does suffer from sudden and severe instabilities brought on by values of K_d chosen too high. This poor choice of K_d is so severe that its' effects can be seen in the e^2 term. Values of e^2 greater than unity indicate severe instability in this situation.

8.4 RANGE OF CONTROL

The range of water levels for which a controller may successfully operate is important to examine in terms of applicability of controller to a specific set of circumstances. If, for instance, the controller is only expected to operate where only small changes (or large changes) in water level occur, it may be optimized to meet these needs. If, on the other hand, a controller is required to regulate the upstream water level equally well for both small and large water level changes some controllers may not be as suitable.

The Littleman controller oscillates wildly about the setpoint without the antihunt device engaged. This behaviour will not differ any for large or small changes in canal water level. This assessment may be made due to the nature of the Littleman operation. This operational nature remains the same for every water level deviation. The main operational components are:

- The gate makes no adjustment if the water level is within the deadband.

- As the water level rises the motors engage to lower the gate and thus the water level. The gate does not become disengaged until the water level is within the deadband.

- As the water level falls the motors engage to raise the gate and thus the water level. The gate does not become disengaged until the water level is within the deadband.

Prevalent in this type of control is the tendency for the water level to continue rising or falling through the deadband and engage the gate in the opposite direction, causing continual gate adjustment.

With the antihunt mechanism engaged the controller would operate similarly with all variations of water level movement. This can be said because the operation of the antihunt device is based on disengagement of the motors (regardless of direction) as soon as the water level changes direction. The motors will not be engaged again until the water level changes sufficiently to engaged in the opposite direction or changes in the same direction to reengage the motors. It can be seen from this chain of operations that a rising water level will always become stable above the desired water level and a falling water level will always become stable below the desired water level. The distance above and below the desired water level will be governed by the deadband.

The range of control for the EL-FLO , Proportional, Proportional + Integral and Proportional + Differential were all tested indirectly. Changing the values of K will indicate how the controllers will react under varying water level changes. This can be illustrated by referring to the proportional part of the EL-FLO controller (Section 3.3.9). The proportional part of this controller is written as follows:

$$\text{Gate Position} = K_p \text{ (YF-YT)}$$

Increasing K_p keeping the errors (YF-YT) small indicates how the controller would respond if K_p were kept constant and the errors (YF-YT) were increased. It is recognized, however, that the proportionality constant is a static term, while the errors are dynamic. However, inferences may still be drawn about the operation of the controller under varying magnitudes of errors from this analysis.

The performance of the EL-FLO controller varies a great deal with the adjustment of the proportionality constant. This reaction varies for very little responsiveness to a disturbance when K_p = 0.10 to an inability to respond when K_p=5.0. The inference which may be drawn as a result of this analysis is that initially large errors may cause the controller to overreact rendering the controller unable to respond (K_p = 5). As the water level reacts to the new gate position the error becomes reduced as the setpoint is approached. This frees the controller to become responsive to actual water level conditions. If, however, the response does not occurs too late the controller may over react in the opposite direction repeating the process. If the magnitude of the maximum errors decreases over time the controller will eventually become stable. If the magnitude of the maximum errors remains the same or increases the controller will never become stable.

Small changes in the water level should not present a problem for the EL-FLO controller, assuming a sufficiently large value of K_p has been chosen. Any offsets from the setpoint which may occur due to the required adjustments will be corrected by the reset term.

Similar arguments for the evaluation of the range of control for the Proportional, Proportional + Integral and Proportional + Differential controllers may be made. The only difference between the inferences which may be made about the EL-FLO controller as opposed to the Proportional controller types is that the EL-FLO controller attempts to adjust the gate position while the Proportional controller types adjust the change in gate position. Due to this difference inferences about the range of control of the Proportional type controllers may only be made during the initial adjustment stages. Any instability in the controller exhibited after initial adjustment is a direct result of the K values amplifying the error to too great an extent.

As the Proportional type controller always converge towards the setpoint regardless of controller K values it may be inferred that this controller will work well under any conditions. One possible exception to this is the Proportional + Differential controller. Large values of K_d cause violent instabilities in the controller. Thus large changes in error from one time step to the next may be enough of a catalyst to make this controller become unstable.

8.5 EFFECT OF DEADBAND

The effects of a changing deadband were only evaluated on the Proportional type controllers. Three controller deadbands were evaluated for the Proportional type controllers. These values were 0.005 m, 0.010 m and 0.025 m.

Generally, as the deadband increased the accuracy to which the actual water level approximated the desired water level decreased. This may be seen graphically by viewing the plots of error squared against K for all the Proportional type controllers (Figures 62, 92, 95 and 116). All plots show the 0.025 m deadband line having greater values than either the 0.010 or 0.005 m deadband lines. The 0.010 m deadband line has error squared values greater than or equal to the 0.005 m deadband line for the most part in all graphs. It should be noted that in all of the graphs the 0.010 and 0.005 m deadband lines are very close together, indicating very little difference in the reaction of the controller.

The maximum overshoot and undershoot of each controller is also affected by the size of the deadband. For the most part the 0.025 m deadband will have higher values of overshoot and undershoot than either the 0.010 or 0.005 m deadbands. (Figures 60, 61, 90, and 91) The overshoot and undershoot values for the 0.010 and 0.005 m deadbands are similar in all cases. The greatest difference in values of overshoot and undershoot between the different deadbands occurs when the values of K are low.

Figures 93, 94, 114 and 115 do not show any relation to each other as seen in the aforementioned Figures. The reason for this is unclear, but may be an indicator of unstable or marginally stable controller operations. However, due to these inconsistencies it is thought that the maximum overshoot and undershoot may not be a good indicator for use in evaluating the performance of a controller.

A general rule for configuring a Proportional type controller may be surmised from the above discussion. This rule is that moderate deadband values should be chosen. Too low a value will give the controller the opportunity to adjust too frequently in the event that the controller becomes unstable. (All controllers oscillate when they are unstable. A smaller deadband requires less of an error to become activated then does a larger deadband. As a longer time is required to accumulate water level error, either through movement of the water or accumulation in the integral term, the oscillations of the unstable controller will become less frequent.) Too high a deadband value will reduce the accuracy to which the controller may adjust the upstream water level.

In order to choose a "moderate" deadband value numerical or field experiments must be performed which monitor the activity of the automatic controller. The deadband value can then be chosen by trial and error.

8.6 EVALUATION OF CONTROLLER FOR USE ON FARM DELIVERIES

The final numerical experiments in this thesis investigate the quality and range of control based on specific parameter settings for the Proportional+ Integral controller (K_p = 2.0, K_i = 2.0, K_d = 0.0, T_r = 1.0, and Deadband = 0.010 m). The parameter which is changed is the Setpoint. The setpoint dictates at what water level the Proportional + Integral controller will attempt to regulate the upstream water surface.

Ten metres upstream of the automatic controller a farm turnout has been installed. Flow through turnouts of this type are dependent on upstream water level, gate opening and downstream water level. In this case it is always assumed that the downstream water level is sufficiently low so as the outlet is always operating in free outlet conditions.

The gate opening of the turnout is initially set to deliver a flow of 0.4 m^3/s. The farm turnout gate opening remains constant throughout the simulation period. Therefore, any changes in flow are a direct result of changes in water level.

Two modes of operation were considered for this analysis. These were the high checking mode and the low checking mode. The water level setpoint for the high checking mode was set to 0.65 m. The low checking setpoint was set to 0.45 m.

Inlet flow types numbers 2, 3 and 4 involve relatively small changes in flow rate (Section 6.2). By reviewing the controllers response in both the high and low checking situations it may be seen that the water deviates negligibly from the desired water level. (Figures 117 to 119, 123 to 125) The flow through the upstream turnout is not affected by the small deviations in water level encountered at the controller. (Figures 129 and 132 to 134) Thus for small deviations in inlet flow conditions the controller can be expected to work equally well in both high and low checking situations.

Large deviations in inlet flow conditions (Run types 5, 6 and 7) produce larger deviations of the actual water level from the desired water level. These deviations are seen in Figures 120, 126, 127 and 128. Changes in upstream water level are not reflected in the flow rate through the farm turnout when high checking is used. (Figure 129) In all cases where low checking is used, upstream water level anomalies cause short changes in flow rate through the farm turnout. (Figures 135, 136 and 137)

In the case of high checking numerical experiments indicated that large deviations from the setpoint would occur if inlet flows similar to types 6 and 7 were used. (Figures 121 and 122). These large deviations are not a result of any automatic controller inability, but rather reflect the physical and hydraulic limits of the structure itself. The large deviations in water level, not surprisingly, have a large effect on the flow through the upstream turnout. (Figures 130 and 131). Using gravity irrigation techniques this fluctuation may be manageable. Using pumped irrigation techniques the pump would likely shutoff. If additional turnouts were placed upstream of the automatic gates, the pumps in these turnouts could quite possibly also shutoff. The direct result of the pump shutdowns would be a large amount of water being wasted either through farm spill or spill through the canal system. This situation could be disastrous for farmer and canal.

The preceding scenario underlines the need to design automatic structures with the complete range of operation in mind. The easiest (and safest) way of accomplishing this is to conduct numerical experiments based on the actual canal dimensions, expected operational and emergency flow rates.

9.0 CONCLUSIONS

The operation of three controllers, namely the Littleman, EL-FLO and the PID controllers were successfully demonstrated using the ICSS 2 model on a single canal system. These three controllers were demonstrated using identical flow conditions but varying the controller parameters. The operation and suitability of the three controllers were then compared (Sections 7 and 8).

The quality of the upstream control was assessed by summing the square of the error between the desired water level and actual water level (e^2 term). Thus the e^2 term gives a quantitative measure of how well the upstream water level is regulated. All of the controllers investigated successfully controlled the upstream water level in varying degrees. All had limitations to their operation. A discussion of the advantages, limitations and possible application of each controller investigated follows.

The Littleman controller has the advantage of being intuitively simple to build and operate. Its operation depends on a cam shaft connected to a float which can engage micro switches which, in turn starts and stops a motor connected to the gates. The limitations of this gate are that the gate continually hunts for the desired water level. If the antihunting device is introduced hunting for the setpoint is eliminated, however the quality of control is poor. Applications for the Littleman controller include areas where water level regulation is not critical and where low technology solutions are appropriated.

The EL-FLO controller has been used to successfully control the upstream water level in the field. Advantages of this controller include the ability to correct for any offset error with the use of the Reset portion of the controller. Limitations include the necessity to carefully select values of proportionality constant K_p for each particular application. Too large a value of K_p can render the controller unable to respond to water level fluctuations, too low a value reduces the response of the controller. Applications for the EL-FLO controller include situations where a high degree of water level control is required over long periods of time.

All Proportional type controls can become unstable if there is not great care taken in selecting values for K_p, K_i, K_d and T_r. No known Proportional type controllers have been tested in the field to date. However, from preliminary investigations in this thesis, all indications are favourable. The Proportional type controllers always converge to the setpoint and will do so over a wide range inlet flow and water level fluctuation conditions. The only instance where this is not the case is with the use of the Proportional + Differential controller. High values of K_d cause severe instabilities. Changing the values of K_d in the lower ranges does not contribute significantly to the controllers operation. It is therefore recommended that the Proportional + Differential controller not be used due to severe instabilities which may be encountered as well as its ineffectiveness when operating in stable conditions.

The Proportional + Integral controller combination was further tested by examining the flow rate through an upstream farm turnout. This controller behaved very well in most cases. Severe changes in turnout flow conditions were found for the high checking example and were a limitation of the structures physical and hydraulic capabilities rather than that of the controllers. When designing an automatic control system these physical and hydraulic characteristics of the control structure must be taken into account for all ranges normal and emergency operations.

Large variations in inlet flow caused short periods of time in which the water delivered to the upstream farm turnout was both more or less than required. The seriousness of these overages or shortages require evaluation on an individual case by case basis.

Although both the EL-FLO controller and the proportional + integral controller both controlled the water level satisfactorily it seems that two differing philosophies motivate the operation of each controller. The EL-FLO controller attempts to control the gate while the P.I.D. controller controls the water level (Section 3.3.5). From the above discussion the selection of the controller parameters K_p and K_i is critical for the EL-FLO controller so as the gate will operate in the proper range, and thus control the water level within the proper limits. Selection of the K_p and K_i paramters for the P.I.D. controller is less critical as any value chosen for which a stable output occurs will change the gate position anywhere within it's range to control the water level directly.

Using the ICSS 2 model, numerical experiments were performed which simulated a range of different controllers, controller settings and inlet flow conditions. As a result the controllers ability to regulate an upstream water level could be evaluated and compared against other controllers. This evaluation and comparison is not only important for the proper selection of a controller, but may be used in the design and actual commissioning of the controller. The ability to simulate an automatically controlled structure can assist in the design in so far as the complete range of expected operations including emergency operations may be simulated and evaluated. Automatic controller simulation may also be used to estimate controller parameter settings resulting in only fine tuning of the controller parameters during commissioning of the automatic controller.

In addition to evaluating the performance of single upstream contollers the possibility of being able to simulate the operation and effects of downstream controllers, systems of automatic controllers and true demand oriented water delivery systems (within the constraints of open channel flow) may all be economically evaluated.

10.0 FUTURE RESEARCH

This thesis is only a preliminary look at the possibilities which may be afforded by simulating the actions of automatic controllers. Although all controllers were able to successfully control the water level, the Proportional type controllers show great promise for the regulation of upstream water surfaces. Further research in the following areas of upstream controllers should be considered in the future:

- Research and development of water level sensing equipment designed to deal with the difficulties of accurately determining the water level.

- Further research into the abilities and limitations of the Proportional + Integral controller using numerical methods.

- Construction of an upstream water level controller prototype to test the actions of the controller as compared to that of the numerical simulation.

In addition to the ability to simulate upstream automatic control systems, great possibilities for use of the ICSS 2 model in the evaluation of downstream controllers, system control and demand oriented system devlopment are possible. Development of control systems in the above areas using the ICSS 2 model will be efficient both in terms of time and economics. Future research into the areas of downstream control are as follows:

- Research and development of suitable downstream control algorithms.

- Research and development of suitable system control algorithms.

- Research and development of demand oriented systems, including the simulation of demands indicative of a particular irrigation district.

- Actual field implementation of downstream, system and demand oriented systems, comparing ICSS 2 predicted system responses to actual system responses.

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