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AUTOMATION OF THE CANAL DE CARTAGENA

BY

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President, Confederacion Hidrografica del Segura
Attention: Sr. Francisco Cabezas Calvo-Rubio
Sr. Jose Luis Nicolas Martinez
Plaza Fontes 1
Murcia 30001
Spain

Subject: U.S.-Spain Cooperative Program on Water Resources Management - Automation Subprogram (Automation)

Dear Sir:

The Automation Subprogram has been primarily involved with the automation of the Canal de Cartagena, which is to serve as a demonstration area for canal automation. As agreed during meetings in Murcia in September 1988, the team members from the United States have prepared the enclosed report of recommendations for the Canal de Cartagena automation. This report was prepared by Mr. David Rogers, Team Leader and Technical Expert for the Automation Subprogram, and Mr. David Ehler, Electronic Engineer.

Because the current agreement for the Cooperative Program on Water Resources Management ends this year, the enclosed report is intended to serve as our final recommendations on the Automation Subprogram. We have attempted to provide complete information so that the automation of the Canal de Cartagena can proceed without requiring our additional involvement. Despite this, we feel very strongly that our continued involvement with the program would be beneficial for the successful implemention of our recommendations. If a new agreement can be reached to extend the program, we will be available for follow-up support for the Canal de Cartagena automation.

Please forward this information to the individuals involved with the Automation Subprogram.

Sincerely,

John D. Smart

John D. Smart, Chief
Civil Engineering Division

Enclosure

bc: Assistant Commissioner - Administration and Liaison, Attention: W-7200 (7062-MIB)(w/encl)
Deputy Assistant Commissioner - Administration
Attention: D-7000 (w/encl)

D-3000 (w/encl), D-3120 (Long)(w/encl), D-3120 (Rogers)(w/encl), D-3750 (w/encl), D-3751 (w/encl), D-3752 (w/encl), D-3752 (Ehler)(w/encl), D-7200 (w/encl)

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March 3, 1989

FINAL REPORT:

AUTOMATION OF THE CANAL DE CARTAGENA

1.0 BACKGROUND

The Canal de Cartagena is serving as a demonstration area for canal automation as part of the Automation Subprogram of the U.S.-Spain Cooperative Program on Water Resources Management. U.S. and Spanish engineers, in conjunction with the Automation Subprogram, have been investigating the automation of the Canal de Cartagena since 1985. Our primary source of information has been a trip to the project site by Bureau engineers in September 1988.

This report contains specific recommendations by Bureau of Reclamation engineers for the operation and control of the Canal de Cartagena, and performance-level specifications for the data collection, communication, and control equipment to be used. These recommendations are based on information obtained between 1985 and the present time and on studies of alternatives performed at the Bureau's Denver Office.

The Canal de Cartagena is a concrete-lined trapezoidal channel approximately 60 kilometers long, with 12 gated check structures and numerous turnouts distributed along its length. The flow capacity ranges from 29 m^3/s at the upstream end to 4 m^3/s at the downstream end. The Canal de Cartagena is one segment of the Tajo-Segura Aqueduct, at the downstream end of the southeastern branch of this larger aqueduct system. A reservoir, Embalse de La Pedrera, is located at the upstream end of the Canal de Cartagena. This reservoir serves as a buffer between the Canal de Cartagena and the rest of the Tajo-Segura Aqueduct, so that short term operations of the Canal de Cartagena are not dependent on the operations of the larger aqueduct system.

Based on our site visit in September 1988, the canal system appears to be well designed and constructed, without any major obstacles to successfully implementing an automatic control system. There are several aspects of the canal which will facilitate and simplify the operation of the system. The following design features will be beneficial to operations:

1. Most of the outflow from the canal through turnouts is delivered by gravity directly into small canal-side reservoirs (balsas). This outflow will be relatively steady and predictable, reducing the amount of flow change in the canal.

2. The canal can withstand relatively rapid drawdown of the water surface without damage. The concrete lining is 15 cm thick on a 1.5:1 side slope and the soil behind the lining is well drained. Spanish engineers stated that the maximum acceptable rate of drawdown during normal operations is 1.5 m in 12 hours, and that the canal could be completely emptied in 12 hours if necessary.

3. Because the Canal de Cartagena is supplied from Embalse de la Pedrera, the canal's supply flow should be flexible and dependable. There should not be any problems with inflexibility, supply shortage, or sudden loss of inflow to the canal. Supply can be a function of the demand, adjusted as needed to satisfy downstream conditions.

4. The check structure spacing is good. The elevation drop between adjacent checks is about one meter or less, and the distance between checks is short enough to allow good control of flow changes.

The following features of the Canal de Cartagena will be detrimental to operations, increasing the difficulty of operating the canal:

1. There will be one major canal-side pumping plant which delivers water from the canal. (Located near station 55700.) A power loss at this plant could create a significant sudden flow change in the canal which must be accommodated in the design.

2. Weeds and silt accumulate in the canal, decreasing its maximum flow capacity. Allowance should be made for up to 20 cm of silt in the canal.

3. There should be no waste of water from the canal. The canal has two wasteways for safety, but operations should be designed for no waste.

2.0 INVESTIGATIONS

A number of alternatives have been evaluated for the operation and control of the Canal de Cartagena. Some of these alternatives were described in our previous report to you, dated August 11, 1988. Using the information gathered during our September 1988 site visit, we have performed more detailed investigations in order to make the best recommendations.

Different operation methods were evaluated first, since a specific control system can only be designed after the method of operation is known. The methods of operation considered were:

1. constant downstream depth,
2. controlled volume, and
3. constant volume.

Control concepts were then studied to determine whether the control responses should be based on conditions upstream or downstream from the control structures. Specific methods of control were analyzed in order to define the functions to be performed by the control system equipment. This included evaluation of local automatic control and supervisory control alternatives. Local manual control, which is the present control method, is not considered to be a feasible alternative for normal operations in the future.

Various hydraulic analyses were performed using three different computer programs. Steady and unsteady flows in the canal were analyzed while testing automatic control software and supervisory manual responses. The computer program USM (Unsteady Model, developed by the Bureau of Reclamation) was used as the primary tool for performing the required hydraulic transient analyses. The performance of automatic control algorithms was analyzed by integrating those algorithms with the transient analysis model. Manual control responses, such as varying depth setpoints to use in-channel storage, were also studied.

The studies considered both normal and abnormal canal operations. In order to be satisfactory, a control system must be stable during typical day to day situations yet responsive enough for sudden flow changes due to emergencies. Testing was therefore performed for both frequent small flow fluctuations and for sudden large flow changes. A severe test for the Canal de Cartagena is a sudden loss of power which causes rejection of turnout flow at the major canal-side pumping plant. The single most difficult control problem will be created when this power loss happens with the canal at full capacity.

A great deal can be learned about the performance of a proposed control system by performing studies such as these, but there are always unknown quantities which prevent all the exact details from being worked out in advance. The exact water use patterns, the size of the balsas, the water level fluctuation in the balsas, and the effect of weeds and silt in the canal are examples of unknowns which must be approximated in preoperation studies of this type.

The effect of these approximations can be minimized by intelligently using the results of analytical studies to compare alternatives. In this way, the best control methods and equipment can be selected without defining all of the details for its future use. Our analyses have shown that the Canal de Cartagena should react to the anticipated operations with responsive and stable control action when using the recommended control system.

The electrical equipment recommendations in section 3.4 below were derived based on the physical aspects of the Canal de Cartagena and the method of control selected. These include the excellent condition of the canal and appurtenances, the terrain, and the requirements of the recommended local control algorithm.

3.0 RECOMMENDATIONS

The following text contains our recommendations for the operation, control, and automation of the Canal de Cartagena. In making these recommendations, we attempted to minimize additions to the existing canal system and to take advantage of those existing features which facilitate operations. The sections which follow include suggested methods of operation and control of the canal, plus performance-level equipment specifications. This information is not intended to be a final specification, but it should serve as a guide for the Spanish engineers responsible for producing the final specifications.

3.1 Operations

The basis of the operation of the Canal de Cartagena is to satisfy the needs of the water users downstream. The amount of water supplied from the Embalse de La Pedrera into the Canal de Cartagena will be based on the projected and actual demands. This goal will be combined with the goal to operate the canal system without wasting any water. Only safety will have a higher priority than these goals.

A secondary goal of the canal operations is to provide flexibility in the delivery of water to the users. The water users will benefit when they can receive water with a minimum of restriction, but some restrictions on the time and quantity of delivery may be required to prevent excessive flow changes in the canal. Advanced scheduling of delivery flows may be necessary if the unrestricted turnout flows create unmanageable fluctuations.

Excessive turnout flow fluctuations do not appear to be a problem for the Canal de Cartagena. With most of the flow being delivered into balsas, it should be relatively easy to balance delivery flows without negatively affecting the water users. The control of delivery flow changes will be most important when the canal flow is near maximum. At low flows, little or no restriction may be required.

We recommend that the method of operation for the Canal de Cartagena be chosen to take advantage of the available in-channel storage without requiring any additional canal lining. This can be accomplished using a simple variation of the constant downstream depth method of operation.

Normally, the depth can remain relatively constant at the downstream end of each canal pool. The water surface profile will pivot about this constant depth point when the flow changes, as shown in figure 1. Our studies have shown that this 'conventional' method of operation will be effective for most situations.

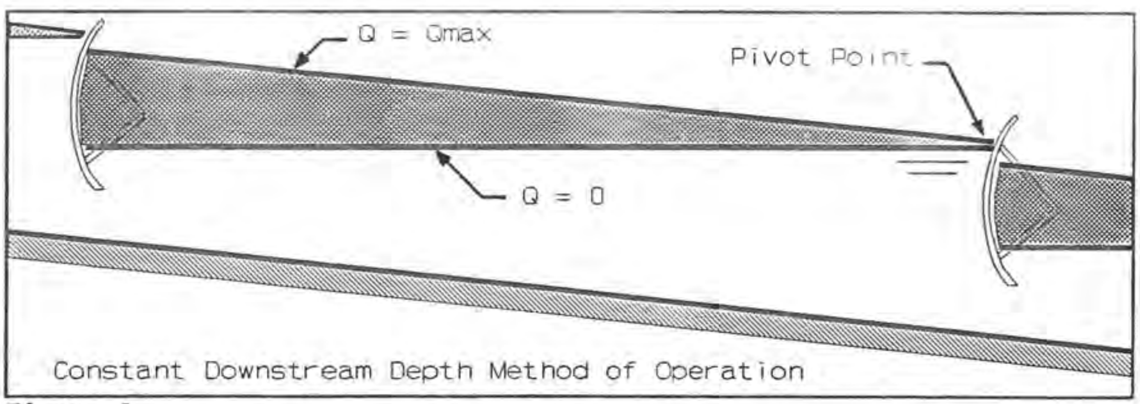

Figure 1

In response to abnormal conditions, the downstream pool depths can be varied to take advantage of storage within the canal prism. Within the limitations of the canal lining height and drawdown criteria, the water depths can be changed to accomplish desired changes in the volume of water stored. Adjusting the volume can prevent waste and minimize flow fluctuations in the canal by absorbing or supplying delivery fluctuations. For example, a sudden decrease of turnout flow could be counteracted by temporarily storing the excess volume of water in the adjacent canal pools. This would be accomplished by allowing the depth at the downstream end of the pools to increase.

Operational storage outside of the canal prism will be available in balsas which have been planned for this purpose. The number, size, and location of these balsas have not yet been finalized, and will be addressed in section 3.3 below. These storage balsas should be able to satisfy longer term flow imbalances than the in-channel storage can accommodate. A terminal balsa at the downstream end of the canal (Balsa T-XIV) should be especially valuable for storing excess canal flow. The canal can therefore be operated to use in-channel storage for short-term imbalances and these balsas for long-term imbalances.

As discussed previously, the supply from the Embalse de La Pedrera into the Canal de Cartagena will be based on the present and predicted needs of the downstream water users. Once this supply has entered the canal, however, we recommend that it is passed downstream by operating the check structures in response to upstream conditions. This upstream operational concept for the check structures is not entirely compatible with the demand-based priorities, but it has the following advantages:

a. The upstream operational concept is compatible with the constant downstream depth method of operation. There is a natural tendency for the water surface to change in the desired direction when the flow changes. This results in more responsive and stable control. (A downstream operational concept is more responsive to downstream demand, but it is less compatible with the constant downstream depth method of operation. For a more detailed explanation, see the previously supplied publication entitled "Operation of Canal Systems", by D.C.Rogers.)

b. The demands should normally be fairly steady and predictable, so that the correct supply from the Embalse de La Pedrera can be predicted accurately. This should minimize the error between the quantity of water supplied and the actual delivery flows.

c. Imbalances between the supply flow and the actual deliveries can be absorbed by using in-channel storage, intermediate balsas, and the terminal balsa. Some imbalance is inevitable, but the availability of these sources of storage will prevent this from being a problem.

d. Control will be simplified but will also be more flexible and stable. Control points can be located adjacent to the check structures, so that the communication distance between sensors and remote controllers is very short. Varying the control setpoints will create a proper and stable control response. (More control details are presented in section 3.2.)

e. The accumulation of weeds and silt in the canal will have a minimal effect on the automatic control. When using the upstream operational concept, the calibration of control parameters will not change as the hydraulic properties of the canal change due to weed and silt buildup. (It would be difficult to maintain proper control parameters in other types of systems.)

The operations recommended here are intended to maximize the benefits to the water users while minimizing costs. Although other methods of operation could also be used, we do not believe that they would be as cost effective.

3.2 Control

We recommend that local automatic control be used for normal operations, with supervisory monitoring. At each of the check structures which is used for control, a canal-side local automatic controller should control the gate to maintain a desired (setpoint) depth upstream from the gate. The controllers should have the ability to perform their canal control function without communications with the master station. Upon loss of power, gates should remain in their current position until power is restored. When power is restored, the controllers should be able to reinitialize and then resume normal automatic control.

The local automatic controllers will use internal logic, commonly called an algorithm, to calculate a gate position based on input data from the water depth sensor. Based on our analysis, we recommend an algorithm with proportional and integral components. This algorithm has been used successfully for canal control in the United States under the name Proportional + Proportional Reset (P+PR). It is described in detail in the enclosed technical report entitled "Study of an Automatic Upstream Control System for Canals".

The P+PR control algorithm has several adjustable control parameters which allow it to be customized for each particular application. Initial values for these parameters are listed below, values which we have determined will provide good control on the Canal de Cartagena based on our analyses. These values should be further refined after control system installation, based on actual operations.

PARAMETER	DESCRIPTION	INITIAL VALUE
K1	Proportional controller gain	2.0 (dimensionless)
K2	Reset controller gain	0.01 (seconds^{-1})
TC	Filter time constant	200 (seconds)
GDB	Gate movement deadband	0.03 (meters)
RDB	Reset controller deadband	0.03 (meters)
YT	Target depth (setpoint)	**

** Target depths will be variable, but typically will be set near the normal depth for the maximum design flow at each specific check site.

In addition to the above-described P+PR control algorithm, the local automatic controllers should be capable of executing gate position setpoint control. This will allow a target gate position to be input rather than a target water depth, so that the controller will position the gate to the target gate opening value regardless of water depth.

Supervisory monitoring and control should also be provided for the Canal de Cartagena. A master station should serve as the center of supervisory control. During our site visit in September 1988, we discussed locating the master station near the Embalse de La Pedrera initially, with the ultimate location being in Murcia.

We recommend comprehensive monitoring of data from the master station, including water depths, gate positions, flow (where measured or calculated), pump on/off status, gate control mode (P+PR or gate position setpoint), setpoint values, and all other controller parameters. In addition, alarms should be provided at the master station for abnormal conditions. Example alarm conditions are high and low water levels, a gate not moving as commanded, pump failure, entry of building and loss of communication.

Various levels of control from the master station are possible. Initially, this should take the form of manual supervisory adjustments and override of the local automatic controllers. When abnormal situations arise on the canal, an operator at the master station will be able to assume control. One option will be for the operator to change the depth setpoint for the local automatic controller, to create a desired volume change as discussed in section 3.1. The controller can remain in the P+PR mode so that the operator involvement is minimized.

Changing the depth setpoint will trigger an immediate control response unless the change is smaller than the depth deadband. As an example, assume that there is a sudden turnout flow decrease. This will cause the depths in the adjacent canal to rise due to the excess flow in the canal. Normally, the local controllers will open the gates downstream from the turnout, returning the canal depths to the target and passing the excess flow downstream. Raising the depth setpoints in the vicinity of the turnout will allow excess water to be temporarily stored in the canal instead of being passed downstream. At each check where the setpoint is raised, the controller will start closing the gate until the water rises to the new setpoint.

Our studies have shown that this technique can be effective to absorb or supply short term flow imbalances. By changing the setpoint at several checks, excess flow problems can be avoided for about one hour. If there is still an imbalance beyond that time, water can be diverted to or from the storage balsas until the effect of a change in supply flow from Embalse de La Pedrera reaches the affected points downstream.

Another option for canal operators at the master station will be to switch the local controllers to gate setpoint control and specify new gate positions directly. This will produce even quicker response for severe conditions.

Manual supervisory control should be used for the supply flow from the Embalse de La Pedrera. Normally, a supply schedule can be based on the predicted and/or scheduled deliveries. Software can be developed to calculate this supply schedule, simplifying the operator decisions. Occasionally, it may be desirable to make adjustments to the scheduled supply flow based on actual conditions in the canal system downstream. Supply control decisions should be based on the entire canal system, not just on information from a single point.

Supervisory control during emergencies should be based on predefined emergency control procedures. These procedures should be worked out in advance by studying as many potential scenarios as possible. The optimum control actions can then be available to canal operators when an emergency arises. Control sequences could also be preprogrammed for rapid execution on the command of a canal operator.

Supervisory manual control could be used for major turnouts if desired. This would be most feasible for gravity turnouts into canal-side balsas. Control of these turnouts from the master station would improve the flow balance and increase the operational flexibility of the canal system. Turnouts which do not feed balsas should be controlled based on downstream conditions in the delivery network.

3.3 Structural and Mechanical

Small canal-side reservoirs, or balsas, are planned for the Canal de Cartagena to provide regulatory storage. As discussed previously, these balsas will improve the canal operations by storing excess water and by providing an additional supply to prevent shortages. The benefits received from the balsas will be a function of their number, location, and size.

The most critical need for additional storage will occur when there is a sudden turnout flow decrease, such as a power failure at the canal-side pumping plants. An existing pumping plant located near station 41000 is to be converted to deliver 1.5 m^3/s to a new balsa (T-IV-V). The future turnout pumping plant near station 55700 is projected to deliver a maximum flow of 4.64 m^3/s. A power failure could therefore create a turnout flow reduction of 6.14 m^3/s, and this same amount of excess canal flow until power is restored or a flow correction from the Embalse de La Pedrera has time to traverse the length of the canal. Some of the excess canal flow can be stored in the canal, but most of the excess will need to be stored in balsas. Approximately 90,000 m^3 of total operational storage in balsas will be required in order to avoid any waste during this situation. ('Operational storage' meaning the volume which is available above the minimum static water level.) This storage volume could be distributed among two or more of the proposed balsa locations.

The terminal balsa (T-XIV), at the downstream end of the Canal de Cartagena, will be particularly valuable for storing excess water. Minor discrepancies between inflow and outflow throughout the length of the canal will eventually end up at the downstream end. Without this terminal balsa, these discrepancies could become a problem at the canal end. Therefore, a large amount of storage at the terminus will be very beneficial. We recommend that 30000 m^3 to 50000 m^3 of operational storage volume be provided at terminal balsa T-XIV.

When the large pumping plant near station 55700 shuts down suddenly, much of the excess canal flow can be passed to the terminal balsa. To avoid exceeding the carrying capacity of the canal downstream from the pumping plant, however, some flow should be diverted to one or more balsas upstream from the pumping plant. At least 30000 m^3 of balsa storage volume should be provided upstream from the plant. Ideally, a balsa should be located as near to the large pumping plant as possible. Of the previously proposed balsa locations, balsa T-VIII-IX would best meet this need.

It will probably be many years before the canal operates at the maximum design flow. Until it does, less regulatory storage will be required than the total of 90000 m^3 recommended above. Balsa T-XIV and balsa T-VIII-IX could be constructed initially and the construction of other balsas postponed until they are needed. The need for additional balsas could then be based on operational experience instead of projections.

Sudden turnout flow increases should not present problems. Unlike the uncontrolled turnout flow decreases caused by power failure, the rate of turnout flow increase can be limited. The combination of in-channel storage and balsa storage should be able to meet demand increases and avoid shortages without causing excessive drawdown in canal water levels.

Diversion of water from the canal into the balsas must be dependable, especially during power failures when it will be needed most. We recommend that water flow from the canal into each balsa by gravity if the topography allows it. Return flows from the balsas back into the canal would need to be pumped when power is available. The terminal balsa should be fed by gravity, because there will not normally be any return flow. If water must be pumped from the canal into a balsa, backup power will be required if that balsa's storage is to be used during a power loss.

The existing Canal de Cartagena conveyance channel should not require any modifications to meet system operational needs. The canal lining freeboard is adequate to contain all maximum flow depths that should occur. As discussed previously, in-channel storage can be used to improve operations. This will take advantage of excess storage that is available in the canal by occasionally raising the water level above the normal flow depth. Although this may sometimes reduce the amount of freeboard above the water surface, no additional canal lining or embankment will be required.

The existing check structures appear to be adequate for controlling the canal system. It is possible that some of the gate motors may not be well suited to the frequent gate movements required by an automatic control system. These can be replaced with motors with a higher duty cycle when and if it becomes necessary. The gate motors normally require power from the AC main power supply. For critical sites, a motor generator set with automatic start may be desirable to allow operation of the gates with loss of primary AC power.

The location and spacing of the existing check structures is good. One additional gated check structure is recommended in the Canal de Cartagena downstream from the branch to the Canal de La Pedrera, near station 9000 (9 kilometers downstream from Embalse de La Pedrera). This will divide one long pool into two shorter pools, improving operations and decreasing depth fluctuations in this area. It will also help to insure a sufficient water depth for supplying the Canal de La Pedrera. There has apparently been a submerged weir near this location in the Canal de Cartagena which is being removed.

3.4 Electrical Equipment

The RTU (Remote Terminal Unit) and master station equipment and software must provide the man-machine interface, display of all canal parameters, monitoring and logging of the system variables, limit checking to provide failure alarms, control algorithm, mode of control, and communications. This system must include the monitoring of water levels, gate positions, and control algorithm parameters, plus both manual and automatic control of the canal check structures. Contact alarms such as high and low water, loss of power, and illegal entry are also recommended. The system described below provides for all the required tasks. Because it is modular in both hardware and software, it also provides for expansion and future developments.

3.4.1 Master Station Equipment. - The VAX master stations should be able to accommodate the remote terminal units and provide the man-machine interface. This will require an analysis of the present utilization of the VAX machines and determination if the new requirements are compatible with the existing communication and VAX systems. New VAX machines can be acquired if the existing VAX computer network is unable to satisfactorily perform the new supervisory control tasks.

The master station must provide display, data manipulation and storage, control, alarms, and communication. In addition, there are many background tasks that may be desirable such as recordkeeping, scheduling, analysis, and other data base applications. A number of manufacturers in the United States have incorporated the Digital Equipment Corporation VAX computers as a master station in their canal control systems.

The specific tasks to be performed by the master station include:

a. Communications message formatting, interpreting, and error checking for the packet protocol. This should include a function which checks for loss of communications and deteriorating communications (unable to receive or verify transmitted messages).

b. Maintaining a database, logging, limit checking, and alarming of telemetered data.

c. Control of the remote terminal units including parameter changes, mode control, and gate position control.

3.4.2 Remote Terminal Units (RTU). - Intelligent, microprocessor or computer-based remote terminal units are required to provide the power for a 'stand alone' control capability and the communications protocol. Various input/output systems are available to interface the microprocessor system to the telemetry, alarm, and control parameters. Intelligent RTUs can easily be reprogrammed and expanded to meet future needs.

The minimum instrumentation configuration for the P+PR control algorithm requires inputs for water level, gate position, and gate control. Other desirable inputs for canal automation include power failure, intrusion alarms, and high and low water level sensors. Other parameters such as turnout flow, reservoir levels, and weather data can also be included. RTUs are required for all check structures and suggested for the Embalse de La Pedrera, the pumping plant near station 55700, and any other structures on the canal which impact the flow. These sites might include the major storage reservoirs along the canal.

The check sites will require motor operated gates and electric power. The existing checks appear to meet these requirements, so the upgrade to automated checks should not require extensive modifications. The RTUs should use a battery operated power supply and charger. This configuration allows continued monitoring in the event of the loss of primary power.

The RTU hardware includes a radio transmitter and receiver, modem, power supply and batteries, remote computer, and an interface for the various outputs and transducer inputs. Each RTU should be equipped with transient protection hardware such as a Radio Frequency (RF) filter and Metal Oxide Varistor (MOV), and should be installed in durable and weather-proof structure. The remote computer should be modular and serviceable at the card level.

Setpoints, control parameters, and other variables should be stored in random access memory (RAM). The basic system parameters and the local control program should be stored in read-only memory (ROM), to allow reloading of this information if it is lost from RAM. Another option is to download this information from the master station instead of from ROM's, but this could create a problem if a reload is needed when communications are lost.

The RTUs should have stored programs for remote gate setpoint control, P+PR control, mode change, and parameter modification, as well as communications, telemetry, and remote parameter adjustment. Each RTU should be capable of operating independently if communications are lost. They should be battery operated to provide alarms and telemetry during the loss of primary power.

The RTUs should be microprocessor based with modular software. FORTRAN77 is suggested for most of the modular software programming. This software should include memory checking routines to detect undesirable changes in RAM content. Software should provide remote canal side operation in the P+PR mode, communications with the master station, full telemetry with failure diagnosis, and remote control. Failure diagnostics should include parameter checking, component checking such as loss of analog signals, and peripheral equipment failure (for example "gate did not operate"). STD Bus products have worked well for these applications. (STD Bus is a card-level communication system developed by Pro-Log Corporation and supported by numerous manufacturers.)

The following considerations should be included when specifying the RTU:

a. Battery-backed Random Access Memory (RAM). - The RAM should have battery backup to retain information through intermittent power fluctuations or transients.

b. Battery operation with battery charger. - The RTUs should run on battery power, with charging from the AC main power supply or from solar panels.

c. Software checks to assure the validity of the contents of RAM. - The software should include a check of RAM contents. This check should verify that the contents have not been damaged by electrical transients, RAM failure or other such error. This should be a two parameter check that calculates a check sum and a second parameter to verify RAM accuracy.

d. Modular software to ease software modifications. - Remote software should be modular to allow easy modification or expansion in the future. A separate module should be used for each major function, such as the communications driver, analog input, control algorithm, gate control, etc. There should also be a software module to provide error and limit checking on the telemetered quantities. This routine should detect rapid changes in the telemetered quantities and check for values out of the expected range of the variable. Indication should also be given for variables out of limits set by the operator.

   The control program should contain a Proportional+Integral (PI) algorithm, such as the P+PR algorithm discussed in section 3.2. This algorithm uses the water level as input and calculates a desired gate position. It should include an input filter to filter out short-term disturbances in the water level, such as wind waves. A closed loop gate positioning routine should also be provided to position the gate based on the algorithm when in the automatic mode or based on the gate position setpoint when in the remote control mode. All of the basic parameters for the PI algorithm should be modifiable from the master station.

e. Lightning and transient protection on all power and signal inputs. - The RTU hardware should include transient and RF protection on all conductors coming in or going out of the enclosure including power, radio, analog and digital inputs and control outputs.

f. Provision for both automatic and remote manual control modes. - The automatic mode should calculate gate position based on the upstream water level using the P+PR algorithm, then pass the gate position to the gate control algorithm which operates the gate(s). The manual mode should set the gate to a specified gate position when first placed in the gate control mode, then allow the gate position to be set from the master station. The gate algorithm should operate the gate while monitoring the gate position. The software should then stop the gate, making allowances for overshoot and/or coasting. The gates must be provided with operators designed for automatic operation and reversing starters. Mechanical and software interlocks are required to prevent operating the gates in the wrong direction or before they have stopped. A position indicating sensor is required to provide the algorithm and the telemetry with gate position.

3.4.3 **Interface Equipment.** - The Bureau of Reclamation has used both analog and digital components for input of gate position and water level. Mechanical analog systems, typically consisting of a directly driven potentiometer attached to an intermediate gate shaft or float assembly, have proven very reliable. The new digital devices are also being specified, but in our earlier systems these devices were not reliable.

3.4.4 **Communications.** - Because of the terrain and the existing radio system, a radio communications network is suggested for the Canal de Cartagena. The new control communications network can be designed to use the existing VAX radio communication system. If the increased data traffic can not be tolerated, a separate network can be installed at a later date. A hard-wired system was not considered because of the terrain and the difficult installation on an existing project. Other communications systems, such as satellite or meteor burst, are not applicable due to the need for real time control, and the frequency of updating data and alarms.

Packet message techniques should be used for data communications. Packet is fast and efficient and includes message verification and error checking to assure that all data are received and are error free.

The following items should be considered in evaluating the existing radio network for use in operating the supervisory control and data acquisition system:

a. The number of new sites added to the system,

b. The update time desired for the system,

c. The present utilization of the system,

d. The amount of data required from each RTU,

e. The method of data update, whether by exception or all variable data. (Note: Update by exception can burden the system at critical times with numerous data changes.)

Radio communications should use a poll from the master to interrogate the remote terminal units. Major alarms should be by interrupt from the RTU.

3.4.5 General Comments. - Two examples of technical and performance level specifications are attached to further illustrate our electrical equipment recommendations. These examples include the most current control equipment specifications and algorithms for Bureau of Reclamation facilities. They incorporate many of our recommendations, and should provide additional ideas and sample specifications paragraphs for the automation of the Canal de Cartagena.

Attachment 1 contains specifications for the West Oakes Test Area Programmable Master Supervisory Control System. This control system is comprised of a master station and 7 RTU's, to control a canal system which includes pumping plants and gated check structures.

Attachment 2 contains specifications for the Programmable Master Supervisory Control System for the Dolores Project, a canal system which includes check structures, pumping plants, and a powerplant. This control system will include a master station and 90 RTU's, 49 of which are provided under this specification.

3.5 Summary of Recommendations

The above recommendations can be summarized as follows:

1. Operations

   a. Constant downstream depth method of operation for normal operations. Vary downstream depth to use in-channel storage for short-term flow imbalances, and use operational storage in balsas for longer-term imbalances.

   b. Use prediction and schedules to base the canal supply from Embalse de La Pedrera on the anticipated demands.

   c. Operate check structures using an upstream operational concept, moving gates so as to maintain the desired depth in the canal just upstream from each check.

2. Control

   a. Local automatic control of canal check gates for normal operations.

   b. Controllers to use a proportional plus integral algorithm (P+PR) to maintain a setpoint depth upstream from each check structure. Also provide gate position setpoint control.

   c. Supervisory monitoring of system status from a central station. Supervisory control for abnormal and emergency operations.

3. Structural and Mechanical

   a. Terminal balsa T-XIV to have 30000 - 50000 m^3 of operational storage. Balsa T-VIII-IX, or other balsa(s) near that location, to have 30000 m^3 of storage. Total operational storage in balsas of approximately 90000 m^3 required to prevent any waste during emergency operations at full canal flow.

   b. One additional check structure is needed, approximately at station 9000, instead of existing submerged weir.

4. Electrical

   a. Intelligent, microprocessor-based RTUs, to provide local automatic control, telemetry, and communications for each control point.

   b. Radio based communications using packet techniques and the existing radio network.

   c. Use of the existing VAX system for the master station.

4.0 FUTURE CONSIDERATIONS

The recommendations contained within this report deal with conditions which are presently known or anticipated for the Canal de Cartagena. As more details on the operating canal system are known, our recommendations can be refined. It is possible that future conditions may justify additional features or control capabilities beyond those which we have proposed in this report. We recommend that the additional expense of any additional features be delayed until it is certain that they are necessary.

Initially, top priority should be given to getting all the basic parts of the control system working correctly. This includes assuring that all of the communication, computer, and other electrical components are compatible, so as to function properly after the entire system is assembled. Most of the problems with a new control system will be caused by failures of the system to perform as intended, rather than by shortcomings in the design.

After the control system has been successfully put into operation, it will be possible to refine some of the control details. For example, startup values such as the controller parameters in section 3.2 may require additional calibration during the beginning stages of operation. This type of refinement will be beneficial in the future to help "fine-tune" the control system, and will become more important as the total flow in the system increases towards maximum capacity.

As future needs dictate, modifications to our proposed methods of operation and control may be warranted. If the depth or flow fluctuations in the canal become excessive, delivery flows may have to be scheduled to achieve a better flow balance. Alternatively, control improvements could be made by adding supervisory control software.

It is impractical to develop comprehensive supervisory control software in advance of the installation of the control system. If this were done, much of what is developed will need to be changed or replaced after all of the operational details are more clearly defined. Supervisory control software should be developed during operation, based on the working canal system, so that automatic responses can gradually replace manual control from the master station.

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