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ABSTRACT

The Central Arizona Project (CAP) is designed to bring about 1.85 billion cubic meters (1.5 million acre-feet) of Colorado River water per year to Maricopa, Pima, and Pinal counties in Arizona. The CAP canal system is a 540-km (336-mile) long system of conveyance aqueducts, tunnels, pumping plants, and pipelines that is monitored and remotely controlled using Supervisory Control and Data Acquisition (SCADA) software from CAP headquarters in Phoenix, AZ. Because the CAP is crucial to the renewable water supply in Arizona, operating the canal effectively is of utmost importance. Typical day-to-day operations for Water System Operators on the CAP involve efficiently conveying water through the system while meeting water orders from the various customers along the canal. The Water System Operators are also expected to respond to emergency conditions while protecting the infrastructure in the canal and minimizing interruptions to the water orders. Since day-to-day operations do not adequately prepare Water System Operators for emergency conditions, CAP has utilized a unique training tool that replaces the real canal with a hydraulic simulation model without requiring any modifications to the existing SCADA setup. Using this training tool, the new Water System Operators can now be trained to operate the CAP canal system under a much wider range of flow conditions and emergency situations without endangering the actual canal system, wasting water, or interrupting water orders. The training tool gives the Water System Operators a larger knowledge base with which to handle emergency situations and conveys experience and institutional knowledge to new Water System Operators.

Keywords: Irrigation systems, canal and diversion structures, canal management, operator training

1. INTRODUCTION

1.1. The Central Arizona Project

The Central Arizona Project (CAP) is Arizona’s largest renewable water supply and was constructed to help the state conserve its groundwater by importing surface water from the Colorado River. CAP was designed to deliver an average of 1.85 billion cubic meters (1.5 million acre-feet) of water per year to residents of Maricopa, Pima, and Pinal counties (see Figure 1), making it a critical economic lynchpin for the region. CAP delivers untreated water to three major types of customers: municipal and industrial, agricultural, and Native American users. The customers are then responsible for their own water treatment. The CAP canal travels 540 km (336 miles) across the state of Arizona. The canal begins at Lake Havasu, continues through the Phoenix metropolitan area, and ends in Tucson. CAP consists of 14 pumping plants, 1 pump/generating plant, 10 siphons, 3 tunnels, and more than 45 turnouts for customer deliveries. During its travels across the state of Arizona, water is pumped more than 850 vertical meters (2,800 vertical feet) and flows through the canal via gravity following the natural contours of the land. Construction of the system began in 1973 and was substantially complete in 1993.
1.2. Central Arizona Project’s Control Center

The entire CAP canal system is remotely monitored and controlled via a Supervisory Control and Data Acquisition (SCADA) system from CAP’s Control Center, located at CAP headquarters in Phoenix, AZ. Real-time data from the CAP canal system is transmitted to the CAP’s headquarters and displayed on various computer screens (a typical SCADA screen is shown in Figure 2). Information displayed includes water levels in the various pools, gate positions, flow rate estimates through structures, turnout deliveries, and pump status (e.g., on, off, or failed). There are more than 1,000 real-time SCADA displays that the operators can use to assist in the operation of the system. At any given time, 30 million cubic meters (8 billion gallons) of water are managed from the Control Center, which is staffed by at least 2 Water System Operators 24 hours a day, 7 days a week.

The main goal of the CAP Water System Operators is to effectively route flow changes through the canal system in order to meet customer demands without causing fluctuations in water levels that could disrupt service to other customers or potentially overtop and damage the canal. The Water System Operators have various tools at their disposal with which to operate the canal system. The Water System Operators can

- Turn pumps on or off;
- Move gates up or down; and
- Change customer deliveries
2. COMPLEXITIES IN OPERATING OPEN-CHANNEL SYSTEMS

Initially, operating an open-channel system like the CAP canal system may appear to be fairly straightforward because, for any pool in the system, the inflow into the pool equals the outflow from the pool plus the change in storage volume over time. However, there are many aspects of open-channel flow that make the operation of the system more difficult than it first seems:

- Operators must handle unscheduled changes in demand, which can arise from check structure failures, pump failures, vandalism, or other emergency situations.
- Operators must deal with safety concerns. Obviously, overtopping the canal can cause serious damage to the canal system. In addition, lowering the water surface too quickly can cause structural damage to the canal lining.
- Operators must deal with the uncertainties inherent in the canal system. Regardless of the measurement method used, there will always be uncertainty associated with various properties of the system, such as flow rate, stage, and roughness. In addition, some of these properties, such as canal roughness, can change with time (e.g., weeds or algae can grow in the summer, changing the roughness of the canal). If left unaccounted for, these uncertainties cause the water deliveries to be different than desired.
- Operators must deal with transient effects that characterize unsteady flow, such as delay times, dispersion effects, changes in storage volume, and hydraulic interactions between the pools.
- Operators must rely on experience to effectively operate an open-channel system. Even after learning how to manage the canal on a day-to-day basis, operators may not be able to handle emergency situations effectively because these scenarios were never addressed in their training.

Because of the importance, difficulty, and complexity of operating an open-channel canal system like CAP, Water System Operators require a significant amount of training before they can effectively manage the system.
2.1. SCADA Systems and Open-Channel Systems

SCADA systems are very popular in manufacturing plants and municipal water delivery systems. In recent years, SCADA systems have become more popular with irrigation districts. Currently, there are several irrigation districts that use a SCADA system to monitor and control their open-channel systems. A few of the irrigation districts with SCADA systems include the Central Arizona Project, the Salt River Project, the Imperial Irrigation District, the Maricopa-Stanfield Irrigation and Drainage District, and the Central Arizona Irrigation and Drainage District.

2.2. SCADA Training at the Central Arizona Project

Typically, new Water System Operators at CAP are required to complete up to 18 months of training and supervision before they are allowed to operate the canal system independently. Even after this training period is complete, the Water System Operators’ training will have been limited to day-to-day operations. The newly trained Water System Operators will have little experience operating the canal under a wide range of flow conditions. The new operators will also have little training on how to operate the canal under emergency conditions, since setting up a real-world emergency training scenario would put the canal system at risk or interrupt water deliveries.

2.3. Additional Difficulties with SCADA Training

Strand et al. (2005) lists several problems associated with the SCADA training at typical irrigation districts. Some of these issues do not apply to the CAP Canal but are common in smaller irrigation districts. These problems are summarized in the following paragraphs.

First, the Water System Operators employed by many irrigation districts can come from a wide variety of backgrounds and have varying levels of canal experience. For example, at the Salt River Project (SRP), a very large organization, operators generally work their way through the hierarchy of the canal operations system. Most start as a zanjero (i.e., someone who patrols irrigation ditches and opens canal gates to deliver water) and eventually work their way to the control room. Through this experience, they gain working knowledge of system topology, pool transmission delays, problem check structures, etc. This knowledge is invaluable once they are in the control room. While smaller organizations do promote some field operators, or zanjeros, to SCADA operator positions, these smaller districts are sometimes forced to hire SCADA operators with little or no canal operation experience.

Second, regardless of the level of applicable canal experience, the learning curve for a SCADA system can be quite steep, especially for an operator with limited computer experience. Many operators require some training to gain familiarity with a networked computer environment as well as managing other duties in conjunction with operating the canal.

Finally, SCADA operators are also trained in a “live” environment while operating a real canal. At CAP and SRP, the environment is generally focused on running the canal system on a day-to-day basis. There are separate departments that handle ordering, billing, and payment receipts. At smaller irrigation districts, like the Central Arizona Irrigation and Drainage District (CAIDD), the canal operators handle all of those financial/clerical tasks in addition to operating the canal. For those with little or no canal experience, the distraction of dealing with the business functions can be overwhelming and can hinder progress in understanding the canal system from an operational perspective.

3. SCADA TRAINING TOOL FOR CAP

Effective operation of the canal system is imperative at CAP from both a safety aspect and a customer satisfaction aspect. Water System Operators must learn how to efficiently utilize the tools at their disposal in order to effectively route water to their customers. In an effort to have more robust training of their Water System Operators, CAP commissioned the development of a training tool that allows their Water System Operators to be trained on a hydraulic model of the canal instead of the real canal. In essence, the simulation tool would act like a flight
simulator does in training pilots. Using this training system, Water System Operators can be trained to operate a canal system under a wide range of flow conditions, including emergency situations, without endangering the actual canal system, interrupting customer deliveries, or wasting water. This training tool was developed for Segment 2 of the CAP canal system, which stretches 100 km (62 miles) from the Little Harquahala pumping plant to the Hassayampa pumping plant (see Figure 1).

### 3.1. SCADA Training with Hydraulic Simulation

In the past, researchers at the U.S. Arid Land Agricultural Research Center (ALARC) created a training tool that replaces the real canal with a hydraulic simulation model (SOBEK) without requiring any modifications to the existing SCADA set up. Employees at WEST Consultants, Inc. modified this training tool so that it works with HEC-RAS as the hydraulic simulation model. The training tool is composed of five main components:

- a SCADA system;
- a hydraulic model of the canal system and the HEC-RAS computer program;
- an intermediate software package (SimSuite) that emulates field hardware and maintains physical information such as gate positions, water levels, and turnout flows;
- an External Data Interface (WEST-EDI) software package that communicates between the hydraulic and intermediate software package; and
- a proctor software program (SimProctor) used to assist in the training of the Water System Operators.

In a typical set up for Water System Operator training, the SCADA system would be installed on one computer (i.e., the Trainee Computer) while the hydraulic model, SimSuite, SimProctor, and WEST-EDI would be installed on a second computer (i.e., the Proctor Computer) as shown in Figure 3. The two computers are then connected using a serial cable. Setting the training tool up in this manner isolates the SCADA system from the rest of the training tool. In addition, setting the training tool up in this manner does not allow the training tool to make changes to the actual canal system (i.e., the training tool is “offline”).

Water System Operator trainees can be given tasks to route flows through the system or respond to emergencies using the SCADA system on the Trainee Computer. Using the Proctor Computer, the proctor can observe the effectiveness with which the trainees perform the tasks. In addition, the SimProctor program can be used to make unexpected or emergency changes to the system that the trainees must respond to in an effective manner (e.g., change offtake flows, freeze gates, fail pumps, etc.). If the trainees do not perform satisfactorily on a given test, the entire system can be reset, and the scenario can be repeated until the trainee’s performance improves. All of this is accomplished without endangering the real canal system, interrupting customer deliveries, or wasting water.
3.2. CAP SCADA System

In this application for CAP, the decision was made to re-create the SCADA screens on a completely separate computer system that was not connected to CAP’s local area network or the internet. Since only Segment 2 was being analyzed, the re-development of the SCADA screens was not difficult or time consuming. The newly developed SCADA screens for Segment 2 of the CAP canal system were almost identical to the screens being used by the CAP operators at the time. Separate SCADA screens were developed for:

- Check structures 5 through 13;
- Havasu pumping station;
- Little Harquahala pumping station;
- Hassayampa pumping station;
- Vidler turnout;
- Harquahala turnout;
- Tonopah turnout;
- Tonopah Desert Recharge (TDR) turnout; and
- Western Maricopa Combine (WMC) turnout.

Figure 4 shows a Google Earth image of Segment 2 with the pumping plants and check structures labelled. The turnouts mentioned in the list above are typically just upstream of a check structure. In Segment 2, all check structures consist of two radial gates (a typical check structure can be seen in Figure 6). Trainees have the ability to change the gate positions for each gate individually at each check structure as well as the flow deliveries at each turnout. In addition, trainees can turn each individual pump on and off at each pumping plant (the Hassayampa Pumping Plant is shown in Figure 5). For definition, pump control refers to whether a pump is on or off (as set by the trainees). Pump status refers to whether a pump is nominal (can be turned on or off) or failed. While the pump control is set by trainees from the SCADA screens, the pump status is set by the proctor through the SimProctor program.
Figure 4. Google Earth image of Segment 2 of the CAP Canal

Figure 5. Hassayampa Pumping Plant
3.3. Hydraulic Simulator and Model

The hydraulic simulator for the SCADA training tool is HEC-RAS v. 4.1, which is an unsteady hydraulic simulator developed by the Hydrologic Engineering Center of the U.S. Army Corps of Engineers. HEC-RAS is designed to perform one-dimensional hydraulic calculations for a full network of natural and constructed channels (note that the recently released HEC-RAS v. 5.0 can also perform two-dimensional hydraulic simulations). An unsteady HEC-RAS model was created for Segment 2 of the CAP canal. This unsteady hydraulic model was the most important component of the training tool. If the hydraulic model does not accurately predict water levels for various changes in gate position, turnout flow, or pumping, then the training tool will not be effective because the hydraulic responses that the trainees learn from the training tool will not be the same as those found in the real world. To assure that the hydraulic model was correct, the CAP’s custom calibrations for the radial gates were coded into HEC-RAS using the Rules internal boundary conditions. The roughness coefficient for the canal was chosen based on recommendations from CAP personnel. The final hydraulic model for Segment 2 was approximately 100 km (62 miles), and it consisted of 3 pumping stations, 9 radial gate check structures, 5 turnouts, 3 siphons, and one tunnel.
3.4. SimSuite

The SCADA training tool also requires an intermediate software package that emulates the Remote Terminal Unit (RTU) or Programmable Logic Controller (PLC), its associated sensors and relays, and the gate motor. In the real system, RTUs pass canal information (e.g., gate positions, water levels, etc.) to the SCADA system via some sort of radio system. The RTUs also take commands from the SCADA system (e.g., changes in gate position) and implement those commands in the field. In the training tool, the SimSuite program acts as a virtual RTU that gathers information from the HEC-RAS model (e.g., gate positions, water levels, etc.) and passes it to the SCADA system. Likewise, commands from the SCADA system (e.g., changes in gate position) are sent to the virtual RTU in SimSuite, and these commands are then passed on to the HEC-RAS model. Perturbations such as noise, a stuck gate, or a failed pump can be introduced into SimSuite through SimProctor and transmitted to the SCADA system. This software was written by ALARC employees for their applications and was used unchanged here.

3.5. SimProctor

The SimProctor program is used to observe the canal model status from the Proctor Computer. Using this program, the proctor or supervisor can observe the following:

- water levels of the various pools in the canal system;
- gate positions at the various check structures;
- control of each individual pump;
- status of each individual pump; and
- flow rate through each check structure, turnout, and pump station.

The proctor also has the ability to

- change the gate positions for each gate;
- fail any gate;
- change the flow rate at each turnout;
- change the control for each pump (i.e., turn the pumps on or off); and
- change the status of each pump (i.e., change the status from nominal to fail).

Note that there is no indication on the SCADA screens that the gate has failed; the gate simply does not move to the requested position. When a pump fails, it is displayed as orange on the SCADA system.

3.6. WEST-EDI

In the application described by Strand et al. (2005), MATLAB was used as the interface from SimSuite to the unsteady flow simulation software. Since a connection between MATLAB and HEC-RAS does not exist, the WEST-External Data Interface (EDI) program was developed to connect HEC-RAS to SimSuite. The function of the WEST-EDI program is to pull information (e.g., water levels, gate positions, etc.) from the HEC-RAS program and then pass it to the SimSuite program. Also, commands from the SCADA system are passed to the WEST-EDI program via SimSuite. These commands are then passed to HEC-RAS. A screen shot of the WEST-EDI program is shown in Figure 7.

4. SCENARIO DEVELOPMENT

Initially, three basic flow scenarios were developed along with the training tool for CAP: a high flow condition, a medium flow condition, and a low flow condition. All three of these scenarios start out with the water levels near typical operating levels. Once the training tool has started, trainees must operate the SCADA system to effectively route flow changes through the hydraulic model of Segment 2 while also responding to uncertainties and
emergencies that cause the water levels to deviate. In using these basic scenarios, personnel at CAP have indicated that the hydraulic model responds to flow changes in a similar manner to the real system. Obviously, these three basic flow scenarios were not sufficient to effectively train their Water System Operators over a wide range of flow conditions. Thus, CAP developed a test bank of ten scenarios that their Water System Operator trainees must pass before they are allowed to operate the canal system independently. This test bank of flow scenarios covered a wide range of flow conditions, including emergency scenarios.

Figure 7. Screen shot of the WEST-EDI program interface

5. SUMMARY

A training tool, designed to train new Water System Operators on how to operate the canal system more effectively, was developed for the Central Arizona Project. The main idea behind the training tool concept is that the communication between the SCADA system and the radios in the field is “cut” and replaced with a connection between the SCADA system and a hydraulic model of the canal system. In this way, the Water System Operators can be trained on the hydraulic model of the canal system instead of the real canal. The training tool operates in a manner similar to how a flight simulator is used to train pilots.

The training tool is composed of five components installed on two different computers: 1) the SCADA system, 2) the SimSuite program, 3) the SimProctor program, 4) the WEST-EDI program, and 5) the HEC-RAS unsteady hydraulic model and computer program. The Trainee Computer has the SCADA system installed on it. The Proctor Computer has SimSuite, SimProctor, WEST-EDI, HEC-RAS, and the corresponding hydraulic model of the canal system installed on it.

The key component to the training tool is an accurate hydraulic model. A hydraulic model that does not accurately predict water surface changes due to gate movements, turnout flow changes, or pump changes will not effectively train the Water System Operators on the real system. Care was taken in the development of the hydraulic model to assure that the hydraulic modeling accurately predicts the real world. CAP personnel have stated that training tool does respond like the real canal system, indicating that the hydraulic model is adequate.

CAP developed a test bank of scenarios that Water System Operator trainees must pass before they are allowed to operate the canal system independently. This test bank of flow scenarios covered a wide range of flow conditions, including emergency scenarios. Because of this training tool, Water System Operators at CAP now have a much broader experience base from which to draw upon while operating the canal system.

6. REFERENCES