MANAGEMENT OF WATER SUPPLIES FOR IRRIGATION

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PROJECT SUMMARY

Water supplies are limited in many areas of the country, particularly in the arid west where irrigated agriculture is the largest user of fresh water. Expanding urban populations and environmental water needs will potentially reduce water available for irrigation in the future. Water users are faced with requirements to more accurately document water uses and return flows. Water measurement and control in irrigated agriculture has experienced significant advances over the last two decades, yet further advancement is both possible and needed. Under this research project, we intend to develop improved water measurement technology, improved water accounting methods, and improved water control technology. New measurement methods will be developed for steep, sediment laden channels, channels with little or no head available, low-head pipelines (culverts), and submerged radial gates. A new canal automation system will be released to a CRADA partner to provide greater water control and operational flexibility to meet user needs. Water balance methods will be further developed to assist water purveyors with documenting water use, including methods to determine sources of error, which indicate where measurement effort should be focused.

OBJECTIVES

1. Flow Measurement and Accounting: We will develop a series of improvements to existing methods for measuring water flow rates and volumes in rivers, streams, canals, and culverts (low pressure or not flowing full). A series of laboratory studies is planned for currently identified water measurement problems (see research approach). We will continue to support software developed for design and calibration of long-throated flumes, will cooperate with customers to evaluate their water measurement and accounting methods, and will work toward solutions to their flow measurement problems.

2. Water Control: We will develop a series of methods, hardware, and software for improving the control of water in open-channel distribution systems typical of irrigation projects or large water supply projects. A new canal automation system currently under development will be turned over to our CRADA partner. The mechanical/hydraulic controller (DACL), used to maintain constant flow rates at canal offtakes, will be improved to make it more usable in remote sites.

NEED FOR RESEARCH

Description of Problem to be Solved

Competition for limited water resources among various users is increasing in many areas of the country, but particularly in the arid west. Irrigated agriculture is the largest user of fresh water resources and, thus, it needs to improve its water management (CAST 1996, National Research Council 1996). Important elements for improving agricultural water management are improved measurement, control, and ultimately, accountability of water resources at the irrigation project level. Water uses at the project or hydrologic unit scale are often poorly documented making meaningful management of water supplies difficult. Also, water supplies for agriculture from large irrigation projects are often not controlled well, resulting in over-delivery to individual users and ineffective use at the farm level. As water moves downstream through various projects and uses, its quality degrades as salts, trace metals, and other contaminants are concentrated, often to the point of being unusable or having a negative impact on the environment. The objectives of this project are to develop tools for improving the management of water supplies, particularly for irrigation.

Relevance to ARS National Program Action Plan

The research is part of National Program 201, Water Quality and Management. The project falls under Component 2, Irrigation and Drainage Management. Both objectives deal with agricultural water conservation and fit under Problem Area 2.3 (Water Conservation Management), Goal 2.3.1 (Water Conservation Technologies). The research also supports Goal 2.3.3 (Agricultural Water Conservation and Environmental Quality).

Potential benefits expected from attaining objectives

Large-scale water supplies will be better managed in arid regions with the tools developed here. Water measurement, accounting, and control will be improved in irrigated agriculture, supporting more rational analysis of the impact of irrigated agriculture on the environment and allowing more rational decisions by society about water allocation and use.

Anticipated Products

New technology is provided for improving the operation and management of water projects, including canal automation/control and water measurement/accounting technology.

Customers of the research and their involvement

Based on past successful technology transfer and the anticipated products, customers will include the U.S. Bureau of Reclamation (USBR), Natural Resources Conservation Service, U.S. Geological Survey, Army Corp of Engineers, Bureau of Indian Affairs, State Departments of Water Resources (particularly Arizona and California), land-grant universities, civil and agricultural consulting engineers, and water purveyors (water conservancy districts, irrigation districts, municipalities, etc.). We have cooperated with NRCS staff on the application of flow measurement technology and related research needs at all levels (field office to national) and in states across all regions of the country. Our main point of contact is Tom Spofford, Water and Climate Center, Portland OR (letter attached), who disseminates information widely within NRCS. With USBR, cooperation on water measurement and control has been mainly with the Water Resources Research Lab, Denver CO (Cliff Pugh, letter attached). They transfer our technology to regional and area offices through manuals and technical assistance programs. Research on water-balance methods has primarily been with the Lower Colorado Region of USBR (Steve Jones), who along with other regions are transferring this technology to water purveyors through their water conservation plans. Further planned activities with Paul Matuska (letter attached) are expected to have additional impact on water conservation plans. Several water purveyors (e.g., Salt River Project, Maricopa Stanfield I&D District, Imperial Irrigation District) have been directly involved in various studies and technology transfer activities since much of this research must be conducted within real, full-size water systems. Water meter, remote monitoring, and hydrologic instrumentation manufacturers have been customers, which is expected to continue with this project (e.g., Automata, Global Water, Micrometer, Nu-Way Flume Co., Plastifab, etc.). Individual water users also will be customers, particularly for the water measurement devices.

SCIENTIFIC BACKGROUND

Water demands by a growing urban population, concern over protection of water quality and natural habitats, decreasing political support for subsidies to the agricultural sector, and Native American water claims are key factors that are forcing state and federal governments to examine more carefully how water is allocated and distributed in irrigated agricultural regions. This has implications for water measurement, control, and accounting. Policies and programs to promote better water management are constrained by incomplete understanding of the hydrology of irrigated regions and inadequate or insufficient data on water use.

The Central Valley Project Improvement Act (CVPIA) of 1992 is a recent example of legislation that potentially reallocates water supplies within a basin. CVPIA requires water users to develop water management plans (USBR 1999). Within these plans, all water diverted must be measured and accounted for. Guidelines for formulating the conservation plans did not exist when CVPIA was enacted and have gradually evolved over the last decade. Not surprisingly, irrigation districts in the Central Valley are struggling to develop accurate water budgets, even though improved water measurement and water control are required under these plans. The Bureau of Reclamation is in the process of instituting these requirements for water users in other regions, as well. The ability to measure and control water supplies and to properly account for the disposition of water is paramount to achieving the required level of management, as highlighted at a recent USCID conference "*Benchmarking Irrigation System Performance Using Water Measurement and Water Balances*" (Davids and Anderson, 1999).

A large percentage of agricultural water users receive their water supplies through networks of open channels. Most of these systems were originally built to deliver water at a fixed rate and fixed timing. Providing flexible and accurate water deliveries, so that users can match crop and on-farm irrigation demands, represents a significant water conservation opportunity (Cross 2000). In recent years, many U.S. irrigation districts have modernized their canal physical infrastructure and operational procedures in an effort to provide greater delivery flexibility and accuracy (Burt and Styles 2000). Although most open-channel distribution systems still cannot offer the flexibility needed for farmers to convert to pressurized farm irrigation systems, increasing flexibility without also improving control of the delivery system can result in an increase in water that is "unaccounted-for." One district in central Arizona (unofficially) reported unaccounted-for water as 30-35% of diversions. With an intensive water measurement program where several dozen water measurement devices were installed, unaccounted-for water was reduced to 10-15%. This district still has a policy of delivering 10% more water than ordered so that when fluctuations occur, they will still deliver at least the requested rate. The Arizona Department of Water Resources limits water duties to individual farmers. However, for those served from irrigation districts, they allow 10% more water to be diverted (ADWR 1999). Cost-effective technology is strongly needed for improving project water control.

Performance indicators for irrigation and drainage projects proposed over the last several decades were summarized by an ICID working group (Bos 1997). That group is currently preparing a manual on performance assessment (ICID 2000). Three groups of performance indicators are given, dealing with 1) water balance and operational issues (e.g., related to water measurement, accounting and control), 2) economic and social issues, and 3) drainage and sustainability issues. Completely different indicators are used for each specific purpose (i.e., there is no crossover). There are two dozen parameters to choose from, and many of these vary over a project spatially and temporally. No single performance parameter fully addresses water control or delivery service issues. For poorly operated schemes, deliveries to users are grossly inequitable . As operations improve, the focus shifts to proper timing of water deliveries, then to proper flow rate, then to ability to vary duration, then to ability to maintain a constant flow rate, and then to the ability of the irrigator to vary shut off and/or flow rate with short notice. As operations improve, the type of demands placed on the system shift. The result is a continuously moving and more refined target. As a result, the performance indicators needed to define adequate service change. Since the quantitative values of the various performance indicators also vary with the physical limitations imposed by the canal system, no one has been able to set target quantitative values for any of these performance indicators. Further, the link between operational and economic or sustainability performance indicators is site specific and thus not generally quantifiable.

In a complementary effort, Burt et al. (1997) suggest a new paradigm for evaluation of traditional performance parameters such as irrigation efficiency, including accurate geographic boundaries, a defined time period, and an accurate water balance. Clemmens and Burt (1997) show that the accuracy of project performance measures can be determined based on the accuracy of individual volume estimates. This provides information on which quantities have the most influence on the overall accuracy and therefore demand more attention. These methods have been applied to the Imperial and Coachella Valleys in several studies (TWG 1994 and WST 1998). Unfortunately these reports are not routinely available because of the political sensitivity involved. Poor understanding of the hydrology of irrigated areas and improper interpretation of terms such as irrigation efficiency (IE) has lead to the unfounded expectation that improved efficiency will provide additional water supplies (Burt et al. 1997), when often irrigation return flows are used downstream. Solomon and Davidoff (1999) describe the differences between field and project IE based on the amount of reuse that occurs within a project. Difficulties in accounting for water exacerbate this problem.

Flow Measurement and Accounting

A key obstacle to improved water measurement and accounting is the cost of measurement programs (e.g., instrumentation, data collection, maintenance, data analysis). Many irrigation districts measure and continuously monitor water diversions at key control points, but do not do so for delivery to individual users. In one study, Palmer et al. (1991) showed that water accounting was poor (17% of deliveries not billed) and water metering was inaccurate when flow rates were measured only once per day (average rate varied by 20%). Accuracy of volumetric estimates depends on the accuracy and frequency of individual measurements (Wahlin et al. 1997, and Thoreson et al. 1999). Reliable and inexpensive data collection and communication technologies are needed to overcome this financial barrier. There are also hydraulic difficulties; i.e., field conditions under which measurement is difficult, uncertain, and/or costly.

Many existing primary flow measurement devices have accuracy (±2 standard deviations) under ideal conditions that vary from ±0.1% to ±2% (primarily systematic errors). Under field conditions, with the addition of secondary devices (e.g. transducers that provide readout of primary device), accuracy degrades to ±3% to ±5% for an instantaneous reading. Repeated readings over time reduce the random errors, but the systematic errors remain. Non-ideal field installations often cause additional systematic errors. Each measurement site within a project will have a different systematic error, part of which can be considered random from site to site. Thus the overall accuracy of total volume from many measurement sites will be better than the individual sites. The Arizona Department of Water Resources requires that annual reporting of groundwater pumping have an accuracy of ±10%. This may give a total volume accuracy on the order of ±5 to ±10%. This is similar to the water balance accuracy for the Imperial Valley reported by WST (1998). The cost for measurement devices for small flows (up to 15 cfs) range from a few hundred dollars for flumes and weirs (up to $1000 when a transducer and logger or totalizer are added) to $500 to $1000 for common pipe meters.

On the Lower Colorado River, water used by individual users along the river is determined by a Decree Accounting Method (USBR 1998). Under this method, unmeasured return flows to the river (i.e., ungauged surface drains, subsurface flow, etc.) are determined as a percentage of diversion. This percentage of return flows is essentially a negotiated value. The Bureau of Reclamation is trying to develop a more scientifically-based method (LCRAS) to determine water use based on remote sensing, weather-based ET estimates, and river flows. There is currently no information on the accuracy of either the current or proposed accounting method.

While significant strides have been made over the last two decades in measuring open-channel flows with flumes and weirs, there are open-channel flow conditions where existing measurement devices are not adequate (Replogle 2000). Of particular concern are open channels where little head loss is available for measurement, but channels that are too steep and sediment laden will also be studied, subject to support from cooperators. Most of these measurement problems are for relatively small flows (particularly 10 cfs and below). A variety of critical-depth and super-critical-depth flumes have been developed for steep channels. Super-critical flumes pass sediment, but are difficult to calibrate. Critical depth flumes can be designed to pass normal bed-load sediment, but sediment dunes can bury them. Flow measurement in low-head situations generally requires measurement of velocities, the trick being finding ways to infer the "average" velocity from the "measured" velocity(s), and doing it at low cost and high accuracy (Replogle 2000). This applies also to low-head pipes and culverts. A CRIS search on water measurement and flow measurement (and not in soil, plants, etc.) identified only one related project, other than those from this management unit. This project was on cut-throat flumes, which we consider an inappropriate technology and discourage their use (USBR 1997). We know of no other research projects working on improving water measurement technologies.

Water Control

The state-of-the-art in canal automation and control was summarized through a special issue of the *Journal of Irrigation and Drainage Engineering* (vol. 124, no. 1, 1998), *An International Workshop on Regulation of Irrigation Canals* in Morocco (RIC 1997) and a recent *USCID Workshop on*

Modernization of Irrigation Water Delivery Systems (Clemmens and Anderson 1999). Various canal control theories have been proposed, some have been tested to a limited degree with simulation models, but few have been tested in the field. Automatic controls have been applied mostly to individual gate structures.

Most canals are currently operated under manual upstream water-level control. Under this scheme, water released from the headgate is routed downstream through a series of gates, each passing the flow through to keep it's upstream water level constant. The disadvantage of such systems is that any errors in flow settings end up at the tail of the canal. Improved routing (feedforward control) schemes are needed to improve this type of operation; e.g., gate stroking (Bautista et al. 1997). Even with improved routing, imprecise measurements and unknown disturbances can cause flow mismatches (spills or shortages) downstream. Such mismatches need to be corrected through feedback control (typically based on the downstream water levels). Remote control from a central location with Supervisory Control And Data Acquisition (SCADA) systems is becoming more and more common. Supervisory control allows operators to see what is happening throughout the system at once. However, such systems are based on the skill of the operator and the information available to him/her, and results have been mixed.

We have attempted to improve on existing open-loop (feedforward) routing schemes (Bautista et al., 1997; Bautista and Clemmens, 1999). We concluded that the gate-stroking method is not feasible in many situations since it causes excessive flow changes, sometimes exceeding canal capacity, sometimes requiring negative inflows. Simple routing based on volume changes and delay times can produce satisfactory water level control without excessive flow changes (Bautista and Clemmens, 1999). These procedures have only been tested with simulation and still require field testing.

Downstream water-level feedback control strategies adjust canal inflow upstream to eliminate flow mismatches. A variety of downstream control schemes have been proposed (Malaterre et al. 1998). The main ones of practical interest are simple proportional integral (PI) controllers, linear quadratic regulators (LQR and related LQG and similar optimal control methods), model predictive control (MPC), and neural network/fuzzy controllers. Currently, we are focusing only on PI, LQR, and MPC systems. A special class of LQR controllers allows for flexible design and simple tuning without the appearance of being a "black box" (Clemmens and Schuurmans 1999). In fact, this control theory can be used to design a series of simple PI controllers as well. We have used this method to design controllers for several canals, which have worked well under simulation testing (Clemmens and Wahlin 1999 and Clemmens et al. 1997). Limited field trials also suggest that these will work successfully (Strand et al. 1999).

Strelkoff et al. (1998) and Bautista et al. (1996) studied the influence of canal physical characteristics on canal controllability. These studies demonstrate that different canals respond differently to control actions. Thus, the performance of canal control methods is site specific. Because of this, the ASCE Task Committee on Canal Automation Algorithms developed a set of standard test cases with standard performance measures so that various algorithms could be directly compared (Clemmens et al. 1998). Because of the wide variety of performance parameters possible to describe water delivery performance and the varied requirement of different project, the task committee chose to use water level control in the canal (rather than variations in delivery flow rate, etc.) as the basis for comparing different algorithms. Three performance parameters for the downstream water level in each canal pool were recommended: 1) the maximum absolute deviation; 2) the integrated absolute deviation (a measure of the effort required to reject a system disturbance); 3) the steady-state error over the last two hours of each test. A fourth parameter was recommended to penalize unnecessary flow changes: 4) the integrated absolute discharge change. For a given test, the maximum of any pool and the average value for all pools were to be compared for both the first and last 12 hours of each test. These tests had both scheduled and unscheduled flow changes. Tradeoffs between water level deviations and amount of flow changes were expected, particularly as a result of individual choices during the tuning of each controller (Clemmens and Wahlin 1999).

There are many situations where electrical power is not available to operate motorized gates. Hydraulic/mechanical automatic gate controllers have been in use in the arid southwest for nearly a century (Clemmens and Replogle 1987). These controlled-leak controllers have the disadvantage of a large decrement where the water level changes significantly for different gate flow rates. An improvement on this gate was developed by Clemmens and Replogle (1987), the so-called dual-acting controlled-leak (DACL) controller. These have not been adopted, partially because of their complexity. However, several recent improvements in gate designs may make them more useful (e.g., Langemann gates by Aqua Systems 2000 Inc.).

A CRIS search of active projects on canal automation showed no projects other than those of this research unit. Those currently conducting canal automation research are typically not part of the CRIS system; however, we are aware of several complementary research efforts in this area, including Irrigation Training and Research Center, Cal Poly, San Luis Obispo; Water Resources Research Lab, USBR, Denver; the Water Management Group at Delft Technical University, Delft, The Netherlands, and the canal automation group at CEMAGREF, Montpellier, France. In the area of water delivery, we identified two related projects: one at Colorado State University dealing with management issues (as opposed to physical control) and one at U. of Hawaii dealing with reallocation of supply. Several other projects dealing with project performance were found and will be discussed in the next section. A CRIS search of active projects on water project or water delivery and irrigation identified nine related research projects on project performance. Two are ARS projects (Riverside CA and Ft. Pierce FL), 3 are from Colorado State Univ., one is from Univ. California, Berkeley, 2 are from Univ Nevada, Reno, and one is from Texas A&M. Several of these deal with field-scale rather than project-scale issues. Several of these are complementary to the research proposed here. None duplicate the research proposed here. Results from those projects could have implications for the research conducted under this project, although indirectly.

NATIONAL COLLABORATION

This research project contributes to the ARS initiative on Drought and Water Scarcity. This initiative will provide a series of tools to assist farmers, water districts, cities, water resource managers, and government agencies in managing both periodic water shortages due to drought and the long-term decline in available water resources. Research under this initiative will develop drought mitigation and forecasting methods, water conservation and reuse technologies, and tools for water managers to plan effectively for the future. This research will examine water availability and use at watershed and larger scales over both short and long time periods. The result will be specific tools to provide more effective use of the Nation's water supplies.

The objectives contribute to the initiative deliverable on improved water conservation technologies. No other ARS locations are conducting similar research, although many use the water measurement technology developed here. Other locations cooperating with this research include Riverside CA, Parlier CA, Kimberly ID, and Bushland TX.

APPROACH AND RESEARCH PROCEDURES

The research conducted under this project falls primarily in the area of "Technology Development" rather than "Experimental Observation," and thus is not driven by hypothesis testing. Even where observational studies (e.g., hydraulics lab studies) are performed, they are oriented toward defining useful relationship rather than confirming hypotheses.

Objective 1 - Flow Measurement and Accounting

Experimental Design

The intent of this research is to develop new flow measurement technology and extend the range of usefulness of existing technology. Our target is better than ±10% accuracy for an individual reading (random and systematic) and better than ±5% systematic errors, with costs that are similar to existing devices for the range of flows to be measured.

<u>Correcting unreliable velocity distributions in short culverts</u>: Upstream elbows, the pump head, or other pipe fittings that may produce a distorted flow profile that is detrimental to the proper installation and operation of commonly available pipe meters. In open channels, flumes must sometimes be installed closer to upstream disturbances than specified by standard installation recommendations. Methods to condition flows to present proper profiles to meters over a short distance, have been successful on some field trials. Examples include a large diameter orifice (opening 90% of pipe diameter) to control wall jets and surface skimmer to settle the water surface upstream from flumes. Such ad hoc "fixes" cannot be generally recommended or reliably repeated without further study. An existing 30 inch diameter concrete pipe in the hydraulics laboratory will be used to test various methods to overcome a variety of introduced disturbances (e.g., twisting flow, jet from partial open gate, etc.). These methods (orifices, wall fins, etc.) will be evaluated by measuring downstream velocity distributions. A pitot-tube array has been constructed to measure all velocity heads simultaneously so that swirling flow will not distort the results.

<u>Debris-shedding propeller meter for continuous monitoring in culverts</u>: Propeller meters have long been used in pipe flows. Low-head pipelines and culverts often contain debris and trash that thwart the use of propeller meters for all but intermittent use. We have tested a nose-hung propeller meter that appears to shed almost all debris when located in the center of the pipe. Commercially available propeller blades are usually on the order of 6 in. diameter or less. Use of these small propellers in large culverts facilitates debris shedding, but compromise the measurement because they are sensitive to the velocity distribution which is a function of roughness and other effects. Replogle and

Wahlin (2000) showed that an average velocity could be accurately estimated (within 3%) with two velocity measurement made at the centers of the two concentric areas of equal size (i.e., center ½ of center area and concentric ½ area, as shown in Figure 1). We plan to explore whether we can obtain accurate measurements with a small propeller meter in a large pipe regardless of velocity profile. Can one propeller be located to accomplish this? How large does it need to be? Are two propellers needed? and where should they be placed?

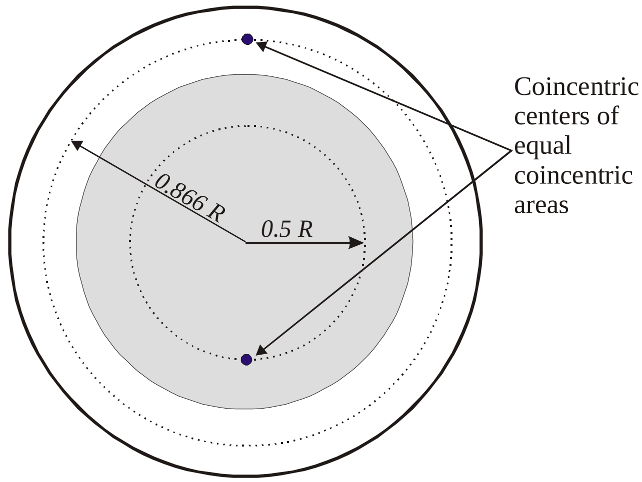

Figure 1. Two velocity measurements representing the centers of two concentric areas give a reasonable estimate of average velocity.

Surface-Velocity-Based Method: Measuring flows in flat sluggish canals is usually expensive when structural changes are required, for example raising the canal banks upstream. One of the oldest methods available is to measure the surface velocity with a single float. This has proven inaccurate (e.g., ±50%) and unreliable since the velocity of a single float cannot be related to average cross-section velocity. Historical work of Bazin (1865) and Replogle and Chow (1964) and application of turbulent velocity distribution models, such as the Seventh-Power Law and secondary currents (Schlichting, 1960), indicate that the location of the maximum velocity in a channel is influenced by the shape of the boundary and the boundary roughness and is located somewhat below the water surface. These references also indicate that this submerged maximum velocity may be reliably related to the average flow velocity, if the boundary roughness and channel shape can be characterized. A reliable indicator of the maximum velocity is needed to make this a viable flow measurement technique. The hypothesis is that if numerous floating particles are dumped simultaneously across a stream of interest, some of the particles statistically are likely to define the maximum surface flow element and that this maximum surface velocity can be related to the true maximum and hence the average velocity in the channel. Preliminary studies of a series of floating particles (e.g., sawdust, popcorn, or ice cubes) suggests that the average velocity is between 0.7 and 0.9 times the fastest particle velocity. This relationship should be a function of channel roughness. Preliminary data is shown in Figure 2. The spread in the particle velocities is also related to channel roughness. Thus

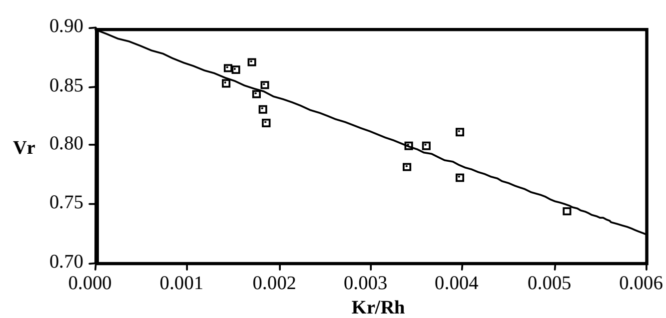

Figure 2. Relationship between the ratio of maximum surface velocity and the average channel velocity (Vr on the y-axis), and the ratio of the absolute roughness, Kr, and the hydraulic radius Rh (Kr/Rh on the x-axis).

by measuring the distribution of particle velocities, a more accurate estimate of average velocity may be possible. We propose to test these relationships in a series of small canals in Arizona with different relative roughness conditions, where accurate flow rates are available by other methods. Travel time for the fastest and slowest particles will be measured over a distance of 30 m. Relative channel roughness will be estimated by measuring the water surface gradient, cross sectional flow area, and discharge. This is intended for simple flow survey work, where ±10% accuracy is acceptable, since it might not be convenient for continuous monitoring.

Submerged Radial Gates: Gates and weirs are commonly used to control flows in irrigation canals; however, flow measurement with such devices is often inaccurate. There are a variety of ways to modify gate structures to make them more accurate measuring devices. We have developed calibrations for broad-crested weirs, leaf gates, etc. (Bos et al. 1984 and Wahlin and Replogle 1994). Radial gates pose an interesting challenge since their (unsubmerged) discharge coefficient tends to change with gate position. Submerged radial gates have proven even more difficult. Published submerged-gate calibration equations are insensitive and lead to large errors (e.g., ±50%). Furthermore, all calibration studies published on radial gates were conducted with a single gate and with the upstream and downstream channels of the same width as the gate. The calibration equations reflect this physical condition and are essentially not applicable under typical field conditions where the radial gate structure is placed in a much wider channel. Further, many large canals have banks of radial gates as check structures. If all gates are in the same position, then the published calibration equations have the best chance of being appropriate. However, for operational reasons, many such structures are operated with one or more gates closed and the others more fully open, particularly at low flows to avoid trapping debris.

We have conducted preliminary laboratory studies on a radial gate with a width less than half that of the approach and tailwater channels (Tel 2000). Free-flow studies confirmed prior relationships developed for the contraction coefficient (ratio of vena contracta depth to gate opening). We also found a useful relationship for the energy loss based on jet velocity head and Reynolds number. Then the energy (Bernoulli) equation is sufficient to determine flow rate with no additional coefficients. Submerged calibration has proven more difficult. Because of the large energy loss downstream from the gate, as with a hydraulic jump, the momentum equation is more appropriate on the downstream side of the structure. Use of the momentum equation from the upstream to the downstream side requires estimates of all the forces (in the direction of flow) on the gate and walls. We chose to use the energy equation on the upstream side, since we have a useful relationship under free flow, and the momentum equation on the downstream side, since energy losses there are too difficult to estimate accurately. The equations are matched at the vena contracta, where we assume that the jet thickness, y_j, is the same under free and submerged flow. This approach proved to work very well when the gates were highly submerged, but not during initial submergence. The problem was with the energy equation on the upstream side of the structure, where assumption of the free-flow jet thickness gave the appearance of an increase in energy. We found that during initial submergence, the increase in pressure (water depth) was almost entirely offset by a decrease in jet velocity head. At higher submergence, an increase in downstream depth translated directly into an increase in upstream energy head. For a single gate opening at four discharges, we found a common relationship for the amount of energy adjustment needed, as shown in Figure 3. Combining the energy equation upstream, with the relationship in Figure 3 included, with the momentum equation downstream results in two equations with two unknowns; the flow rate and the water depth at the vena contracta, y_2. Solution of these two equations assumes that we can estimate the water depth (and thus force) on the downstream wall of the structure based on the downstream depths (y_2 and the depth in the downstream channel), which could be problematic in some situations. Even so, if the relationship in Figure 3 proves to be consistent, it would provide a means of calibrating submerged radial gates right though the transition zone, from free to submerged flow.

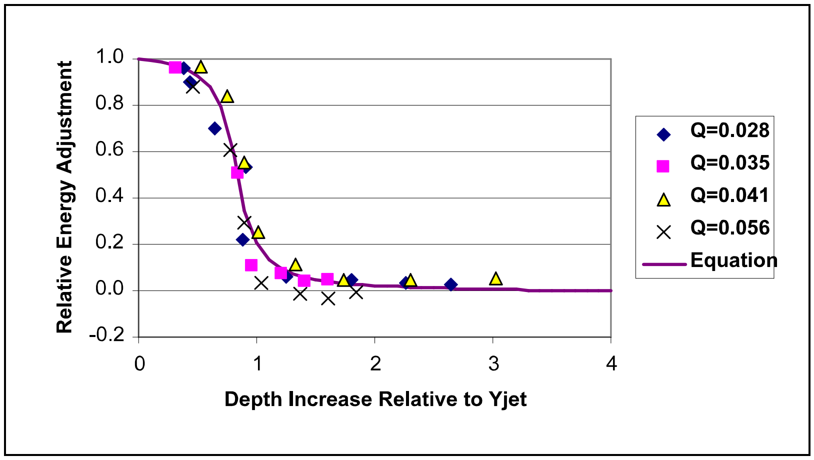

Figure **3**. Energy adjustment (relative to y_2-y_{jet}) required for simple energy equation based on free flow to balance under submerged flow.

We intend to continue these studies by running tests at several gates openings, at least three. We also plan to add a J-seal, as used in the field, to the model gate to determine its effects on these relationships. We expect the J-seal to change the contraction coefficient, which makes the above relationships less general and more difficult to apply. We also plan to modify the lip of the radial gate model in the hydraulics laboratory so that the contraction coefficient remains more constant with gate angle. If this does not alter the energy loss significantly, it may provide more constant conditions for calibration. We also plan to compare this method with data from the literature.

Support to Flume and Weir Design and Calibration Software: The Bureau of Reclamation took our existing software for long-throated flumes (Clemmens et al. 1993) and put it in a windows environment. It is now called WinFlume (Wahl and Clemmens 1998). The program is widely used and we continue to assist the Bureau with unforeseen technical problems, enhancements, etc. We expect this to continue indefinitely, as long as the program is still widely used. A book on these flumes and weirs that includes the WinFlume software has been written and should be published in early FY02.

Steep Channels/Natural Channels: A prototype self-calibrating flume for sediment-laden flows was designed and installed in northern California for the California Water Quality Control Board. The objective was to develop a self-calibrating flume system and to determine its operational limitations. The design was based on estimated hydraulic behavior of a chute outlet attached to a "computable" trapezoidal long-throated flume. Two stilling wells, one on the main flume and one on the chute, provided field calibration for the chute after the main flume no longer functioned because of sediment deposits. Carrillo-Garcia (1999) subsequently conducted studies on a laboratory model of this flume, under our direction, to determine the limits of sediment handling, the best slope for the chute, and whether the calibration of the chute remains stable after the sediment fills the main flume. The sediment altered the upstream (sub-critical) stilling well as predicted. The model indicated that the head detection in the chute will provide discharge rates with systematic errors on the order of ±5% for a given storm, compared to ±2% for the critical-depth flume. Total errors (random and systematic) for a single head measurement exceeded ±10% due to fluctuating water levels, compared to ±3% to ±5% for the critical-depth flume. The downstream stilling well in the chute (super-critical) has about the same response with and without sand, as postulated. Findings include that the midpoint of the chute is a more reliable point of depth detection than points near the downstream end of the chute. This may be related to the non-symmetric entry due to dune formation. If outside support is available, we plan to place obstructions upstream from the flume (vanes, low weir, vertical elements, etc.) to force more symmetric entry into the flume and see whether we can reduce water level fluctuations and obtain ±5% total accuracy for a single head measurement. These studies will be conducted in the hydraulics lab, and possibly other flumes in the field that have experienced similar problems (e.g., several flumes of the Salt River Project and the one in California discussed above).

Water balance and its accuracy: We have cooperated with the Lower Colorado Region of the Bureau of Reclamation on conducting water balances for various projects (e.g., Imperial and Coachella Valleys) (TWG 1994 and WST 1998). An analysis of errors was used to determine which factors contributed the most to the water balance uncertainty (Figure 4). They have requested our assistance in comparing the accuracy of (a) their decree accounting method for assigning water uses along the main stem of the Lower Colorado River (Hoover Dam to the Mexican Border) and (b) their proposed LCRAS method; however, collaborative arrangements have not been finalized (USBR 2000). They are using some of our preliminary work (developed in cooperation with others) to assist water users with defining a water balance and its associated accuracy. USGS is cooperating with them to define the accuracy of volumes for the river measurements and the major diversions and surface drains. Large diversions also have relatively accurate measurement (e.g., Central Arizona Project, California Aqueduct, All American Canal). It's the 70 or more other measurement sites plus the unmeasured return flow that pose the most problems with the water balance. We have not surveyed these sites, so we don't know what problems (opportunities) will be encountered. At this point, all we have is agreement to cooperate with USBR on this project. Our specific role in their ongoing programs is still being negotiated.

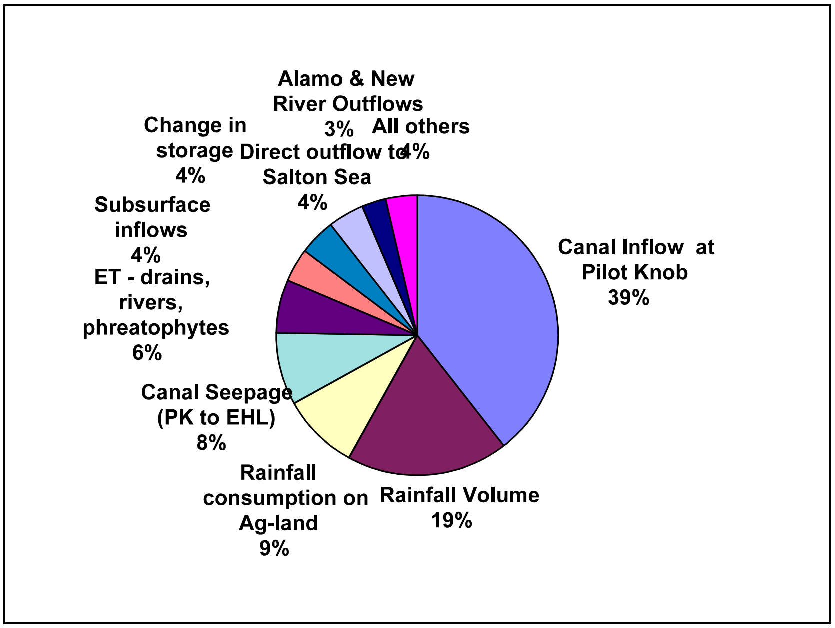

Figure 4. Distribution of error variance for estimation of net evapotranspiration of water from land area within the Imperial Valley based on a water balance. Larger wedge contribute more error to estimate. (WST 1998).

Contingencies

Other laboratory facilities could be contracted if ours are insufficient for a particular study. We have a strong track record at solving water measurement problems and expect these studies to provide useful measurement methods. In a few cases, it is not known whether or not the methods that we are testing will prove useful in the long run. If not, we will explore other user-defined measurement problems. These problems are continuously being brought to our attention by cooperators. If cooperation on the Lower Colorado River main stem does not materialize, we have several other contacts with which to pursue this research.

Collaborations

Necessary (within ARS) – None.

Necessary (external to ARS) – No cooperation is required to conduct laboratory studies. For field application we rely on the Natural Resources Conservation Service (NRCS, Tom Spofford) and the Bureau of Reclamation (USBR, Cliff Pugh and Paul Matuska).

Objective 2 - Water Control

Experimental Design

The intent of this research is to develop a complete control system for canals that is adaptable to a wide range of canal physical configurations and subject to a wide range of demands. Because there are no specific performance standards with which to judge the impact of improved water control on the performance of irrigation projects, application has been slow. Adoption is based on the desire by the water delivery agency for incremental improvement in control, improved reliability (e.g., from remote monitoring), and cost savings in labor and vehicle travel (e.g., from remote control). The proposed simulation and field studies can be used to compare various control methods and suggest which ones might be preferred in various applications as part of this control package. However, adoption of the overall control technology developed here is based on the acceptance of the users and the expectation of improved operations. For this reason, studies on the application of the technology are conducted in parallel with the more scientific controller comparison studies.

Canal control logic: Our USWCL canal control scheme consists of three component: 1) downstream water level feedback control, 2) open-loop or feedforward control (routing) of scheduled water delivery changes, and 3) flow rate control of check structures, based on flow changes from 1) and 2). We currently use a downstream feedback control scheme based on a variation of Linear Quadratic Regulator theory which allows us to develop both centralized controllers that include time delays and a series of local proportional-integral (PI) controllers (Clemmens and Schuurmans 1999). Our scheme also includes routing of scheduled water delivery changes (i.e., a modified form of gate stroking) (Bautista and Clemmens 1999). The flow controller adjusts gate position based on the gate head-discharge equations. Some testing of this system has been done through simulation (Clemmens et al. 1997, Clemmens and Wahlin 1999, and Walhlin and Clemmens 1999) under ideal conditions but also by subjecting the control system to unscheduled disturbances and system noise. Field testing is needed to verify that the robustness and effectiveness of the system (logic and software) with given actual perturbations, system noise, and possible hardware limitations. Tuning of the feedback controllers relies on weighting coefficients in the optimization procedure that describe the tradeoff between water level errors and gate movements. To date, selection of these weighting coefficients is based on subjective judgement about controller performance. Additional simulation testing is needed to provide recommendation on these weighting coefficients. Simulation tests will be run with CanalCAD (Holly and Parrish 1992). Controllers for these and all tests discussed below will be compared with the evaluation criteria determined by the ASCE task committee on canal control algorithms (Clemmens et al. 1998). Those tests will allow to identify those controller configurations more likely to perform well under a wide range of conditions, and also controller configurations that would work best for particularly difficult situations.

We have been working with the Irrigation Training and Research Center (ITRC at Cal Poly, San Luis Obispo) on upstream control where a series of individual controllers each tries to maintain water levels upstream from a check structure. This can create oscillations in flow rates that grow in the downstream direction. ITRC has been using modified versions of our controller design programs (in MATLAB) to develop controllers for upstream control for several of their clients. We plan to conduct more general studies on upstream controller design to provide a more solid theoretical foundation. These studies are not planned for several years and details will likely be based on the results from ITRC's efforts and results of our field studies discussed below.

Our preliminary results suggest that sending control signals from one water level to more than one upstream gate improves the responsiveness of the controller. Current LQR controller design methods only consider a single canal with no branches. Thus our control scheme does not allow downstream control signals to influence gates upstream from a branch point. We have modified the standard LQR technique to design controllers for a branching canal network. We intend to test the resulting controllers through unsteady-flow simulation with SOBEK (Delft Hydraulics 2000). Initial simulation testing will be performed with ASCE test canal 1, with several downstream pools connected in the middle of the canal. If successful, we will test the branching controller with simulation of canals within the Salt River Project.

Another limitation of the proposed controllers is that they are "static," that is they are design for one set of flow conditions. If control is not robust and stable over the full range of conditions, the controller must be tuned for different ranges of conditions (i.e., gain scheduling). Model Predictive Control (MPC) has the advantage that the controller is tuned for the current conditions, however this requires on-line optimization. With the current state-of-the-art in canal control, we are not comfortable with on-line optimization. However, we will test MPC for the branching canal tests discussed above.

<u>Canal automation software</u>: The research unit has developed a canal automation software system that controls canals remotely through a commercial Supervisory Control and Data Acquisition (SCADA) System using commercially available hardware in the Windows NT environment. We have entered into a Cooperative Research and Development Agreement with Automata Inc. to develop a canal automation product line. Our automation software runs in parallel with the SCADA software (Fix Dynamics, by Intellution Inc.) and accesses the SCADA database to determine the

current status and to cause actions to take place (e.g., change in gate position). Automata's remote terminal unit (RTU) provides sensing and control functions. Preliminary field testing in the fall of 1999 was successful (Strand et al. 1999). Figure 5 shows a sample SCADA screen with water level output. We are in the process of adding fail-safe routines so that the controller does not act inappropriately when data are missing or sensors malfunction (as for WM-5 in Figure 5). More rigorous field testing of this system will start in mid 2001 and continue through at least 2002. The system should be turned over to the CRADA partner within FY02. Continued software upgrading is planned through FY03. We plan to support the CRADA partner's efforts through 2004.

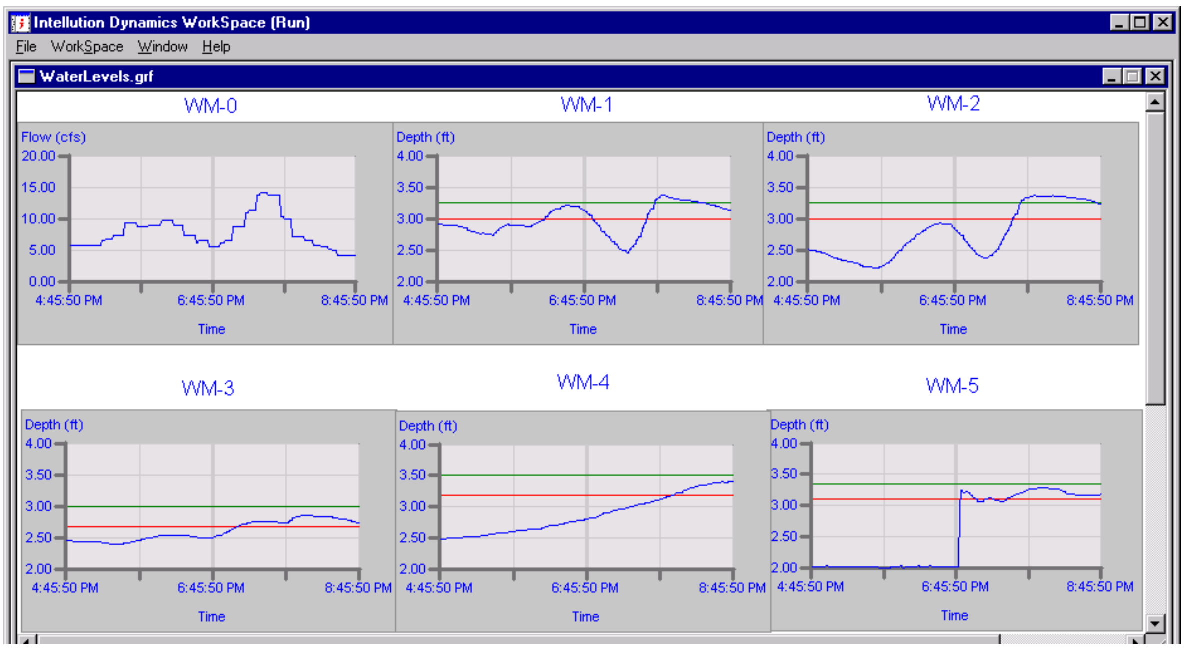

Figure 5. FIX SCADA screen showing results of test on October 19,1999. Red lines are water level set points and green lines are overflow weirs.

<u>Field testing on WM canal</u>: The field testing of the canal automation system will be performed on the WM canal of the Maricopa Stanfield Irrigation and Drainage District (MSIDD), which has a 2.5 m^3/s capacity. This canal is at one extreme of hydraulic conditions (small, steep, with little storage). Groundwater wells are available that pump water directly into the canal (roughly 0.1 m^3/s). These can be turned off or on to simulate demand changes. The district allows us to operate the canal, either manually or automatically, while their normal deliveries are taking place. The main focus will be on downstream water-level feedback control methods, both centralized and local. We will start by testing a series of simple PI controllers on only the upstream half of the canal. Initially, we will test only downstream feedback control with pseudo-demand changes, generated by turning pumps on or off. Then we will route these pseudo-demand changes down the canal with our routing program as if they were scheduled, and with the feedback system still on. Performance will be measured with the ASCE Task Comimittee performancee indicators under a variety of flow conditions. If successful, we will expand to control of the entire canal and eventually route the actual demand changes down the canal and operate it automatically during normal delivery changes. We also will test downstream controllers that include lag-time predictions and the fully centralized

LQR controllers and several intermediate controllers as discussed in Clemmens and Wahlin (1999). We will attempt to run these various controllers under different flow and demand conditions. Further testing on canals with different properties, for example where backwater effects as significant, is planed for later stages of this project. Possible sites include lateral E12 at MSIDD and one of the lateral off the East Highline Canal in the Imperial Valley. However, we will not pursue these sites (or collaboration at Imperial) until testing is competed at MSIDD and the system can be demonstrated.

SRP pilot study: We are currently completing studies on one of the larger canals of the Salt River Project (SRP) to test the feasibility of applying this technology within SRP's operating environment. We are also using this cooperation to test the acceptability of such control methods to their operating staff. We conducted simulation studies with the unsteady-flow simulation software program Mike 11 (DHI 1992) to demonstrate the technical feasibility of the feedback and feedforward (routing) scheme (Clemmens et al. 1997). Example simulation results are shown in Figure 6. We have also examined various practical issues, including: (1) comparison of water level deviations for real demand conditions under (a) simulated automation and (b) actual manual control (Brouwer 1997); (2) use of identification techniques to estimate canal hydraulic parameters for controller design (Silvis 1997 & Silvis et al. 1998), (3) analysis of the limitations imposed by the limit storage at the diversion structure which supplies water to the canal (This suggested the need to control a section of the river between the storage and diversion dams (Visser 1998), and the need for control of branching systems.); (4) analysis of start-up procedures for the feedback system (Bautista et al. 1999); (5) analysis of performance for alternative controller designs (Wahlin and Clemmens 1999); and (6) calibration of the head-discharge relationship for radial gates (Tel, 2000). Several of these studies were conducted in collaboration with graduate students from Delft Technical University.

We are currently testing the routing procedures in cooperation with Salt River Project by comparing the program's and the operator's schedules of flow changes. The objective is to identify possible problems with the control algorithm given the range of operational conditions experienced in the real canal. Furthermore, these tests should help reassure operators that the computed schedules are reasonable and would not endanger the canal. We plan to complete these tests by September 2001. Depending on the outcome of these tests, we propose to conduct off-line tests in FY02. With these tests, we plan to demonstrate that the proposed open-loop control algorithm can improve water level control relative to the heuristic approach currently employed by the operators. If the off-line testing is successful, we will request SRP's approval to automate the execution of the computed schedules, in real time. This will require our routing software to be implemented within SRP's computer operating systems and, thus, will serve to identify practical implementation problems. If this is successful, we will propose implementation of the feedback control system. (SRP is already implementing their own flow-control function).

Dual-acting controlled leak: For situations where communication and remote power are not available, mechanical/hydraulic automatic control devices are needed. The research unit developed such devices in the late 1980s and proposes to do additional development and testing of these devices (Clemmens and Replogle 1987). The DACL controllers have two limitations: (1) the two values have to be carefully adjusted relative to one another and (2) the gate controls were done with very large counter balanced floats on radial gates. We propose to develop a single valve with the required dual action and to use inflatable bladders to do away with the current float/ counterweight system. This will make such devices much more easy to retrofit to existing gate structures, including sluice gates. Two prototype values have been built, but not yet tested under operational conditions. Several bladder systems have been tried, but finding the right combination of materials has proved challenging.

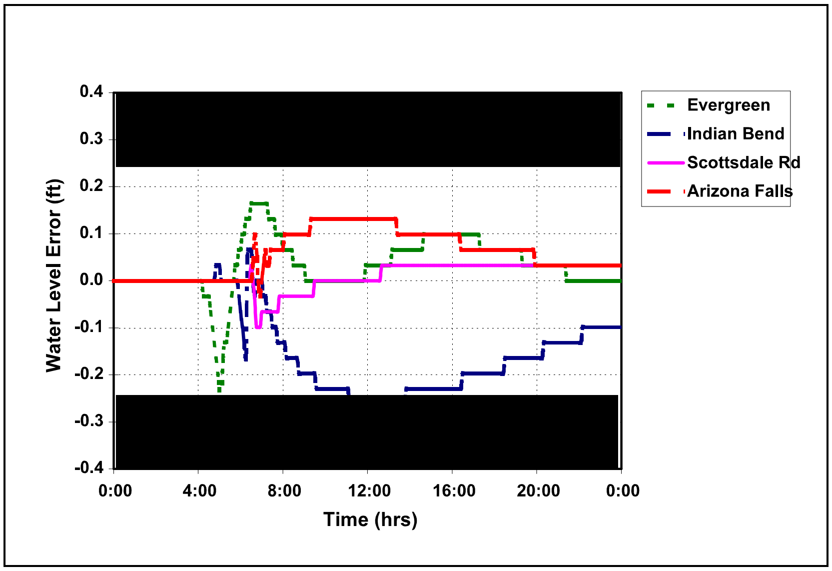

Figure 6. Difference between actual and target forebay water level under simulated automated control in four Upper Arizona Canal pools for Test 5 from SRP Canal Automation Pilot Project. (Clemmens et al. 1997). (Inside band is acceptable or "green" zone, shaded is "yellow warning zone, outside figure is "red" zone).

Contingencies

Field studies rely on cooperation with irrigation districts and a CRADA partner to test these systems in real time on operating canals. If the current collaborations were to end, new collaborators would be found to continue the research. We are just ending a canal automation research project with the Salt River Project. Implementation was postponed, but they are a potential alternative site if cooperation with MSIDD doesn't work out. We also have had close cooperation with Imperial Irrigation district in the past, so they are another potential candidate for cooperation. If the controller design methods being used/developed do not work for a particular canal, there are a number of other control methods that can be used (e.g.. Model Predictive Control). Some of these other controllers will be examined through simulation so that we gain familiarity with them.

Collaborations

Necessary (within ARS) – None.

Necessary (external to ARS) – Maricopa Stanfield Irrigation and Drainage District (Gary Sloan), Salt River Project (Bob Gooch), Automata, Inc. (Lenny Feuer), Irrigation Training and Research Center (Charles Burt), and USBR Water Resources Research Laboratory (Cliff Pugh).

Physical and Human Resources:

This research project includes three category I research scientists (1.79 SY), two category III research scientists (1.4 FTE), and an engineering technician (1.0 FTE, GS-9 on temporary term appointment). We will hire additional temporary personnel as needed. This labor force is sufficient to carry out the needed work.

The research is conducted at the U.S. Water Conservation Lab which has office and laboratory space available for a wide variety of studies. Employees utilize the 372 m^2 hydraulics lab for small-scale studies on flow measurement and canal automation. However, these are currently utilized primarily for another project. The hydraulics lab includes 5 pumps (30, 20, 20, 15 and 15 Hp), two large sumps, a constant head tank, 25 ton hanging weigh tank, 15.2 m long glass lined flume (1.2 m wide by 0.6 m high), and a 760 mm diameter concrete pipe section 12 m long. The system has a capacity of 450 l/s, depending on which experimental apparatus is being used. The weight tank system can measure flow rates to within 0.1%. A soils lab is available to conduct soil particle size analysis. An electronics shop is available for development and repair of electronic instruments as needed. Water chemistry labs, primarily associated with other projects, are available for testing soil and water for constituents if needed. The laboratory has an internet connection (T1 line), a local area network, and numerous personal computers for the staff. Much of the research of this group is conducted with customers and cooperators on their sites to assure relevance.

MILESTONES AND EXPECTED OUTCOMES

Expected outcomes include: (1) improved water measurement devices, (2) new canal automation technology, and (3) improved water use assessment methods and performance indicators.

Milestone Timeline

Research Component	end of year 1	end of year 2	end of year 3	end of year 4	end of year 5
Water Measurement and Accounting	Lab study on flow conditioning for pipes/culverts completed (Replogle)	Lab study on debris-shedding propeller meter completed (Replogle)	Field studies on surface-velocity-based method completed (Replogle)	Lab study on high sediment load flume completed (Replogle)	
		Laboratory studies on submerged radial gates completed (Clemmens)	Verification of radial gate calibration method completed (Clemmens)		Field study on water balance accuracy completed (Clemmens)
Water Control	Initial version of canal automation system turned over to CRADA partner (Clemmens)	Improved interface for canal automation system provided to CRADA partner (Clemmens/Bautista)	Final version of canal automation technology given to CRADA partner (Clemmens)		New DACL control system developed and lab testing completed (Replogle)
		Field studies of canal automation on steep canal (WM at MSIDD) completed (Clemmens)	Field application of feedforward routing method completed (Bautista)		Field studies of canal automation on canal with mild slope complete (Clemmens)
	Feedback control method for branching canals developed and simulation testing completed (Clemmens)	Simulation testing of Model Predictive Control for branching canal completed (Clemmens)		Upstream control method developed and simulation testing completed (Clemmens)	

PROGRESS

Improving the operation of large water projects is an important step in water conservation efforts to spread limited available water supplies. Engineers from the U.S. Water Conservation Lab, in cooperation with CRADA partner Automata Inc., have developed and canal automation system, which includes Software for Automated Canal MANagement – SacMan. The first version of SacMan was provided to Automata Inc. in 2002, covering manual control with intelligent assistance. This software, including future versions with full automatic control, has significant potential for improving water management in irrigation projects and the CRADA partner has already sold one copy and has interest from several other districts.

Laboratory studies on flow conditioning in pipes and culvert is ongoing. The bugs have been worked out the the measurement methods and the pipe has been set up to handle the variety of tests planned. Several instrument manufacturers have cooperated in various tests and more such cooperation is expected.

The main features of the SacMan canal automation software have been field tested. An initial version of the software, handling manual control systems, was turned over to our CRADA partner. The control system is being installed at the Central Arizona Irrigation and Drainage District, Eloy, AZ. The initial installation is manual control, with full automatic control being phased in over the next year or so. The first full version of the software will be provided in early FY03.

Initial studies on the control of branching canals were successful. Both Linear Quadratic Regulators and Model Predictive Control were successfully applied to one of the ASCE test canals through computer simulation. The controller design methods were able to account for the interacting influences of the various branches.

Through cooperation with the Bureau of Reclamation, Water Resources Management Lab, we were able to analyze the data collected on radial gates by the Bureau in the early 1980s. This data supported our approach in calibrating submerged radial gates, but also showed that a wider range of data is needed to provide useful calibration. Preliminary field studies at the Salt River Project also supported our approach.

Dr. Clemmens assisted the South Australian government with planning for the rehabilitation of major irrigation works along the Lower Murray River. Technology transferred included 1)flow measurement techniques, including flume, weirs, and flow conditioning for pipe meters, 2) recommendations on improvements in surface irrigation layouts, including use of SRFR software developed under another CRIS project at the lab, 3) recommendations on the organization of the water users and the distribution system layout, and 4)recommendations on separating sources of drainage water to avoid water quality problems in the Murray River.

Drs. Bautista and Replogle assisted the Lahontan Conservation District and the NRCS with rehabilitation priorities for water conservation in the Newlands Project, Fallon, NV.