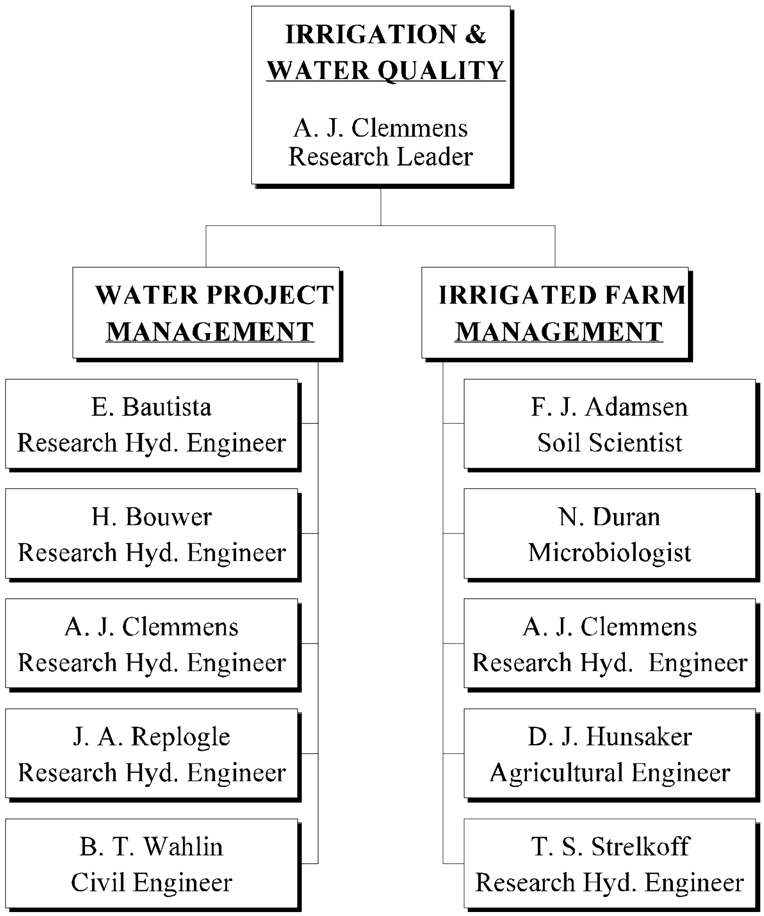
I&WQ Management Unit

I&WQ Organization



Mission

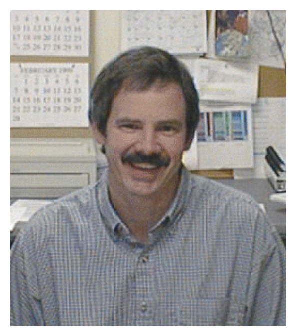
The mission of the Irrigation and Water Quality Research Unit is to develop management strategies for the efficient use of water and the protection of groundwater quality in irrigated agriculture. The unit addresses high priority research needs for ARS's National Programs in the area of Natural Resources & Sustainable Agricultural Systems. The unit primarily addresses the Water Quality and Management National Program. It also addresses the application of advanced technology to irrigated agriculture.

I&WQ RESEARCH STAFF

FLOYD J. ADAMSEN, B.S., M.S., Ph.D., Soil Scientist
Management practices that reduce nitrate contamination of groundwater while maintaining crop productivity; application of 100% irrigation efficiency; winter crops for the irrigated Southwest that can be double-cropped with cotton; contributions of natural and urban systems to nitrate in groundwater.

EDUARDO BAUTISTA, B.S., M.S., Ph.D., Research Hydraulic Engineer
On-farm irrigation system hydraulic modeling; hydraulic modeling of irrigation delivery and distribution systems; control systems for delivery and distribution systems; effect of the performance of water delivery and distribution systems on-farm water management practices and water use efficiency; integrated resource management and organizational development for irrigated agricultural systems.

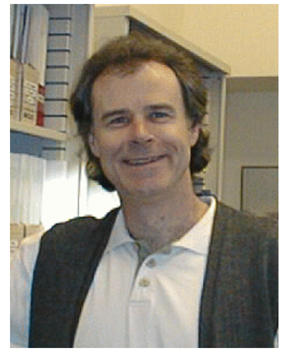
HERMAN BOUWER, B.S., M.S., Ph.D., P.E., Chief Engineer and Research Hydraulic Engineer
Water reuse; artificial recharge of groundwater; soil-aquifer treatment of sewage effluent for underground storage and water reuse; effect of groundwater pumping on stream-flow, surface and groundwater relations.

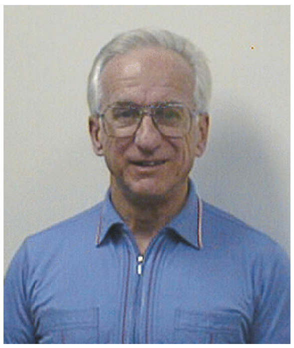


ALBERT J. CLEMMENS, B.S., M.S., Ph.D., P.E., Laboratory Director, Research Leader for Irrigation and Water Quality, and Supervisory Research Hydraulic Engineer
Surface irrigation system modeling, design, evaluation, and operations; flow measurement in irrigation canals; irrigation water delivery system structures, operations management, and automation.

NORMA L. DURAN, B.S., Ph.D., Microbiologist
Wastewater irrigation; molecular detection of waterborne pathogens; pathogen regrowth assessment in water distribution systems; fate and transport of pathogens in the subsurface environment.

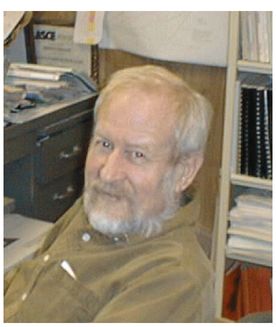
DOUGLAS J. HUNSAKER, B.S., M.S., Ph.D., Agricultural Engineer
Effects of soil and irrigation spatial variability on crop water use and yield in large irrigated fields; level basin irrigation design and management procedures for applying light, frequent water applications to cotton; CO2 effects, in particular, of evapotranspiration in the free-air CO2 enrichment (FACE) environment; evaluation of water requirements and irrigation management of new industrial crops--lesquerella and vernonia.





JOHN A. REPLOGLE, B.S., M.S., Ph.D., P.E., Chief Scientist and Research Hydraulic Engineer
Flow measurement in open channels and pipelines for irrigation; irrigation water delivery system structures, operations, and management.

ROBERT J. STRAND, B.S., Electrical Engineer
Automatic control of irrigation delivery systems; development and integration of field sensors, intelligent field hardware, USWCL feedback and feedforward control software, and commercial supervisory control software to create a plug-and-play control system.



THEODOR S. STRELKOFF, B.C.E., M.S., Ph.D., Research Hydraulic Engineer
Surface-irrigation modeling: borders, furrows, two-dimensional basins; erosion and deposition; design and management of surface-irrigation systems; canal-control hydraulics; flood-routing methodologies; dam-break floodwaves; flow in hydraulic structures.

BRIAN T. WAHLIN, B.S., M.S., Civil Engineer
Flow measurement in open channels and pipelines for irrigation; irrigation water delivery system structures, operations, and management.

IRRIGATED FARM MANAGEMENT ANALYTICAL LABORATORY

K. Johnson, S. Colbert, and J. Askins, Physical Science Technicians; K. VanMeeteren, Biological Science Technician; and A. Jacques, Physical Science Technician

Following is a description of the functions of the Irrigated Farm Management (IFM) Analytical Laboratory. The IFM Lab is staffed by the technicians listed above, two of whom are students.

High performance liquid chromatography (HPLC) is used to test for nitrate and other anions in soil samples. The autoanalyzer utilizes colorimetry to determine nitrate, and ammonium, and bromide content of water samples and extracts of soil samples. Three stations allow collection of data from weighings directly into a spreadsheet. The extraction step has been aided by replacement of two centrifuges. C^{13} and N^{15} analyses are run on the isotope ratio mass spectrometer.

In addition to running and maintaining instruments, research technicians process data and address the precision of the data. Technicians also weigh soil samples, collect samples in the field, help with irrigation and other field work, write and update protocols for both reference and training, count seeds, and perform numerous other duties as needed. Facilities in this lab are sometimes used by other groups, and occasionally a technician from another group with extra time will lend a hand here.

IRRIGATED FARM MANAGEMENT

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IRRIGATED FARM MANAGEMENT

MISSION

To develop irrigation farm management systems for arid zones that integrate year-round crop rotational strategies with best management practices (BMPs) for water, fertilizer and other agricultural chemicals. These systems will be environmentally sustainable, protect groundwater quality, and be economically viable.

STUDIES ON CONSUMPTIVE USE AND IRRIGATION EFFICIENCY

D.J. Hunsaker, Agricultural Engineer

PROBLEM: Effective irrigation management provides the timely and correct amount of water consistent with crop water demands, soil conditions, crop production goals, and environmental quality goals. Irrigation efficiency (IE) is a term often used to describe the effectiveness of irrigation, where IE is defined as the ratio of the average depth of irrigation water that is beneficially used to the average depth of irrigation water applied. Beneficial uses include crop evapotranspiration (ET_c), salt leaching, frost protection, etc. General measures that can be taken to improve surface irrigation efficiencies include increasing the uniformity of the water applied, reducing deep percolation and surface runoff, and improving the control of application depths. However, proper irrigation management is a vital requirement for attaining the optimum irrigation efficiency of the system. Thus, the ability to predict actual daily crop water consumption, or ET_c, is of major importance.

A practical and widely used method for estimating actual ET_c is the crop coefficient approach, which involves calculating a reference crop ET with climatic data. ET_c can then be determined by multiplying the reference ET with an appropriate crop coefficient (K_c). Recently, the Food and Agricultural Organization (FAO) published FAO-56, *Crop Evapotranspiration*, a revision of FAO-24, which presents updated procedures for calculating reference and crop ET from meteorological data and crop coefficients. In addition to the single K_c approach which combines basal crop ET and soil evaporation into a single value, FAO-56 also includes a dual, or basal, crop coefficient approach. In the dual approach, K_c is determined on a daily basis as the summation of two terms: the basal crop coefficient (K_{cb}) and the contribution of evaporation from wet soil surfaces following irrigations or rain (K_e). The usefulness of the dual crop coefficient model is that it can provide better estimates of day-to-day variations in soil surface wetness and the resulting impacts of irrigation frequency on daily crop water use. FAO-56 also introduced the need to standardize one method to compute reference ET from weather data and thus recommended the FAO Penman-Monteith (PM) as the standard equation for the calculation of grass-reference ET (ET_o). Although FAO-56 presents generalized crop coefficient values based on FAO PM ET_o, derivation of localized crop coefficients is advisable due to the effects of local climatic conditions, cultural practices, and crop varieties on the crop coefficient.

Several different entities have approached the U.S. Water Conservation Laboratory (USWCL) with interest in current information on the ET requirements for crops grown in the Southwest. A particular concern is that many farmers have been unable to meet water duties established by the Arizona Deptartment of Water Resources. The objective of this project is to determine the consumptive use and attainable irrigation efficiencies for crops presently produced, as well as for several new industrial crops that are being developed in the region.

APPROACH: Research is being conducted through a series of experiments to determine crop evapotranspiration and localized crop coefficient curves for cotton, alfalfa, wheat, rape, lesquerella, and guayule grown under irrigation and soil conditions common in the region. Crop ET and soil evaporation will be determined locally from soil water measurements using neutron probes and time-domain-reflectometry (TDR) for crops grown in farm-scale fields and from previous lysimeter studies at the USWCL. These data also will be used to derive crop coefficients for local conditions based on the FAO-PM equation for grass-reference ET_o. The crop ET and K_c derived from the various experiments will be used to develop and test various crop K_c models, including the FAO-56 model, to provide better information on crop water requirements and irrigation management for the region.

During 1984 to 1986, an Arizona-adapted cultivar of alfalfa [*Medicago sativa* (L.) Lew] was grown in a 0.65-ha field located at the USWCL. The rectangular field site (70 by 90 m) contained three electronic weighing lysimeters each 1.0 m^2 and 1.6 m deep. Alfalfa was planted in February, 1984, on 18 plots, separated by border dikes. The three lysimeters (designated as L1, L2, and L3) were situated within three adjacent plots. After planting, all plots were kept well-watered via surface irrigation until late 1984, after which the plots were intermittently subjected to water-stress during subsequent growing cycles. After each alfalfa cutting, water-stress treatments were rotated to different plots so that plants were not exposed to severe drought stress during consecutive regrowth periods. The evapotranspiration in lysimeters (ET_m) and meteorlogical data were measured every 1.5 minutes and reported as time-averaged values at 0.5-hr intervals.

This report will focus primarily on the data of 1985. In 1985, alfalfa was harvested a total of nine times, where the first harvest occurred on Feb. 12 (DOY 043) and the ninth on Dec. 17 (DOY 351). At each harvest, the larger plot areas were mowed using a tractor-mounted cutter bar. Biomass from the lysimeters was harvested using a curved-blade knife. All of the aboveground plant material in the lysimeters was cut leaving a stubble height of about 0.02-0.03 m.

For each day in 1985, the daily grass-reference ET_o was calculated over 0.5-hr time steps. The measured wind speed at the alfalfa field was extrapolated to the FAO-56 standard grass-reference height of 0.12 m, before calculating the grass reference ET_o. Daily K_c values were calculated as the ratio of ET_m to ET_o for each lysimeter. For each harvest cycle in 1985, daily ET_m for lysimeters was compared with daily ET_c predicted for well-watered alfalfa using the single K_c procedure of FAO-56 and their recommended K_c values for alfalfa. The FAO-56 alfalfa K_c values were not adjusted for the effects of increased soil water evaporation due to irrigation and rain. The recommended mid-season and end of season K_c values, however, were adjusted during each cutting cycle based on the climatic and crop height conditions during those growth stages of the cycle.

FINDINGS: Figure 1 shows the daily measured K_c values for each lysimeter and the K_c model constructed from FAO-56 procedures for the second and third harvest cycles of 1985. Measured K_c for all lysimeters was generally higher than modeled K_c during the first half of the harvest cycles because of increased soil water evaporation from rain and irrigation during that period likely being underestimated by the single K_c model of FAO-56. During the mid- to late-season stages of the second harvest cycle, variations in K_c occurred among the three lysimeters although water was applied to all lysimeters on the same day. The FAO-56 K_c curve generally overestimated the K_c for L1 and L2, but underestimated the K_c for L3. During the third cycle, there was a reduction in the

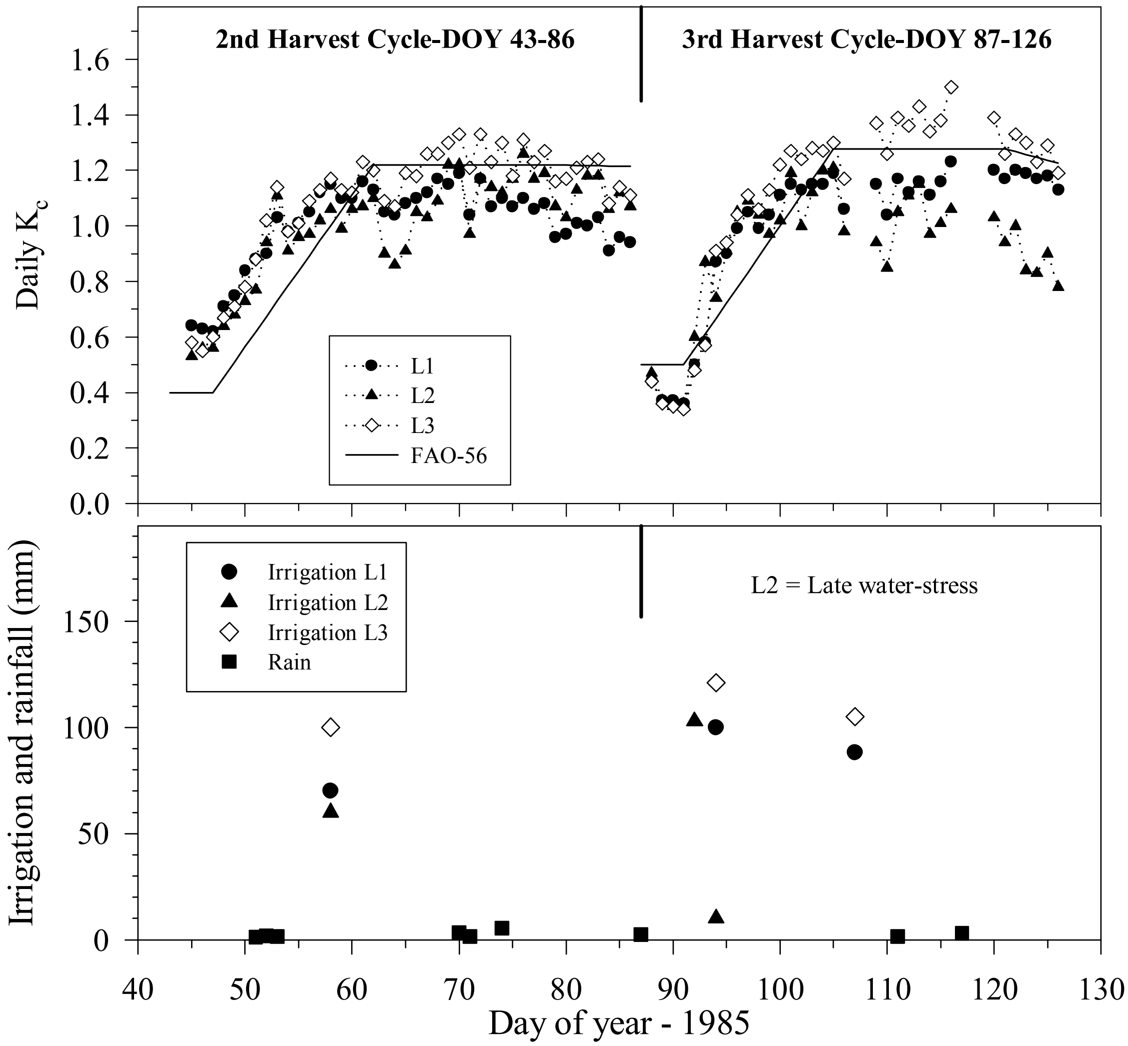

Figure 1. Daily K_c and irrigation and rain during 2nd and 3rd harvest cycles of alfalfa.

K_c values for L2 when water-stress was imposed on that lysimeter during the latter portion of the cycle.

For each lysimeter, linear regression of daily ET_m against the FAO-56 ET was applied over the data from the second to the ninth harvest cycles of 1985 (Fig. 2). Regression coefficients of determination (R^2) for L1, L2, and L3 were 0.78, 0.86, and 0.93, respectively; and for all lysimeter data combined, it was 0.85, indicating that the performance in predicting ET_m on a daily basis with the FAO-56 model was reasonably good. There was a tendency for the FAO-56 model to underestimate ET_m at small rates of measured ET. However, the greatest underestimations of ET_m were noted to occur for days following irrigation or rain, and particularly for days following water applications made during the early regrowth periods following cutting. Again, this was related to the limitations of the single K_c model to account adequately for increased soil water evaporation following water applications.

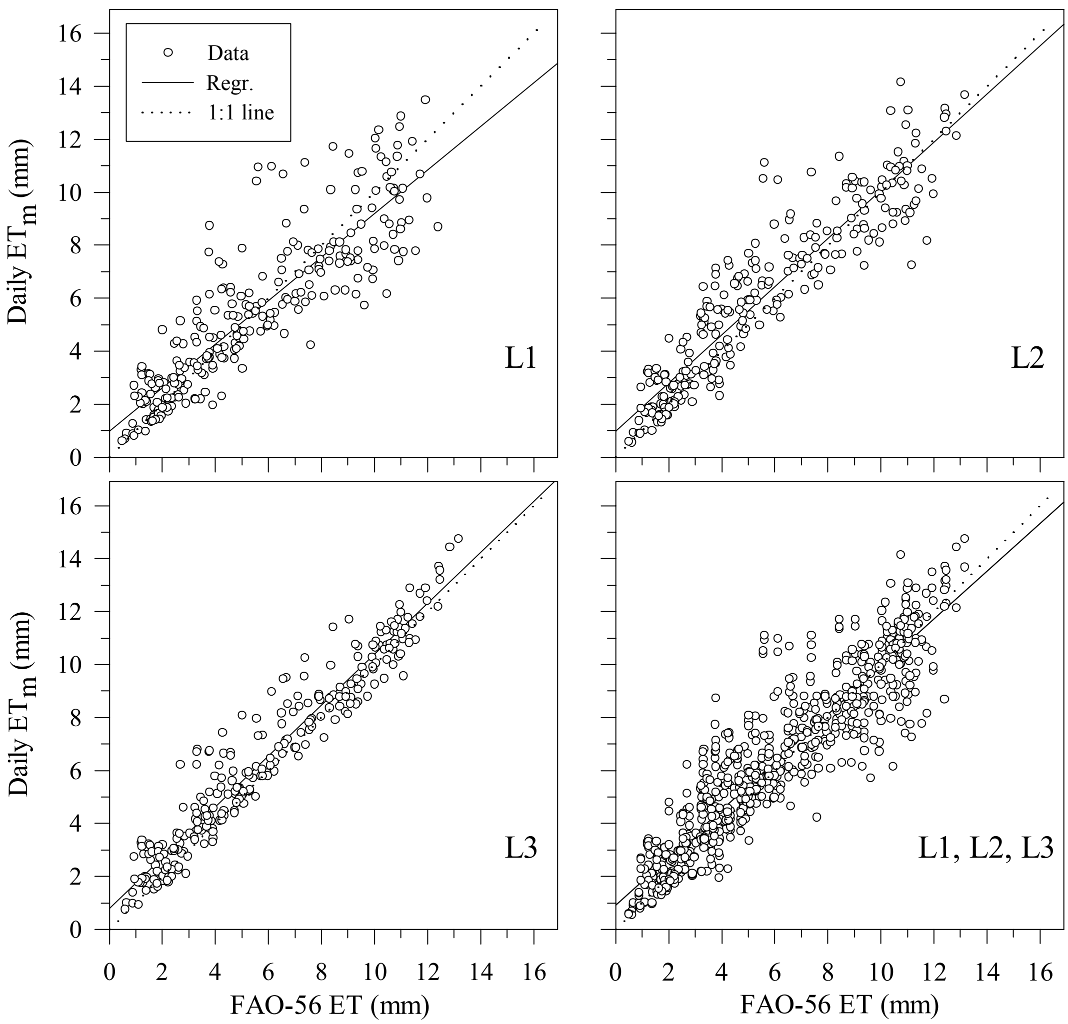

Figure 2. Linear regression of measured and predicted ET using the single K_c model of FAO-56.

INTERPRETATION: Preliminary findings from lysimeter studies indicate the single K_c model of FAO-56 adequately predicts alfalfa ET during mid- and late-season stages of the growing cycle. However, for estimating crop water use on a daily basis at the precision needed to improve irrigation management, evaporative water losses from the soil need to be accounted for more accurately.

FUTURE PLANS: The alfalfa lysimeter data will be used to develop local K_c and K_{cb} curves for alfalfa and also to determine whether the more complicated dual crop coefficient procedure of FAO-56 improves the prediction of measured ET. Additional studies are being conducted more accurately to model the limiting effects of soil water stress on crop ET and to develop information on soil evaporation parameters for soils in the area.

COOPERATORS: Wenzhao Liu, Institute of Soil and Water Conservation, Chinese Academy of Sciences and Ministry of Water Resources Engineering, Yangling, Shaanxi, P.R., China.

DEVELOPING GUIDELINES FOR "FERTIGATION" IN SURFACE-IRRIGATED SYSTEMS

F. J. Adamsen, Soil Scientist; D. J. Hunsaker, Agricultural Engineer; and
A. J. Clemmens, Supervisory Research Hydraulic Engineer

PROBLEM: Applying fertilizer through irrigation water, when properly done, can be a highly effective fertilizer management practice. Compared to conventional field spreading or soil injection techniques, this method of fertilizer application, "fertigation," offers certain advantages such as reduced energy, labor, and machinery costs. Moreover, it allows growers to apply nutrients in small amounts throughout the season in response to crop needs without the potential crop damage or soil compaction caused by machinery based application methods. Although fertigation is more commonly associated with microirrigation and sprinkler irrigation systems, injecting nitrogen (N) into irrigation water has become increasingly frequent and widespread among surface irrigation growers in the western United States. However, unlike pressurized irrigation systems, which are designed to apply controlled and precise amounts of water to the field, application of water by many surface irrigation systems can be highly nonuniform and is often subject to excessive deep percolation and surface water runoff. Consequently, N-fertigation through surface irrigation systems may result in fertilizer being distributed unevenly throughout the field and potential nitrate-nitrogen (NO_3-N) contamination of groundwater through deep percolation and of surface water through tailwater runoff. Because the environmental fate and distribution of nitrogen applied in surface irrigation water has not been studied extensively in the field, adequate N-fertigation management guidelines have not been developed.

APPROACH: The primary objective of the research is to develop information that will lead to best management practices (BMPs) for N-fertigation through surface irrigation systems. The project will derive this information through a series of extensive farm-scale field experiments conducted on representative surface irrigation systems commonly used in the western U.S. The measurement objectives include the determination of the spatial distribution and seasonal variation of N within the field and the relative potential of groundwater and surface water contamination as a function of the timing and duration of N injection during the irrigation event. Irrigation water application distribution will also be determined for each irrigation. Ultimately, the data derived from this project will be used to incorporate chemical fate and transport components into existing soil water and surface irrigation simulation models, which once validated, will allow more comprehensive evaluation of fertigation practices and an expansion of BMPs for conditions and irrigation systems other than those encountered in this project.

In 1999 the mobile tracer potassium bromide (KBr) was used during two simulated N-fertigation events for cotton grown in furrowed level basins on a sandy clay loam at the Maricopa Agricultural Center (MAC). The first fertigation was conducted following cultivation, which provided a rapid infiltration rate and a high degree of surface roughness. The second event was carried out during the third irrigation following cultivation with lower infiltration rates and less surface roughness than the first fertigation. During both events, three fertigation application treatments were evaluated - KBr injection during 100%, first-half, and last-half of the irrigation application. Water was applied to five furrows in a 185-m-long field. Soil samples were taken before and after the event to a depth of 1.2 m in the turnaround area at the head of the field and every 30 m along the run. In the turnaround area, two samples were taken; and at the sampling locations along the length of run, samples were taken from two adjacent cotton beds and from the furrow bottom of a wheel and non-wheel furrow. Samples were analyzed for bromide concentration. Irrigation parameters measured were advance and recession times, flow rate, and surface water depth.

FINDINGS: During the first fertigation event, water advanced more quickly in the wheel furrow than in the non-wheel furrow. As a result, water reached the end more quickly in wheel furrows and filled the non-wheel furrows from tail end. The infiltrated depths for 100% of the irrigation were very close for both furrows in spite of water moving from the wheel furrow to the non-wheel furrow during advance (Figs. 1 and 2). While this did not decrease the overall irrigation uniformity, filling the non-wheel furrow from the tail end changed the pattern of infiltrated depth. In the non-wheel furrow, there was a peak in the water infiltrated depth during the first-half of the irrigation between 100 m and the end of the field that would not have occurred if the furrows had been blocked on the tail end. It is interesting to note that the infiltrated depth of water from the first-half of the irrigation was relatively uniform over the first 100 m for both furrows. There was an equivalent movement of water from the non-wheel furrow that moved back into the wheel furrow during redistribution following the completion of advance.

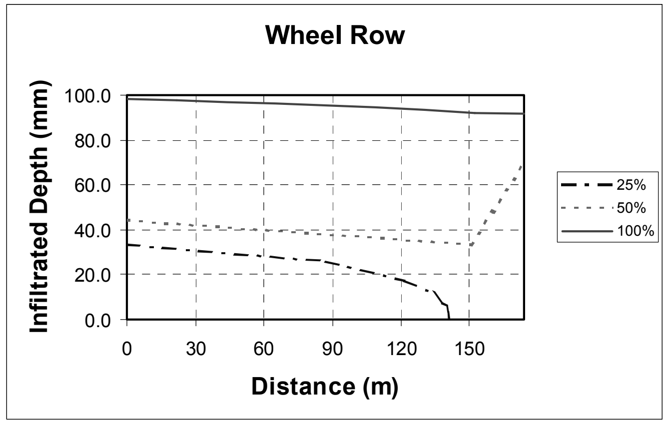

Figure 1. Cumulative one-dimensional infiltrated depth with distance after 25, 50, and 100% completion of irrigation for the wheel furrow of a fertigated furrowed level basin.

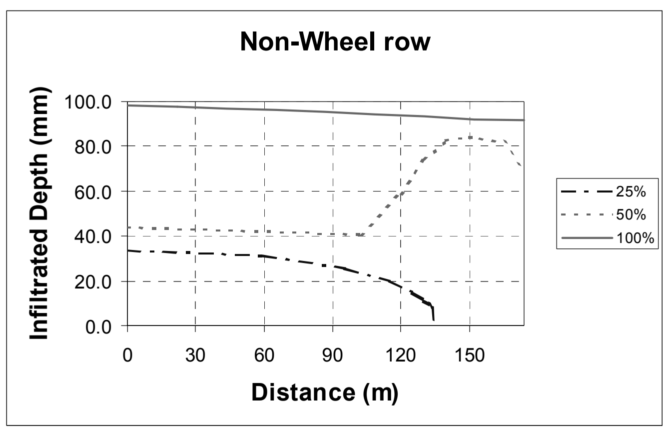

Figure 2. Cumulative one-dimensional infiltrated depth with distance after 25, 50, and 100% completion of irrigation for the non-wheel furrow of a fertigated furrowed level basin.

Presently, bromide concentration has been analyzed only for the top 300 mm of soil. In general, the bromide distributions for the top 300 mm, when averaged across all of the sampling positions within a sampling site, agreed well with the estimated infiltrated water distributions (Fig. 3). The bromide distributions in the first-half and 100% treatments were similar and uniform along the entire field length, as was the infiltrated water (Figs. 1 and 2). There was more bromide at the head end of the field than would be predicted from the infiltrated depths for the last-half treatment (Fig. 3). This may be the result of mixing, or deeper penetration into the soil than the 300 mm of soil depth accounted for here.

An examination of the bromide distribution for individual sampling locations shows some interesting trends (Fig. 3). The in-row concentrations of bromide were higher in the first-half treatment than in the 100% treatment. This is probably due to higher concentrations of the bromide in the water moving laterally into the row from the furrow in the first-half treatment than in the 100% treatment. The bed is infiltrated by the first water applied and the concentration of bromide in the first-half treatment was double the 100% treatment during the injection period. Bromide concentration increased at the tail end of the field in the first-half treatment which corresponds to changes in the infiltrated depth at the tail end of the field, but the trend in bromide concentration was weak.

The change in bromide concentration in the last-half treatment from the head to tail ends of the field is consistent with the infiltrated depth but the magnitude was much greater than would be expected (Fig.34). The peak in the bromide concentrations at 90 m in the last-half treatment for the furrows was unexpected. All of the data suggest that bromide moved below the top 300 mm of soil.

INTERPRETATION: Analysis of the remaining soil depths should provide a more complete picture of the fate of chemicals added in the irrigation stream, but a simple advection model appears to be a promising first step in estimating the application uniformity of water-applied chemicals. This type of experiment needs to be conducted over a variety of conditions to determine the amount of mixing that takes place during an irrigation event.

FUTURE PLANS: Analysis of remaining soil samples will be completed. Additional experiments have been conducted on cotton with longer runs and different soil and on wheat planted on the flat. Samples from those experiments are being analyzed. Similar data sets will be developed for unfurrowed level basins and furrowed and unfurrowed sloping borders with and without runoff over a variety of soil types and lengths of run in Arizona and California. When completed, the data sets will provide a sufficient range to develop fertigation guidelines for a large portion of the surface irrigated acreage in the western United States.

COOPERATORS: Mr. Donald Ackley, Program Coordinator, Coachella Valley Resource Conservation District, Indio CA; Dr. Bob Roth, station director, Maricopa Agricultural Center, Maricopa AZ; Dr. Charles A. Sanchez, director, and Dr. Dawit Zerihun, Irrigation Engineer, Yuma Agricultural Center, Yuma AZ; Dr. Pete Waller, Agricultural Engineer, Dept. of Agricultural and Biosystems Engineering, The University of Arizona, Tucson AZ.

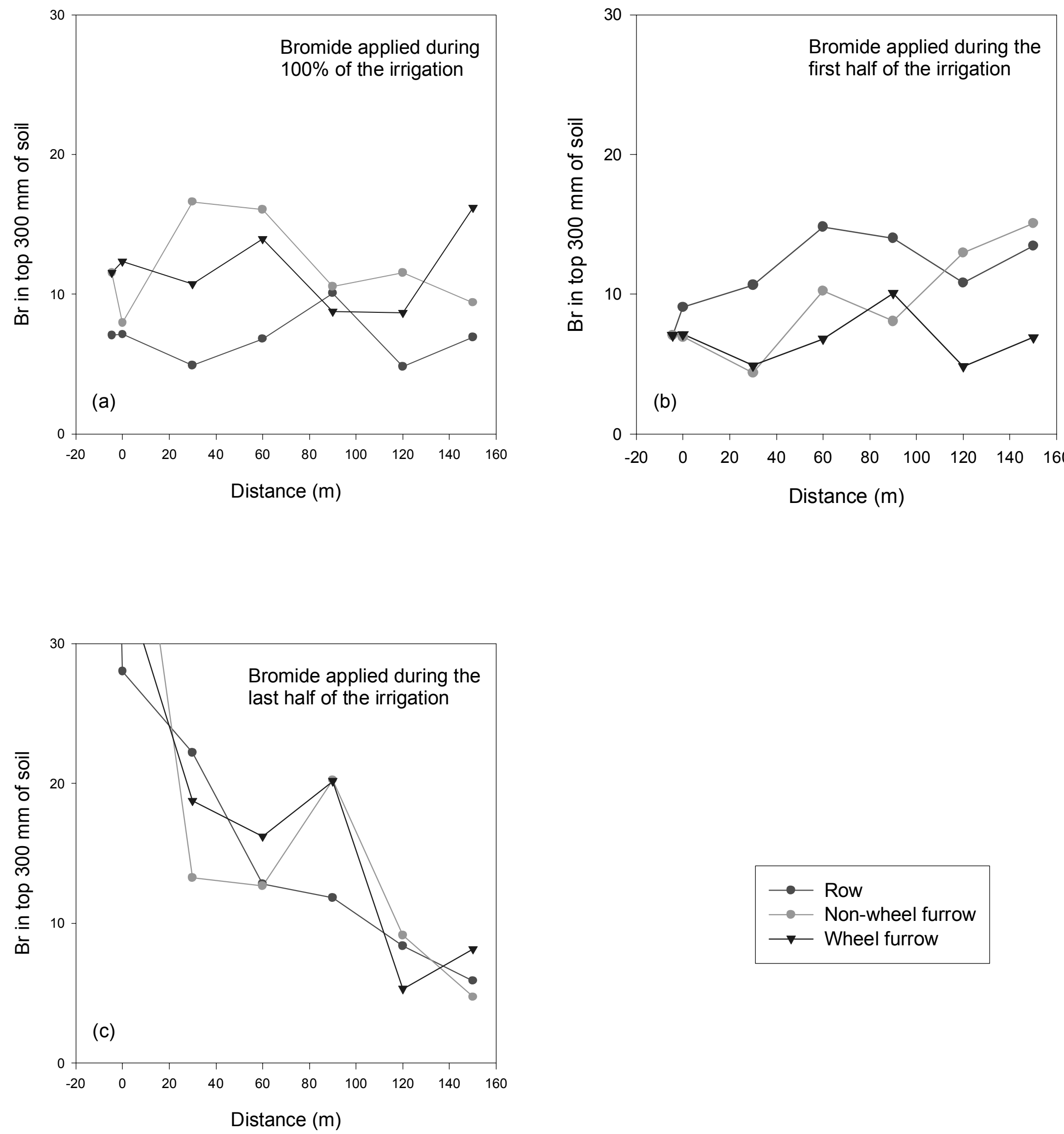

Figure 3. Changes in concentration (mg kg^{-1}) in soil bromide in the top 300 mm of soil from pre-fertigation sampling to post-fertigation sampling for the average of two in row values and for wheel and non-wheel furrow for (a) 100%, (b) first-half and (c) last-half of irrigation injection.

MEASURING SOIL MOISTURE UNDER SALINE CONDITIONS WITH SELF-CONTAINED TDR SENSORS

F. J. Adamsen, Soil Scientist; and D. J. Hunsaker, Agricultural Engineer

PROBLEM: Accurate and reliable soil moisture information is a fundamental requirement in achieving efficient water utilization in irrigated agriculture and in a number of related industries as well. Time domain reflectometry (TDR) and frequency domain reflectometry (FDR) are recognized as established methods for determining soil water content in mineral soils. Both TDR and FDR infer water content from changes in the soil dielectric constant. In the TDR method, this is accomplished by measuring the velocity of an electromagnetic pulse along a pair of rods in the soil. In the FDR method, it is accomplished by measuring the frequency of a tuned circuit which changes as the capacitance of the soil changes due to fluctuations in soil moisture. Initially, the TDR method was considered to be universally applicable over all soil types and soil conditions. However, it is now recognized that widespread application of TDR, and other similar technologies, has been limited due to erratic measurement responses in soils having high salinity. Some success has been made in using TDR signal attenuation to measure soil water salinity, but the technology has not been advanced to the point where this can be accomplished without the use of highly sophisticated and expensive TDR systems.

Soil salinity is recognized as a problem in over one-half of the irrigated lands in the Western United States. It is expected that soil water measurements from commercial TDR and capacitance systems may be used to guide irrigation management on salt affected lands. The objective of this study is to evaluate the effects of soil electrical conductivity on measurements of soil water content by four commercial soil moisture systems (TDR cable tester, two encapsulated TDR systems, and one encapsulated electrical capacitance sensor).

APPROACH: Studies with four commercial dielectric soil moisture systems were conducted in a sand tank in which volumetric soil moisture contents varied from 34 to 12%. The systems evaluated were (1) Trase System 16050x1 (Trase), a TDR cable tester unit with a standard, uncoated, three-rod, “burial-type” probe 0.2 m in length (Soilmoisture Equipment Corp., Santa Barbara, California); (2) Aqua-Tel-TDR (Aqua-Tel), an encapsulated TDR with epoxy-coated multiple probes 0.46 m long (Automata, Inc., Grass Valley, California); (3) Delta-T ThetaProbe ML2x (Theta), an encapsulated electrical capacitance sensor with a four-rod probe 0.06 m in length (Dynamax Inc., Houston, Texas); and (4) Trime-IC (Trime), an encapsulated TDR with a coated two-rod probe 0.11 m in length (Mesa Systems Co., Framingham, Massachusetts).

The tank used in the experiments was a 0.19-m deep tapered masonry trough constructed of high-density polyethylene. The soil medium was a washed sand commercially available for concrete and plaster mixture. Three holes were drilled along the longitudinal center line of the tank bottom. One hole was at the middle of the center line and the other holes were 0.25 m either side of the center hole. The outside holes were fitted with bulkhead fittings and ≈ 0.45 m of tubing attached to the barbed nipple on the fitting. Four pieces of 13 mm diameter cotton-fiberglass wicks 0.2 m long were sewn together to form a double tee pattern. A fifth piece of wick material was attached at the center of the double tee, perpendicular to the plane of the tee. The last piece of wick attached to the system was fed through the center hole and then through a powder funnel with an outlet tube that had been glued to the bottom of the tank with a silicon adhesive. The double-tee pattern was laid in the bottom of the tank extending from either side of the center hole along the longitudinal center line of the tank and forming a tee in each half of the tank. An additional piece of tubing was then forced over the end of the funnel to complete the drainage system in the sand tank. Free water drained from the outside holes, and the wick system drained capillary water from the system and had the effect of creating a water table 0.2 m below the bottom of the tank. The tubes from the three holes were gathered together in a wooden loom and the drainage water was directed into a bucket.

When the tank was filled with sand to a depth of 0.08 m, the three encapsulated systems and the burial probe of the Trase system were placed horizontally across the top of the sand surface approximately 0.10 m apart from one another. Additional sand was then added to the tank, burying the sensors, until the tank was filled to a depth of 0.16 m. Prior to filling, the sand volume within the tank system was estimated by measuring the volume of water required to fill the tank to a depth of 0.16 m. This volume was used to calculate an estimated bulk density of the sand, yielding a value of 1650 kg m^{-3}.

The three encapsulated systems were connected to a data logger and a 12 V DC power source. This configuration allowed simultaneous and automated collection of the mV output from the sensors at desired time intervals. The Trase system provided its own automated logging of volumetric water content measurements.

The soil water salinity of the system was manipulated by adding a range of sodium chloride (NaCl) concentrations to the tank that yielded soil water salinities within the sand bed of approximately 2, 5, 7, 10, 12, and 15 dS m^{-1}. Prior to each test, the sand in the tank was conditioned by leaching it with the desired solution four times to displace any water in the system. After the fourth leaching cycle, sensor testing was begun. After water had drained from the sand tank for seven days the test was ended. At the end of each test, drainage water and soil samples were taken. Holes left from the soil sampling were refilled with new sand.

The output from the Trase system was used to estimate the actual soil water contents of the sand because it was impractical to obtain gravimetric water content samples with sufficient frequency. Salinity level and mV output for each encapsulated sensor were used for the independent variables in multiple linear regression to predict the Trase volumetric water contents over a range of water content data deemed reasonable.

FINDINGS: Including solution salinity along with the sensor output in the regression explained 89 to 93% of the variability in volumetric soil water content for the three encapsulated sensors (Table 1). Negative regression coefficients for solution salinity resulted for all three self-contained sensors, since the outputs for each sensor were increased with increasing salinity.

The deviations from the fitted equations (Fig. 1) indicated that the Aquatel-TDR and Trime sensors both overestimated the soil water contents in the middle of the data range and underestimated the water contents at the high and low ends, whereas the opposite trend was true for the Theta sensor1.

Table 1. Multiple linear regression results for volumetric water content values (θ) as measured by Trase against sensor output in mV and solution salinity in dS m^{-1} (EC_s), where y_0 is the intercept, a is the slope of the sensor output, b is the slope of the solution salinity and R^2 is the multiple coefficient of determination ($\theta = y_0 + a * mV + b * EC_s$).

Sensor	y_0	a	b	R^2
Aquatel-TDR	6.44	0.0074	-0.845	0.893
Theta	-4.46	0.0685	-0.150	0.931
Trime	-2.65	0.127	-0.320	0.886

INTERPRETATION: As a first approximation, a simple multiple linear model fitted the data well. However, because of the systematic deviations of the data from the fitted equations, a more complex model will probably be required to calibrate these sensors in saline soil conditions adequately. The above regressions are also not useful for field use since solution salinity is not an appropriate indicator of soil salinity. What is needed is bulk soil salinity estimates, which can then be used to determine the correction for the sensor output that will yield the true soil water content from the sensor reading. The bulk salinity includes the contribution of the soil matrix as well as the soil contribution.

FUTURE PLANS: We plan to develop a method to estimate the bulk salinity for this data set and to use those values to develop a model that predicts actual soil moisture from the sensor output and bulk salinity. We also plan to determine the response of the sensors to different forms of salt. We will use Mg SO_4 in a similar set of experiments to determine if salt type affects the response of the sensors in addition to salt concentration.

COOPERATORS: Lenny Feuer, Automata Inc., Nevada City CA.

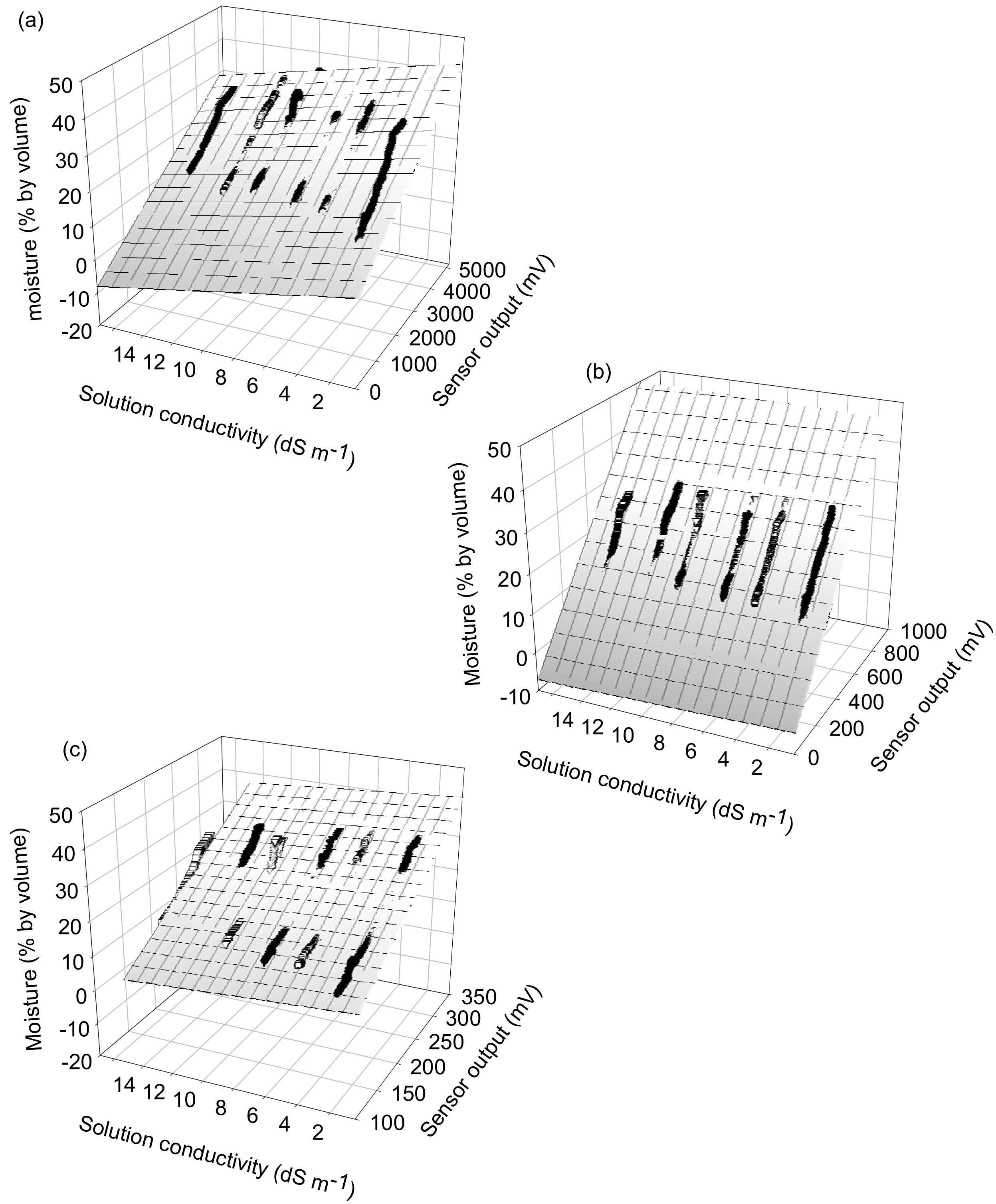

Figure 1. Response surfaces of (a) Aquatel-TDR, (b) Theta, and (c) Trime to moisture content versus solution salinity and sensor output.

SURFACE IRRIGATION MODELING

T.S. Strelkoff, Research Hydraulic Engineer; and
A.J. Clemmens, Supervisory Research Hydraulic Engineer

PROBLEM: Throughout the irrigated world, water is applied to fields unevenly and excessively, leading to wastage, soil loss, and pollution of surface and groundwaters. Computer modeling would allow rapid evaluation of physical layouts and operation in a search for an optimum; but most models are limited to single furrows, or border strips and basins with zero cross-slope and a uniformly distributed inflow at the upstream end. Yet large basins are usually irrigated from a single inlet. The flow spreads out in all possible directions, and any one-dimensional simulation must be viewed as a very coarse approximation. A non-planar basin surface influences the flow as well. An irrigation stream concentrated in the lower-lying areas can significantly affect infiltration uniformity. Only a two-dimensional model can simulate these factors.

While a one-dimensional approach is suitable for furrows in real fields, flows in neighboring furrows of a set are often coupled through common headwater and tailwater ditches. Tailwater from a fast furrow can enter a slower furrow from its tail end and modify its ultimate infiltration profile. To appreciate the effects of such coupling fully, simulation of interconnected furrows is necessary.

Irrigation management can influence the quality of both surface and groundwaters as well as of the field soils. Irrigation streams can be of sufficient power that soil erodes, with the material entrained into the stream and transported downfield, reducing soil fertility upstream. Farther downstream, as infiltration reduces the discharge or as the result of slope reduction, part of the load, perhaps only the coarse fractions, might deposit back onto the bed. Or else, entrained material can run off the field, introducing turbidity into drainage water or deposit in quiescent areas to the detriment of aquatic life.
Chemigation introduces agricultural chemicals into the irrigation water. Alternately, initially clean irrigation water picks up agricultural chemicals and naturally occurring minerals, some toxic, from the surface of fields and from contact by percolation through the porous soil medium. Nitrogen, phosphorus, and heavy metals, for example, brought to farm fields in agricultural operations and naturally occurring chemicals, such as selenium, can be transported to surface or subsurface water supplies by irrigation water to the detriment of both human consumers of the water resource and wildlife dependent on the receiving water bodies. Nutrients or pesticides adsorbed to eroded soil in irrigation tailwater is an important example.

APPROACH: The objectives of current work are validated computer simulation models for providing quick responses to a wide variety of "what-if" situations. For example, the trade-offs between irrigation efficiency and uniformity, on the one hand, and soil loss, on the other, could be explored. Recommendations could then be made on the basis of environmental considerations as well as water conservation and crop yield. Funding for this effort has been provided in part by the Natural Resources Conservation Service.

For one-dimensional single-furrow, border, or basin simulation, user-friendly menu-driven data input, as well as output graphs and text, are linked to a simulation engine based on the universal laws of hydraulics applied implicitly in fully nonlinear form. Constants in commonly accepted empirical equations for infiltration, roughness, and soil erosion are entered as input. The computer model SRFR is based on this approach.

Two-dimensional simulation is also based on hydraulic principles. Under the assumption of flow velocities small enough to neglect accelerations, force components in each of two mutually perpendicular directions on the field are in equilibrium. The resulting parabolic partial differential equations, solved implicitly by locally linearized finite differences in the two directions and time, yield a wave-like solution encompassing both wet and dry areas of the field. A similar but one-dimensional approach, treating wet and dry cells uniformly, is applied to multiple coupled furrows.

Erosion, transport, and deposition of irrigated soil is too complex to simulate on the basis of general physical principles alone. Currently, it is *fundamentally* an empirical science, in which the trend in recent years has been toward ever more general relationships, containing as much general physics as possible. Many conceptual models of parts of the total process have been proposed in order to avoid pure empiricism; but these are only partially convincing, with researchers intuitively leaning toward one or another. The measures of a good predictive relationship or procedure are its generality with respect to different soils and different irrigation conditions and ability to predict soil transport at different locations in a furrow, especially in the tailwater runoff, at all times during the irrigation. Apart from the median size of particles in the soil bed and transported in the irrigation water, the mix of particle sizes plays a significant role in the redistribution of soil along the furrow and in the total load transported with the runoff. An especially critical effect of the size distribution has to do with the total surface area of sediment in transport, for that relates directly to the load of chemicals, such as phosphorus, adsorbed to the eroded soil.

Chemical interactions take place between irrigation water in which the chemical may be dissolved, the soil bed on which the chemical may be precipitated or adsorbed, and sediments in transport on which the chemical may be adsorbed. The partitioning of a chemical amongst these media depends on the specific chemical of interest, upon the soil and water chemistry and temperature, and on the surface areas of sediment particles in transport. In the advection-diffusion equations coupled to the hydraulic water-flow equations and describing the fate and transport of the chemical, these interactions lead simply to source/sink terms. Mixing is assumed complete in the transverse direction. Longitudinal dispersion follows from both the transverse turbulent mixing and the transverse velocity distribution, assumed logarithmic. As a first approximation, fate and transport of any chemical is assumed independent of those for any other.

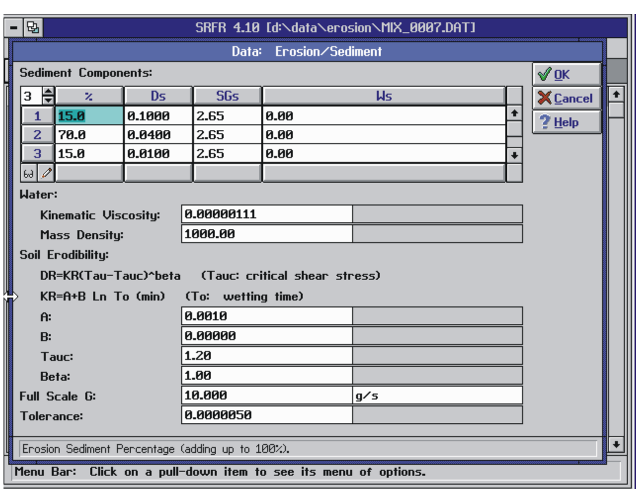

Figure 1 Data-input screen for specifying field data, including particle-size distribution, for erosion computation.

FINDINGS: The SRFR surface-irrigation and erosion simulation model includes three methods to treat particle-size distributions in calculating the flow's sediment-transport capacity. Figure 1 shows the interactive data-input screen for entry of data pertinent to an

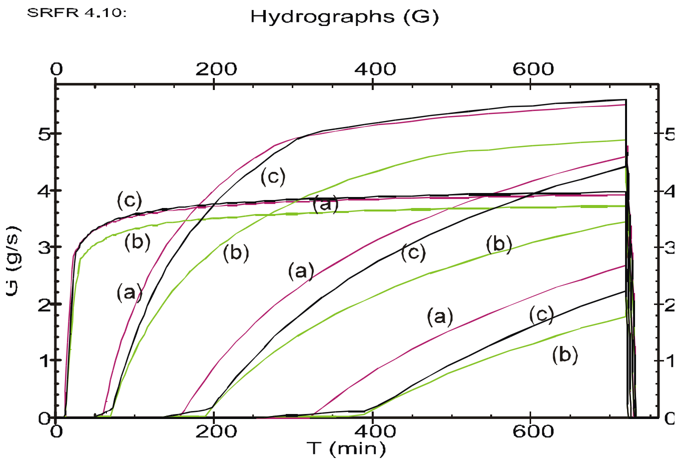

Figure 2 Influence of treatment of particle-size distribution on transport capacity and consequent total sediment load at furrow quarter points; (a) distribution represented by median diameter; (b) as per WEPP (1995); (c) as per Wu and Meyer (1989).

erosion simulation, including the particle size distribution. Figure 2 compares simulated total sediment loads at the quarter points along a furrow's length with the three different treatments of particle-size distribution: (a) a single representative size, the median diameter; (b) weighted in accord with the fraction in the soil mix (WEPP, 1995); and (c) weighted in accord with carrying capacity for the particular size relative to the sum of carrying capacities for each size (Wu and Meyer, 1989; Fernandez, 1997). The particular hypothetical mix of sand (15%), silt (70%), and clay (15%) shown had a mean diameter of 45 microns, a standard deviation of 25 microns and a skew coefficient of 1.2. A less uniform mix with a standard deviation of 33 microns showed considerably more spread in the results.

A pilot two-dimensional model was subjected to intensive validation in a 3 ha irregular basin at the Gila River Farms, which is partially blocked by a raised roadway and irrigated from the center of one side. Figure 3 shows calculated depths after 23 minutes. Monitoring water levels in 26 locations and a land-level survey allowed estimation of the soil infiltration characteristics. Figure 4 shows comparisons of measured water surface elevations at several locations with those computed in the nearest cells. Computational cells straddle depth-measurement station #4. The computations generally agree with field data.

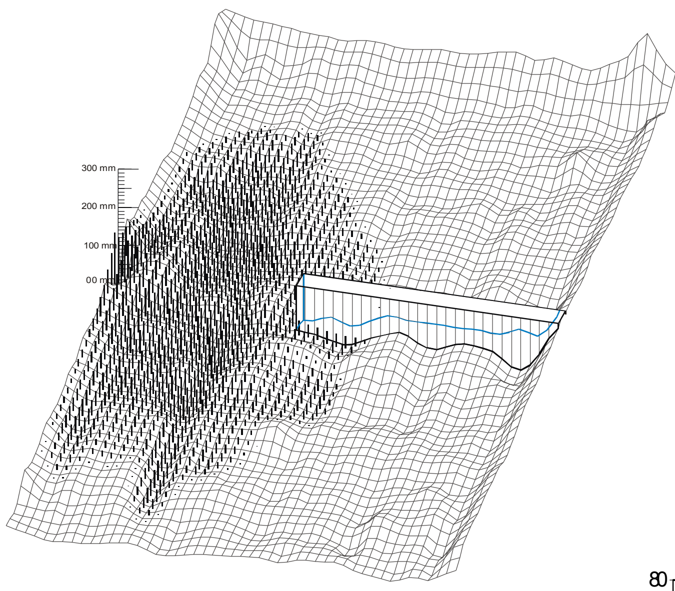

Figure 2 Simulated depths as irrigation stream encounters raised roadway

INTERPRETATION: The growing body of simulation software is finding users in the national and international irrigation community for design, management, and evaluation of surface irrigation. It is likely

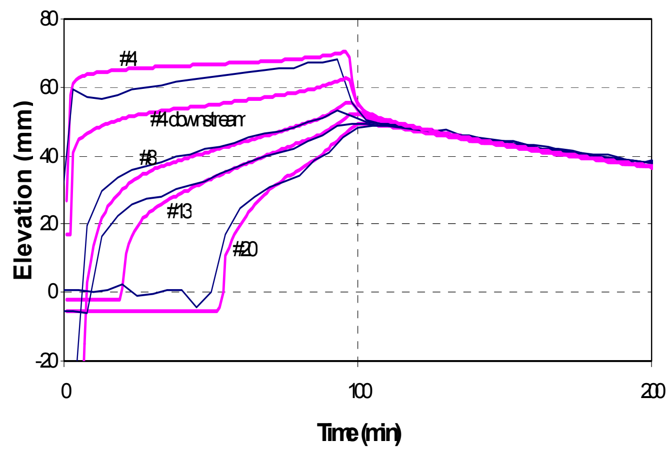

Figure 4 Comparison of simulated (broad grey) and measured (narrow black) depth hydrographs.

that studies of the interrelationship among distribution uniformity, standard deviation of surface elevations, and inflow rate will provide a useful adjunct to current design software. Predictions of soil erosion, transport, and deposition are significantly less accurate than predictions of hydraulic performance; but the influence of design and management is easy to see, so that these aspects also can be taken into account.

FUTURE PLANS: Individual groups of particle sizes will be tracked through the entrainment/transport/deposition process to yield more accurate estimates of total sediment loads less sensitive to field-data values. A fate and transport of phosphorus component will be added to SRFR (requiring calculated estimates of total surface area of transported particles) under a 3-year competitive grant from NRI-CGP (CSREES).

The opportunity to enter field measurements of surface-irrigation performance (advance, recession, hydrographs, etc.) and plot comparisons with simulations will be added to SRFR. As funding becomes available, coalescing of successive surges will be added to SRFR. Likewise, the two-dimensional pilot model will be reoriented toward routine application. Increasing the allowable time step, currently very small in basins with a fine grid of soil and water surfaces, will be explored. A multiple-furrow model will be completed, and additional field verification for both the two-dimensional and the coupled-furrows programs will be sought, pending outside financial support.

Long-term plans include recasting the suite of stand-alone DOS-based surface-irrigation software into true Windows programs sharing common input data screens and allowing linkage to common databases. Incorporation of relationships for cohesive soils, a relatively poorly understood area in the field of sediment transport, is envisaged. Incorporation of soil and water chemistry components is contemplated as water and soil salinities play a great role in erosion, especially in clays. Estimates of the pre-wetting effect for surge irrigation should be included. Pre-wetting phenomena have been shown to have a significant effect on detachment; but virtually all of the WEPP erosion database is for pre-wetted (rained-on) soils, which do not exhibit the violent fine-scale commotion observed at the front of a wave of irrigation water in a dry, powdery bed. Also, soil and water temperature effects on infiltration and erosion require quantification. As funding becomes available, nitrogen transport and fate will be included in SRFR.

COOPERATORS: Thomas Spofford, Natural Resources Conservation Service, National Water and Climate Center, Portland OR; Luciano Mateos and Rafael Fernandez, Instituto de Agricultura Sostenible, CSIC, Cordoba, Spain; Dale Westermann, David Bjorneberg, Rick Lentz, Robert Sojka, ARS Northwest Irrigation and Soils Research Laboratory, Kimberly ID; Thomas Trout, Water Management Research Laboratory, Fresno CA; Charles Sanchez, University of Arizona, Yuma AZ; Marshall English, Oregon State University, Corvallis OR; Roger Stone, Gila River Farms, Pinal County AZ; Rien van Genuchten, Jirka Simunek, Don Suarez, ARS Salinity Laboratory, Riverside, CA.

WATER PROJECT MANAGEMENT

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WATER PROJECT MANAGEMENT

MISSION

To develop tools for the management and augmentation of water supplies in arid-region water projects, particularly those associated with irrigation. This includes methodologies for measuring and monitoring water fluxes with natural and man-made systems, methods for improving control of water within distribution networks, conjunctive management of groundwater and surface water supplies, artificial recharge of groundwater, natural water treatment systems (e.g. soil-aquifer treatment), and methods for assessing the performance of water projects in terms of water quality and quantity management.

MEASUREMENT AND CONTROL OF WATER FLOW UNDER DIFFICULT CONDITIONS

J.A. Replogle, Research Hydraulic Engineer, and B.T. Wahlin, Civil Engineer

PROBLEMS: Many flow conditions in irrigated agriculture and watershed studies are not amenable to the use of simple flumes and weirs. Other measurement devices and methods are often more expensive, more difficult to use, or less accurate than needed for field applications. Improvements in these other methods would compliment flumes and weirs. Interest continues in flow profile conditioning in pipes, applications of flow meters to irrigation wells, and automatic regulation of flow to lateral canals. More design information is needed for flap gates, which are sometimes used to prevent back flows in lowland situations. Radial gates are frequently used to control flows in canals. Their hydraulic behavior needs to be simplified, perhaps with simple structural changes.

Most delivery canal systems use pipes through the canal banks to deliver flows to farm canals. Propeller meters, end-cap orifices, Pitot systems and ultrasonic meters placed in these pipes frequently are subjected to poorly conditioned flow profiles that compromise the meters' operation. All of these are affected by upstream pipe bends and valves. Methods to condition flows and improve the flow profiles would allow the application of many flow metering methods now restricted by these limitations, particularly when short lengths of straight pipe precede the meter.

Even with conditioned flow profiles, some methods experience other limitations. For example, propeller meters readily clog in debris-laden flows and usually can be inserted into trashy flows for only a few minutes. Portable end-cap orifice meters do not attach easily to rusted pipe ends. Pitot systems are considered difficult to apply to discharges from wells without special wall taps and insertion ports. Although effective in solving some pipe and open channel flow measuring problems, ultrasonic flow meters remain too expensive for most irrigation applications.

Fluctuating flow-rate deliveries from a main canal to a secondary canal increase the difficulty of effective irrigation and may require expensive means to monitor total delivered water volume. Mechanical-hydraulic mechanisms hopefully can be developed to stabilize the discharge rate through them, regardless of changes in the level of the source canal. Fluctuating flow-rate deliveries increase the difficulty of effective irrigation and may require expensive means to monitor total delivered water volume. Steady flows can use simple time clocks for total volume.

The several ongoing objectives associated with pipe system flows are: (a) to complete papers and technical notes regarding simplifying the use of portable end-cap orifices (previous Annual Reports); (b) to develop practical methods to achieve effective flow conditioning for flow meters installed in difficult short-pipe situations; (c) to evaluate prototypes of clog-resistant propeller meters that have been manufactured to our suggestions; (d) to place current study of the rubberized flap gates into historical perspective with previous flap gate designs, and (e) to modify the edge of a radial gate in attempts to simplify its hydraulic behavior.

APPROACH: Flow-profile conditioning in pipes will include insertion of orifices and sidewall vanes. A special 30-inch diameter pipe facility is being used for conducting these tests. The same pipe system has been modified to allow testing of a pipe flow control concept using the proposed new valving and bag obstruction system.

Testing will continue on the new design of float-operated valves that can be used in combination with a water inflated bag to maintain a desired flow level in a receiving canal. These are cross-referenced to the related "Pipe-Flow" project report for the pipe flow situations. These modifications for channels will be reported herein. The objective is to develop applicable hydraulic flow control devices where access to electricity may not be convenient and to evaluate the effectiveness of their function. This is an extension of the previously developed DACL (Dual Acting Controlled Leak) systems with a view to generalize the applications and to reduce cost.

Tests on the end-cap orifice system are complete. An alternate pressure tapping method was studied that used a small static pressure tube (with holes drilled through its walls), similar to that used for the Pitot system described last year, to detect the pressure in the approach pipe upstream from the orifice. The tube was inserted through a grommet-sealed hole in the face of the orifice plate near the pipe wall so that the pressure sensed was that for one pipe diameter upstream from the face of the orifice. No further lab data was gathered.

A plastic pipe, O.D.= 1 3/8 inches, was fastened to the closing edge of the radial gate model (Fig. 1) in an attempt to make it less sensitive to the angle of the gate face at different gate openings.

FINDINGS: Flap Gate: The rise of the hydraulic grade line for velocities of approximately 5 feet per second was only 0.01 inches of head even with added weights to the gate. The velocity head (h_v) was calculated to be 0.4 feet. For the higher velocity of about 10 feet per second, the difference was even less, about 0.008 inches, for an h_v of 1.5 feet.

Pipe Flow Control System: The new DACL valving system that was developed, because a commercial version did not provide the needed functions, has only been partly evaluated. The new valve appears to be capable of all required functions but needs further laboratory and field evaluation. A small model of the concept operated as hoped. While the bag concept worked on a small model and appeared to function well, a variety of low-cost bag products tried on the full scale resulted in failures from ripping. Different bag materials are on hand but not yet tested.

End-cap Orifice: The end-cap orifice data have been examined and the data appear consistent. The orifice system calibrated as expected from theory and is more repeatable than corner-taps on a pipe of uncertain end quality. The convenience aspects of the system were demonstrated.

Flow Profile Conditioning: There are no new findings to report.

Propeller Meter: This has been delayed for higher priority studies. There are no new findings to report.

Pitot-tube system for irrigation wells: Second report has been published (Reference.)

Radial Gate: Laboratory testing on the first edge modification involving attachment of a round pipe on the gate edge are completed, but the data have not been fully evaluated.

INTERPRETATION: Flap Gate: While the analysis is still incomplete, preliminary findings are that free discharging flap gates cause negligible increased back pressure on pipelines that are flowing full. This is in contrast to their presence if submerged. Mathematical analysis from historical literature has been only partly successful in describing their behavior. Because design information is not readily available for the free outfall or the submerged gate situations, the current results are being reported in the historical context of some limited previous studies in order to make the information more readily available to designers.

End-Cap Orifice: This version of the end-cap orifice can be installed on well pipe outfalls without any specially drilled holes. The corner tap locations of the original version, which also did not require pipe drilling, are somewhat sensitive to poor pipe-end conditions. While this version cannot be used if the pipe is in badly eroded condition, it is somewhat forgiving. The orifice still requires the installation to provide standard lengths of straight pipe from the last pipe bend.

Pipe Flow Control System: Stable flows in secondary canals permit low-cost totalization of flow deliveries to farms because time clocks will suffice instead of complex recorder systems. Known constant flows allow more precise management of irrigation systems. Indications from limited test runs are that the concept can be made to work. If this proves out, then we should be able to provide economical flow stabilization from main canals to lateral canals (Fig. 2 and 3).

Pitot System: The rugged compact system can be constructed using common shop techniques and standard small pipe fittings, is portable, and disassembles to fit into a standard business brief case. The device can be quickly attached to the flowing well pipe to determine well discharges to within plus or minus 3 to 5 percent. This research facilitates the measurement and management of irrigation wells, providing needed tools for irrigation project technicians worldwide to measure flow from wells and to check the condition of existing meters.

FUTURE PLANS: A report on End-Cap Orifice will be prepared and a technical note on the Flap Gate to make it more available to designers in water resources incorporating some limited historical data. We will continue the laboratory study phase and improve instrumentation for faster data collection on flow velocity distribution and evaluate current data on the Radial Gate to assist in redesigning the lip attachment to a structural angle.

COOPERATORS: Robert Gooch, Salt River Project, Phoenix AZ; John Dickerman, Global Water, Fair Oaks CA ; and John Vitas, Plasti-Fab, Inc., Tualatin OR.

REFERENCE: Replogle, J.A. and Wahlin, B. 2000. Measuring irrigation well discharges. Journal of Hydraulic Engineering, ASCE. 126(5) 335-346.

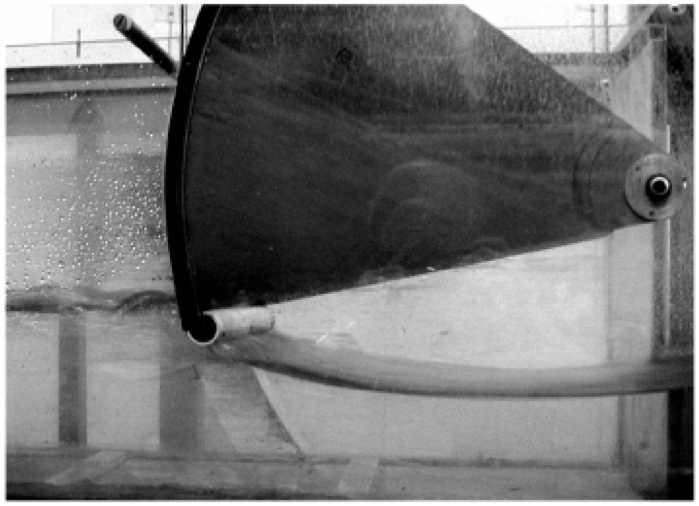

Figure 1. Radial gate with the gate-closure edge modified by attaching a pipe along the edge.

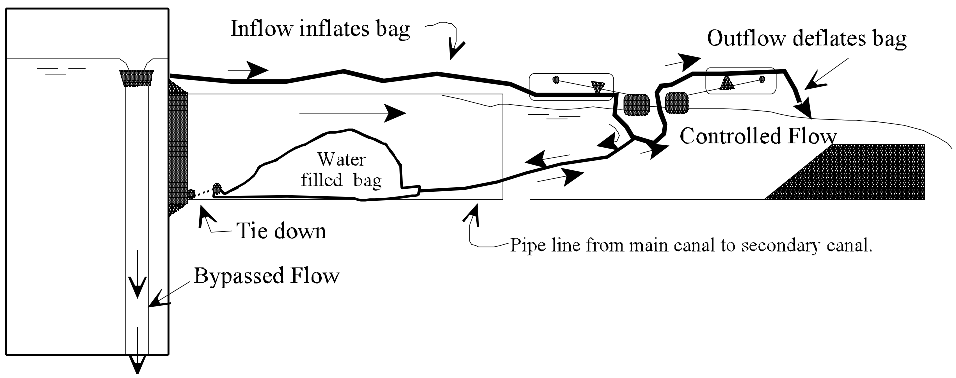

Figure 2. General laboratory set-up for evaluating valve and bag system for flow level control.

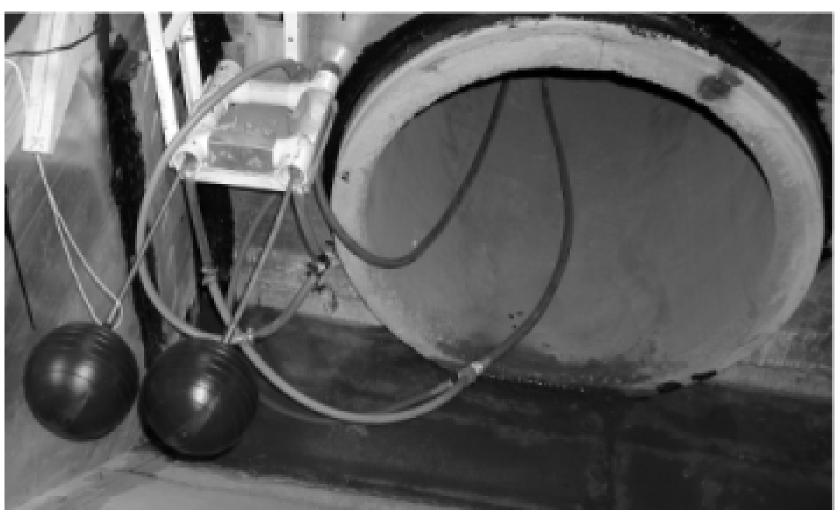

Figure 3. Low-cost float valve system in a pipe outlet channel.

FLOW MEASUREMENT WITH FLUMES AND WEIRS

J.A. Replogle, Research Hydraulic Engineer; B.T. Wahlin, Civil Engineer;
and A.J. Clemmens, Supervisory Research Hydraulic Engineer

PROBLEMS: Continuing concerns involve needs connected to open channel flow measurement and control. These include:

- Sediment-laden discharges in natural streams are difficult to measure because of sediment movements and accumulations.

- One of the most important factors in installing a broad-crested weir is vertical placement of the sill. If the sill is too low, the flume may exceed its limit of submergence. If the sill is too high, upstream canal banks may be breached. While this has been partly addressed with the Adjust-A-Flume, simplifications in its construction and adaptation to economical recorders are still needed.

- The FLUME3 program did not run well with computer systems using Windows operating systems. A revision of the original flume book is needed and should include experiences and construction techniques accumulated over the last decade.

APPROACH: The general objective is to address these problems economically and practically with user-friendly technology.

A prototype self-calibrating flume for sediment-laden flows was designed and installed in northern California (Fig. 1) and has been in operation for over 3 years. The objective was to evaluate the idea of the self-calibrating flume system and to determine its operational limitations in situations where sediment flows ordinarily spoil measurement attempts. 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, are expected to provide field calibration for the chute after the main flume no longer can function because of sediment deposits. A laboratory model was part of a thesis study at The University of Arizona to check 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.

Compilation of field experiences by users of the commercialized version of the patented adjustable-sill, long-throated flume will be used to advise on expansion of the product line and to evaluate field durability and vulnerability to damage from frost and animals. The objective is to evaluate field installations and to assist in design and materials changes that may be needed to hasten technology transfer.

New software being written to make flume calibration and design software compatible with the computer Windows environment will be user tested and supplemented with a user manual, either in paper copy, on-line, or CD versions.

FINDINGS: As previously reported, the California Water Quality Control Board used the flume data from last year to demonstrate the severity of the cinibar (mercury ore) tailings problem to EPA.

Based on that, emergency super-fund money ($2.5 million) to stabilize the mine tailings was authorized. More data have been collected to verify the initial findings and to evaluate progress in the effectiveness of the clean-up.

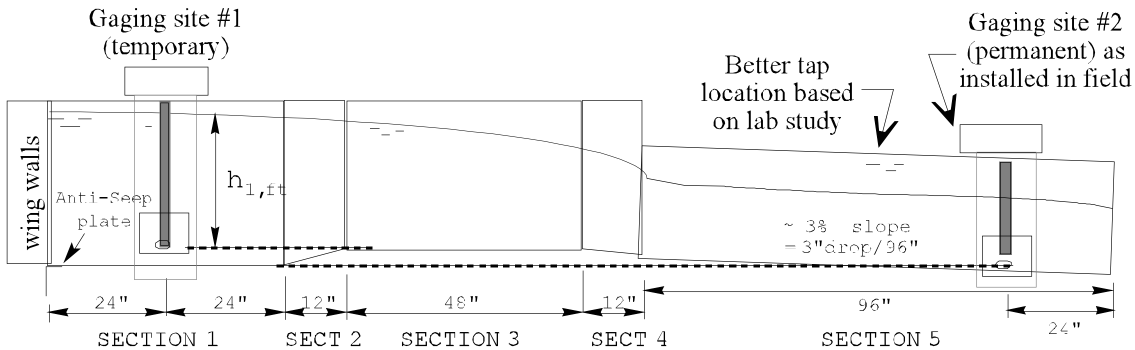

Figure 1. General layout of sediment resistant flume as installed.

The model study of the system showed that the sediment (sand) altered the upstream (subcritical) stilling well as predicted. The model indicated that the detection in the chute will provide discharge rates with errors of less than 5%. The downstream stilling well in the chute (supercritical) 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 the point shown on Figure 1. The speculation is that the chute will need to transition gently to its final slope in order to provide a smooth surface drop. The slight drop provided in the original design caused undulations that made depth measurements difficult. This has not been tested.

As previously reported, field observations and reports have been compiled for flumes ranging in maximum capacity from 200 gpm (12 l/s) to 35 cfs (1 m^3/s). The users continue to find the devices easy to install and able to meet their operating requirements. Widespread acceptance appears to be growing, as is interest in adding recording instrumentation to the product line that is complicated by the movable reference throat level. Commercial components have been identified that hold the possibility for developing a kit to field adjust to many sizes of flumes.

The WinFlume program has been distributed in final versions to over 490 users from 40 countries.

INTERPRETATIONS: The ability to measure flows in heavy sediment carrying flows is important to studies of erosion, runoff, and the effectiveness of best management practices on watersheds. This system expands the range and flume shapes available for such use.

FUTURE PLANS: Design, installation and application changes for adjustable flumes, including evaluation of field performance, will continue. Recent design assistance included changes to accommodate stilling wells to be attached to the smallest flume size. Kits of a possible recording instrumentation system have not been selected or assembled in any kind of final design format. Such a system seems economical and feasible. This system will continue to be investigated to see if it indeed can be demonstrated and evaluated.

Because the WinFlume program has been distributed, we will write a new book/users manual for the WinFlume Program.

COOPERATORS: Informal cooperation exists among: Tony Wahl and Cliff Pugh, US Bureau of Reclamation, Hydraulics Laboratory, Denver CO; Harold Bloom, Natural Resources Conservation Service, Phoenix AZ; Anisa Divine, Imperial Irrigation District, Imperial CA; Joe Kissel and Kirk Kennedy, Salt River Project, Phoenix AZ; Charles Slokum, Wellton Mohawk Irrigation and Drainage District, Wellton AZ; Brian Betcher, Maricopa-Stanfield Irrigation and Drainage District, Stanfield AZ; Jackie Mack, Buckeye Irrigation District, Buckeye AZ; Randy Steward, Plasti-Fab, Inc., Tualatin OR; Don Slack, The University of Arizona, Tucson AZ; Dyan White, California Water Quality Control Board, Sacramento CA; and Charles Overbay, Nu-way Flume and Equipment Company, Raymond WA.

Figure 1. Flow in discharge chute attached to a long-throated flume. The flow calibration is stable despite the rough flow appearance.

SEEPAGE CONTROL WITH MUDDY WATER

H. Bouwer, Research Hydraulic Engineer

PROBLEM: Seepage from ponds, reservoirs, lagoons, wetlands, or other water impoundments often needs to be controlled, usually with earth or plastic linings. Where earth linings are used, the soil material is placed on the bottom and banks and mechanically compacted when the impoundment is dry. However, the soil can also be applied dry or as a slurry to the water itself. The question then is: what gives more seepage control, a compacted soil layer placed on the bottom where the soil is thoroughly mixed, or a soil slurry applied to the water where the coarser particles sink faster than the finer particles, thus creating a lining layer on the bottom that is coarser at the bottom and finer at the top? Another question is: can additional seepage reduction be obtained by applying sodium carbonate or other chemicals that will disperse the clay in the liner?

APPROACH: The effect of placement of an earth lining in an impoundment for seepage control was evaluated in four laboratory columns in 4-inch diameter clear plastic tubing. At the bottom of each column was an 11 cm layer of silica sand. In column 1, the silica sand was covered with a 16 cm layer of Avondale silt loam at optimum water content to give maximum compaction when packed with a rod. The column was then carefully filled with water and a constant water level was maintained to give a water depth of about 160 cm. The other three columns also were filled with water with the same constant level at the top. Column 2 received the same amount (dry weight) of soil as column 1, but it was poured in as a thick slurry at the top of the column. Column 3 also received the same amount of soil as a thick slurry, but it was poured in 5 split applications at least 24 hours apart so that the water in the column had become completely clear when the next slurry was applied. Column 4 received the same amount of soil in the same way but in 15 split applications. Seepage rates were then monitored for about 40 days in which they reached well-defined final values. After the slurries had been applied and the infiltration rates had become essentially constant for at least 20 days, a solution of sodium carbonate was applied to see if further infiltration rate reductions could be obtained by the clay dispersing action of the sodium. Earlier work at the U.S. Water Conservation Laboratory (USWCL) showed that sodium carbonate additions to the water were effective in reducing seepage rates in stock ponds. Using the dose recommendations resulting from that work, each column received 17 grams of sodium carbonate dissolved in 500 ml water. The salt solutions were placed deep into the water so that they would be close to the infiltrating soil surface.

FINDINGS: Table 1 shows the final infiltration rates at about 40 days after the soil liners had been placed. The rates ranged from 0.85 cm/day for the 15 split slurry applications to 2.7 cm/day for the compacted soil. The infiltration rate for column 1 (compacted earth layer) started at about 3.7 cm/day for the first 10 days then decreased gradually to about 2.7 cm/day in the next 20 days, where it remained for the duration of the test (next 15 days). The split slurry applications produced continued declines, as shown in Figure 1. Since the seepage rate for the silica sand alone was 9.6 to 11.1 m/day, the earth lining was very effective in reducing the seepage rate, especially when applied as a slurry. The biggest percentage of reduction from compacted earth to slurry applied soil was achieved when the total amount of soil was given in one slurry application (56%). Five split slurry applications gave further seepage reductions and so did the fifteen split applications. However, the additional seepage reductions (i.e., 17% and 15%) were not as high as the 56% reduction obtained from a compacted lining to a one-application slurry-applied lining. Thus, segregation of soil particles in the earth lining achieved with slurry applications gave better seepage control than a uniform compacted liner. In practice, slurry applications can be repeated until an acceptable seepage level is reached.

After the sodium carbonate solutions had been placed in columns 1, 3, and 4 (column 2 was not used because the soil lining had cracked), infiltration rates began to decrease very slowly. After 150 days, they had reached values of 0.49 cm/day for column 1, 0.25 cm/day for column 3, and 0.19 cm/day for column 4. This amounts to additional infiltration reductions of 82%, 75%, and 78%, respectively.
Because of the slowness of the process, the continued reduction must have been caused mainly by clay dispersion rather than by microbiological action. Regardless, the final infiltration rates of about 0.2 cm/day in columns 3 and 4 were much less than the infiltration rate of about 1000 cm/day for the silica sand alone before the soil liners were placed. This is a very significant seepage reduction which may well be a lot less expensive than plastic or other artificial liners.

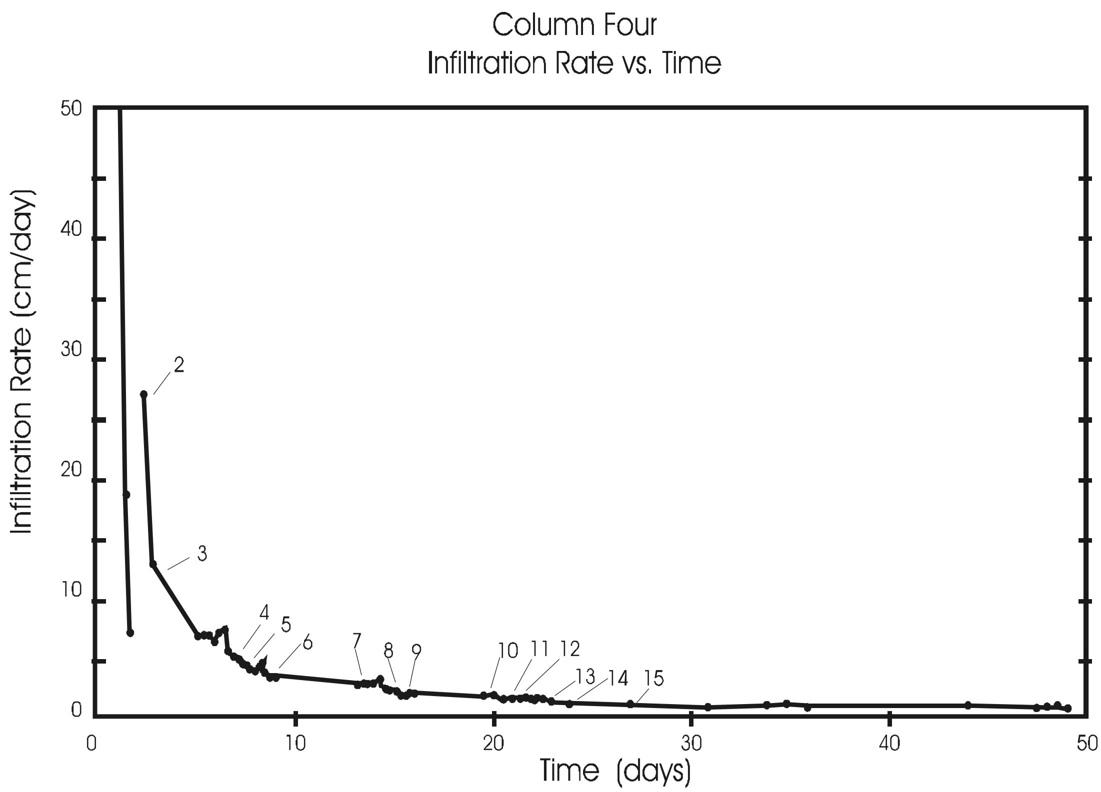

Figure 1. Infiltration rates for column 4 with 15 split slurry applications (indicated on curve).

Table 1. Effects of earth liners and sodium carbonate on seepage rates in soil columns.

	Column 1	Column 2	Column 3	Column 4
	Compacted soil	**1 slurry application**	**5 slurry applications**	**15 slurry applications**
Final thickness in cm	16	21	21	19
Final infiltration rate in cm/day	2.7	1.2	1.0	0.85
Infiltration rate in cm/day after sodium carbonate addition	0.49		0.25	0.19

INTERPRETATION: For the same amount of soil used, earth linings gave lower infiltration rates and, hence, better seepage control when applied as a slurry in split applications to a water filled pond than when applied dry on the bottom of an empty pond and mechanically compacted. Further reductions in seepage losses were obtained by applying sodium carbonate to the water. Repeated slurry applications are naturally achieved in wetlands or other impoundments that receive periodic inflows of muddy water. This is beneficial where seepage losses are to be minimized, but undesirable in infiltration basins for artificial recharge of groundwater. Such basins should then be designed and managed for minimum erosion or other introduction of fine particles into the water.

FUTURE PLANS: The results will be used in interpreting infiltration behavior of impoundments to see what best management practices should be used to maximize infiltration rates (recharge basins) or to minimize infiltration rates (wetlands, ponds, etc.).

FORMATION OF CLOGGING LAYERS IN RECHARGE BASINS

H. Bouwer, Research Hydraulic Engineer; and N.L. Duran, Microbiologist

PROBLEM: Clogging of soil surfaces in infiltration systems for artificial recharge of groundwater or for soil-aquifer treatment is the main problem in maintaining adequate infiltration rates. Even if all clogging parameters like suspended solids, nutrients, and organic carbon are removed, clogging layers may still form on the infiltrating surfaces due to growth of chemotrophic microorganisms. Also, dissolved air in the water may come out of solution as water pressures decrease when the water moves into and through the soil. Other gases, like nitrogen, methane, and hydrogen sulfide may also accumulate due to microbiological processes in the soil.

APPROACH: To evaluate these processes, four plastic columns 10.4 cm in diameter and 90 cm in length were set up in the laboratory. They were packed with four different soils: flint sand, #90 sand, loamy sand of the old Flushing Meadows project in the Salt River bed, and the Mohall-Laveen soil used in the 1 ft x 8 ft stainless steel columns in the greenhouse for studying effects of irrigation and recharge with sewage effluent on groundwater. A coarse sand and gravel layer for drainage was placed at the bottom of the column. Each column was packed with 30 cm of soil. The soil was flooded with Phoenix tap water to a constant depth of 60 cm. The pressure head at the bottom of the soil column was maintained at 60 cm water, thus creating an initial hydraulic gradient of one in the soil column to represent the gravity flow that dominates in actual field systems. The bulk density and saturated hydraulic conductivity of the soils as packed in the column and determined from dry weight and soil volume, and flow rate and head loss, respectively, are shown below.

Soil	Bulk Density, g/cm^3	K, m/day
flint sand	1.50	53.0
#90 sand	1.50	8.5
Flushing Meadows soil	1.54	2.0
Mohall-Laveen	1.74	0.3

RESULTS: Infiltration rates as a function of time for the four columns receiving tap water are shown in figure 1. The infiltration rate started to decrease almost immediately in the two sand columns. The relative infiltration rates (infiltration divided by the initial infiltration rate) are shown in figure 2. The rate at which the infiltration decreased was much faster with the coarser sand columns. The infiltration rate for the fastest three soils approached a common value of about 1 m/day after 45 days. After 95 days, the three columns had an infiltration rate of about 0.7 to 0.8 m/day. The initial rate for the least permeable, Mohall-Laveen soil, was 0.3 m/day and decreased to 0.12 m/day after 95 days. The reduction in infiltration rates could be caused by autotrophic bacteria and/or by formation of entrapped air. Tapping the columns and disturbing the soil surfaces with a rod did not produce ebullition (release of air bubbles) from the soil material, indicating that formation of entrapped air did not contribute to the decline of infiltration rates. However, the soil surface in all four columns was covered with a brown, soft organic layer about 1 mm thick. Stirring up this layer with a rod produced small, sludge-like flocs which, for a while, remained suspended in the water. Undoubtedly, these were flocs of a brown mat of bacteria that grew on the soil surface and their metabolic products like polysaccharides, despite the fact that the water was regular drinking water with some residual chlorine that was given in the water treatment plant to prevent regrowth of microorganisms in the water distribution system. The clogging layer was disturbed for only a small area (about 0.5 cm^2). Nevertheless, infiltration rates immediately increased, but decreased rapidly to the low values before the columns were checked for ebullition (air bubbling). A similar loose, brown deposit of bacterial growth accumulated on the plastic bottom of the constant head reservoir used to maintain constant water levels in the columns, indicating that soil and infiltration played no essential role in the microbiological activity.

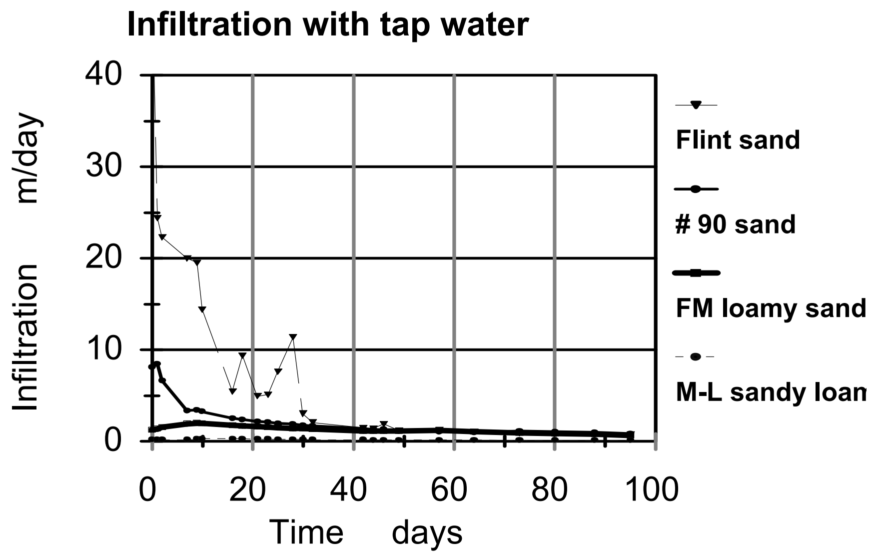

Figure 1. Infiltration with time for columns irrigated with tap water.

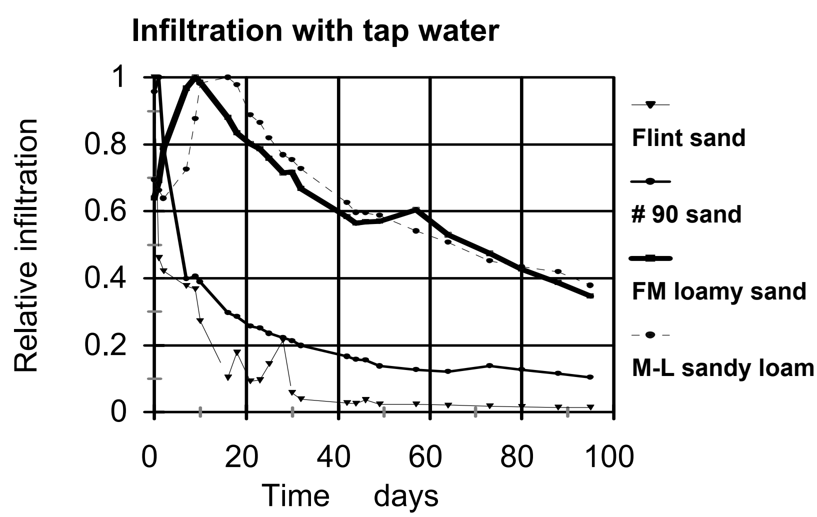

Figure 2. Relative infiltration with time.

Samples were taken from the clogging layer at the top of the columns and analyzed by direct epifluorescent microscopic counts using the nucleic acid fluorochrome stain, acridine orange (AO). Samples were stained with 0.1% acridine orange, filtered through a 0.2μm polycarbonate black filter, and examined with a Nikon epifluorescent microscope equipped with a 410-485 nm excitation filter, an auxiliary excitation filter at 460nm and an absorption filter at 515nm at 100 times magnifications. The biofilm observed on top of the columns appeared to be composed of bacterial cells, dead cell debris and large round cells, possibly aquatic protists. Photomicrographs of spirochetes and bacilli morphologies were taken.

INTERPRETATION: The results show that permeable soils with initially high infiltration rates of finished municipal drinking water clogged faster than less permeable soils, and that eventually all four soils had about the same infiltration rates as controlled by the clogging layer which consisted primarily of bacterial cells and cell debris. Thus, pretreatment of natural water for recharge to remove suspended solids, nutrients, and organic carbon as the main clogging agents will not eliminate clogging problems. Regular drying, cleaning, and disking of the infiltration basins will still be necessary to maintain high infiltration rates. The challenge then is to find the optimum combination of pretreatment of the water and basin maintenance procedures (drying, cleaning, disking) to give the best combination of recharge capacity and operating costs. Where land is scarce, maximizing recharge capacity will be the dominating objective.

FUTURE PLANS: The results of the column studies will be used in developing design and management plans for existing and planned groundwater recharge basins.

WATER REUSE

H. Bouwer, Research Hydraulic Engineer

PROBLEM: Increasing populations and finite water resources necessitate more water reuse. Also, increasingly stringent treatment requirements for discharge of sewage effluent into surface water make water reuse more attractive. The aim of this research is to develop technology for optimum water reuse and the role that groundwater recharge and soil-aquifer treatment can play in the potable and nonpotable use of sewage effluent. Present focus in the U.S. is on sustainability of soil-aquifer treatment, particularly the long-term fate of synthetic organic compounds (including pharmaceutically active chemicals and disinfection byproducts) in the underground environment. The fate of pathogens and nitrogen also needs to be better understood. In Third World countries, simple, low-tech methods must be used to treat sewage for reuse. These methods include lagooning, groundwater recharge, and intermittent sand filtration.

Long-term effects of irrigation with sewage effluent on soil and underlying groundwater must be better understood so that future problems of soil and groundwater contamination can be avoided. Potential problems include accumulation in soils of phosphate, metals, and strongly adsorbed organic compounds, and in groundwater of salts, nitrate, toxic refractory organic compounds, and pathogenic microorganisms. Water reuse for irrigation is a good practice, but it should not ruin the groundwater. Long-term salt build-up in groundwater will occur below any irrigated area (agricultural or urban), regardless of the source water. If there is no drainage, groundwater pumping, or other removal and export of water and salt from the underground environment, groundwater levels then also will rise, which eventually requires drainage or groundwater pumping to avoid waterlogging of surface soils and formation of salt flats. In urban areas, such groundwater rises can damage buildings, pipelines, landfills, cemeteries, parks, landscaping, etc. The salty water removed from the underground environment must be properly managed to avoid problems. Solutions include disposal into evaporation lakes, membrane filtration for water reuse, and disposal of the salty groundwater and reject brines in the ocean. The latter option is feasible only for areas not too far from a coast.

APPROACH: Technologies based on previous research at the U. S. Water Conservation Laboratory (USWCL) and more recent other research are applied to new and existing groundwater recharge and water reuse projects here and abroad. Main purposes of the reuse projects range from protecting water quality and aquatic life in surface water to reuse of sewage effluent for nonpotable (mostly urban and agricultural irrigation) and potable purposes. Ten soil columns in 8 ft x 1 ft stainless steel pipes have been set up in a laboratory greenhouse at the USWCL to study movement of pathogens and chemicals (including trace organics) in systems involving irrigation with sewage effluent, artificial recharge with sewage effluent, and recharge and irrigation with Colorado River water. The columns were filled with a sandy loam from the McMicken Flood Control reservoir northwest of the City of Surprise. This is a desert soil in the Mohall-Laveen Association that has had no agricultural use. The hydraulic conductivity of the soil was determined with a laboratory permeameter test as 28 cm/day, using a disturbed sample. To avoid particle segregation, the soil was placed in the columns in air-dry condition, lowering it in a container and tipping the container when it rested on the bottom of the pipe and then on the top of the soil as the column was filled. The new soil was then compacted with a rod.

Arrangements were made with the Central Arizona Water Conservation District to obtain Colorado River water from the Central Arizona Project (CAP) Aqueduct at a point where the canal has 100% Colorado River water. The CAP water was applied in a recharge mode to one column, starting February 10, 2000.

The sewage effluent to be used in the column studies should be representative of typical treatment for irrigation. As a minimum, the effluent should have had primary and secondary treatment followed by chlorination. Coagulation and granular medium filtration before chlorination removes essentially all microorganisms and makes this so-called tertiary effluent essentially pathogen free and, hence, suitable for unrestricted irrigation. This includes irrigation of lettuce and other crops consumed raw or brought raw into the kitchen, and of parks, playgrounds, golf courses and residential yards. Also, the effluent should primarily be of residential origin with not much industrial input. Proposed irrigation and recharge studies of the 10 columns are shown in Table 1.

Since the U.S. Water Conservation Laboratory does not have analytical capability for the detection of trace amounts of synthetic organics such as pharmaceuticals and other pharmaceutically active chemicals contributed to the effluent by human and industrial waste, samples of sewage effluent were sent to the laboratory of the Civil and Environmental Engineering Department at the University of California at Berkeley, California, where Dr. David L. Sedlak has an active research program on pharmaceuticals in sewage effluent. The first sample was taken from the Goodyear treatment plant because the effluent there was also used for landscape irrigation and artificial recharge of groundwater. The treatment train consisted of primary and secondary treatment, nitrification-denitrification, filtration, and UV disinfection. The sample was taken in mid-August in the late morning when the sewage flow was still relatively small. The results showed very low concentrations of pharmaceuticals, about an order of magnitude less than what is found in San Francisco Bay area sewage effluents, and close to detection limits, which are normally in the 5-10 ng/L range. A better effluent for the column studies may be from the Tolleson sewage treatment plant, which also receives mostly residential sewage and gives only conventional primary and secondary treatment and chlorination. A sample has been sent to the University of California Berkeley for analysis of pharmaceuticals.

FINDINGS: Flooding of the Colorado River water recharge column was started on February 10, 2000, with a 2-week inundation period during which the infiltration rate dropped from 20 to 11 cm/day. The water depth in the column was maintained at 10 cm. When water was first applied to the dry-soil column, it took the wetting front two days to reach the bottom of the column and for outflow to commence. The accumulated infiltration at the time was 75.3 cm, so that the fillable porosity of the air-dry soil in the column was 0.33. This is 84% of the total porosity of the soil, which was calculated as 0.39 from volume and weight of the dry soil in the column. After the first flooding period, drying of the column caused further settlement of the soil. This reduced the length of the column by 11 cm, which decreased the porosity to 0.36. Further settling was not observed. Subsequent infiltration rates were taken as the outflow rates at the bottom of the column. The decline in infiltration rates during the first flooding period may be due to the advance of the wetting front in the column, at least during the first few days of the flooding period. The continued decline may be due to the formation of a clogging layer on the soil surface.

Table 1. Proposed schedule for irrigation and artificial recharge simulation with sewage effluent and Colorado River water for the 10 soil columns in the greenhouse.

Irrigation with Effluent		
COLUMN	**COVER**	**IRRIGATION EFFICIENCY**
1	grass	50%
2	grass	70%
3	grass	90%
4	alfalfa	50%
5	alfalfa	70%
6	alfalfa	90%
7	bare soil	70%[1]
Irrigation with Colorado River Water		
8	grass	70%
	Groundwater Recharge	**Water**
9	bare soil	effluent
10	bare soil	Colorado River water

During the first drying period, the surface soil shrank enough laterally to separate from the pipe, so that it was carefully packed against the pipe again. The second and third flooding periods, which were 21 and 30 days, respectively, showed infiltration rates of around 7 cm/day; but at the end of the third flooding period, an increasing trend developed which continued in the fourth flooding period until infiltration rates reached about 15 cm/day and leveled off at that value. The length of the fourth flooding period was 50 days. During all inundation periods, the Colorado River water above the soil column remained quite clear. A brown mat developed on the bottom, especially in the fourth flooding period, but apparently had no clogging effect. A sustainable infiltration rate of about 15 cm/day is typically achieved in infiltration recharge basins in desert or light agricultural soils. Considering the many factors that affect the relation between infiltration rates and time, the results of the column study did not come as a surprise. The total infiltration amount for the four flooding periods was 12.1 m. Samples of the inflow and outflow were taken for analysis of DOC (dissolved organic carbon) by the Environmental Engineering and Water Resources Department of Arizona State University.

[1] Since evaporation from bare soil will be less than evapotranspiration from a vegetated surface, the bare soil column will be irrigated to give the same volume of leachate as the grass column with 70% irrigation efficiency.

INTERPRETATION: The developments of better technologies or concepts for predicting infiltration rates with cylinder infiltrometers, estimating volumes of water that can be stored underground for water banking, and managing relatively fine textured soils to achieve maximum infiltration for recharge will extend the use of artificial recharge of groundwater to "challenging" soil and aquifer conditions. This will enable water resources planners and managers to benefit from the advantages that artificial recharge offers in conjunctive use of surface water and groundwater, in water reuse, and in integrated water management. The column studies on underground fate and transport of pharmaceuticals and other organic compounds will shed more light on possible effects of both irrigation and artificial recharge on groundwater quality.

FUTURE PLANS: These plans consist primarily of continuing existing research and of developing new field and laboratory research projects, mostly with universities and water districts, on long-term effects of irrigation with sewage effluent on soil and groundwater. Also, infiltration test plots will be installed to verify concepts of recharge basin management developed for finer textured soils where clogging, crusting, fine particle movement or wash-out wash-in, hard setting, and erosion and deposition can seriously reduce infiltration rates.

COOPERATORS: Dr. P. Fox, Dr. P. Westerhoff, and Dr. J. Drewes, Arizona State University, Department of Civil and Environmental Engineering and National Center for Renewable Water Supplies, Tempe AZ; Dr. R. Arnold and Dr. M. Conklin, The University of Arizona, Tucson AZ; Dr. David Sedlak, University of California, Berkeley CA; J. Swanson, The City of Surprise, Surprise AZ; Fort Huachuca AZ, United States Army Garrison through ASU, Tempe AZ; M. Milczarec of GeoSystems Inc., Tucson AZ; and the City of Tolleson AZ.

IRRIGATION CANAL AUTOMATION

A.J. Clemmens, Research Hydraulic Engineer; E. Bautista, Research Hydraulic Engineer;
R.J. Strand, Electrical Engineer; B.T. Wahlin, Civil Engineer;
and B. Schmidt, Computer Programmer;

PROBLEM: Modern, high-efficiency irrigation systems require a flexible and stable water supply. Typically, open-channel water delivery distribution networks are controlled manually and are not capable of providing this high level of service. Stable flows can be achieved when little flexibility is allowed since canal operators can force canals flows to be relatively steady. Allowing more flexibility increases the amount of unsteady flow and leads to more flow fluctuations to users.

Most canal systems operate with manual upstream control. With this approach, all flow errors end up at the tail end of the system and result in water shortages or spills. In some canals supervisory control systems are used to try to match inflows with the expected outflows. Because this adjustment is done by trial-and-error, pool volumes and water levels may oscillate until a balance is achieved. In canals with large storage volumes, these fluctuations may have little impact on deliveries. Smaller canals with insufficient storage need more precise downstream control methods than are currently available. Development of improved canal control methods requires convenient simulation of unsteady flow by computer. Computer models of unsteady canal flow are very complex and expensive because they are designed to model very complicated systems. Only recently have these programs allowed simulation of control algorithms for canal automation.

The objective of this research is to develop technology for the automatic control of canals as a means of improving canal operations. This includes development and testing of canal control algorithms, development of necessary sensors and hardware, development of centralized and local control protocols, refinement of simulation models needed for testing these methods, and field testing.

APPROACH: A Cooperative Research and Development Agreement between ARS and Automata, Inc., was established for the purpose of developing off-the-shelf hardware and software for canal automation; i.e., plug-and-play. We will work closely with Automata in the application and testing of this new hardware and software. The core of this system is the U.S. Water Conservation Laboratory (USWCL) canal automation system that consists of

- feedforward routing of scheduled flow changes (similar to gate stroking),
- feedback control of downstream water levels (to balance canal inflow and outflow), and
- flow control at check structures.

The system is controlled from a personal computer at the irrigation district office. A Supervisory Control and Data Acquisition system (SCADA) is used by operators to monitor the irrigation system and to control gates remotely through radio communications. We are currently using a commercial SCADA package, FIX Dynamics from Intellution, Inc. Originally, standard MODBUS communication protocol was used to communicate between FIX Dynamics and Automata's Base Station, and the base station communicated with the field equipment using Automata's proprietary protocol. All communications in the system now use MODBUS. The USWCL canal control scheme logic (USWCL controller) is interfaced with FIX Dynamics. The research approach will be to use simulation models to test and further develop various control schemes for the proposed automation

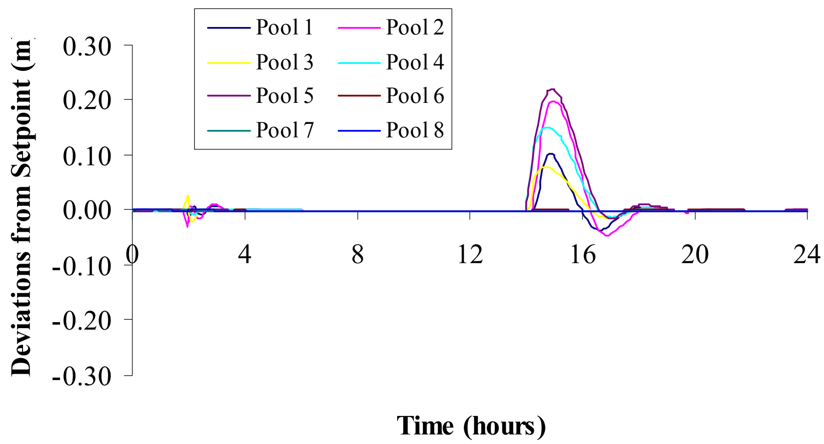

Figure 1. Setpoint deviations for a series of PI controllers on ASCE test case 1-1 (no gate constraints and tuned conditions).

system. The combined hardware and software automation system will be field tested on the WM lateral canal of the Maricopa Stanfield Irrigation and Drainage District (MSIDD).

Simulation of unsteady flow in canals is needed to understand canal pool properties. We routinely use the unsteady-flow simulation package CanalCAD to study canal properties and to test controller performance. The canal properties taken from CanalCAD tests are used within the mathematical analysis software package MATLAB to design various controllers. We have been using a centralized proportional-integral (PI) controller that accounts for system delays. This format allows selection from a family of controllers, including a series of simple local PI controllers. Selections of controllers to test on the WM canal are based on simulation tests of controller performance on the American Society of Civil Engineers (ASCE) test cases and simulation of the WM canal itself.

FINDINGS: Poor canal control performance is caused by a mismatch between pool inflows and outflows and/or incorrect pool volumes. Thus, canal controller methods must address control of both flow rates and pool volumes. An understanding of (1) wave travel times and (2) pool volume as a function of flow rate are necessary and sufficient for the development of feedforward control logic, while for feedback control (1) wave travel times and (2) pool backwater surface area can be used.

<u>Simulation studies of downstream-water-level feedback controllers</u>: Last year a comprehensive set of simulation tests was performed on the ASCE test canal 1. The feedback controllers used ranged from a series of simple, local downstream PI controllers to a fully centralized downstream PI controller. These controllers were tuned using optimization techniques and the integrator-delay model. This year focus shifted slightly, and the tuning method was examined more

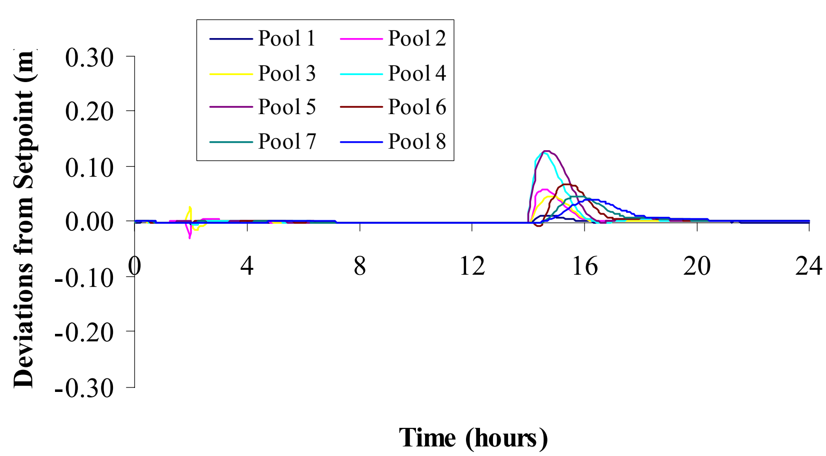

Figure 2. Setpoint deviations for the fully centralized PI controller on ASCE test case 1-1 (no gate constraints and tuned conditions).

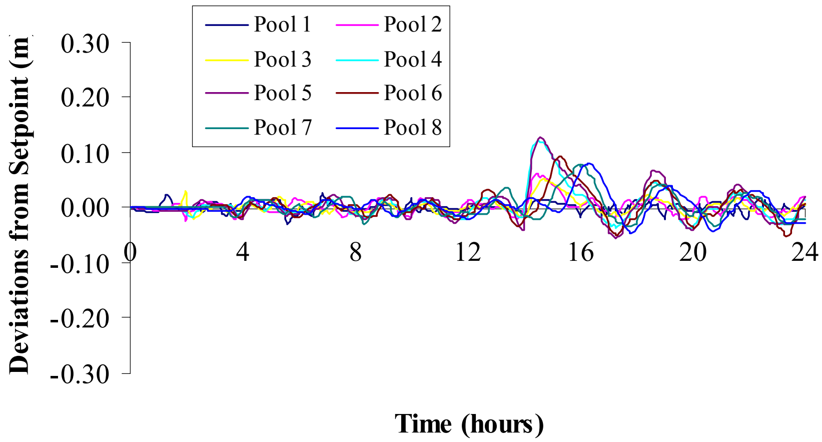

Figure 3. Setpoint deviations for the fully centralized PI controller on ASCE test case 1-1 (gate constraints and tuned conditions).

closely. Specifically, the weights used to penalize water level errors and control actions in the optimization routine were examined. In the initial simulation studies, some of the feedback controllers became unstable when they were run under untuned conditions. This poor performance arose because the controller was fairly aggressive and because of uncertainties in the wave travel time prediction. To avoid this problem, the controller was made less aggressive by increasing the penalty for control actions in the tuning process. Figure 1 shows the simulation results for a series of local PI controllers for the ASCE test case 1-1, while Figure 2 shows the results for the fully centralized PI controller. The minimum gate movement constraints introduced sustained low amplitude oscillations in the water levels (Fig. 3). Most of these optimal controllers were robust enough to handle the untuned conditions without much degradation in performance (Fig. 4).

Also, most of the simulation studies done to this point have been for downstream control of sloping canal systems that are not completely under backwater. Initial work was done with Jan Schuurmans, Peter-Jules van Overloop, and Charles Burt to convert the downstream tuning procedure into an upstream tuning procedure. The initial work indicates that upstream and downstream control require quite different weighting factors on the control actions. In addition, work was also done on adding a high frequency filter to the tuning procedure to account for the resonance problems that may occur in pools that are completely under backwater. Schuurmans and van Overloop have written an initial optimal tuning method in MATLAB that will add a filter to a series of local PI controllers and allow the user to choose either upstream or downstream control. We are in the process of reviewing that code now, and no simulation tests have been performed yet.

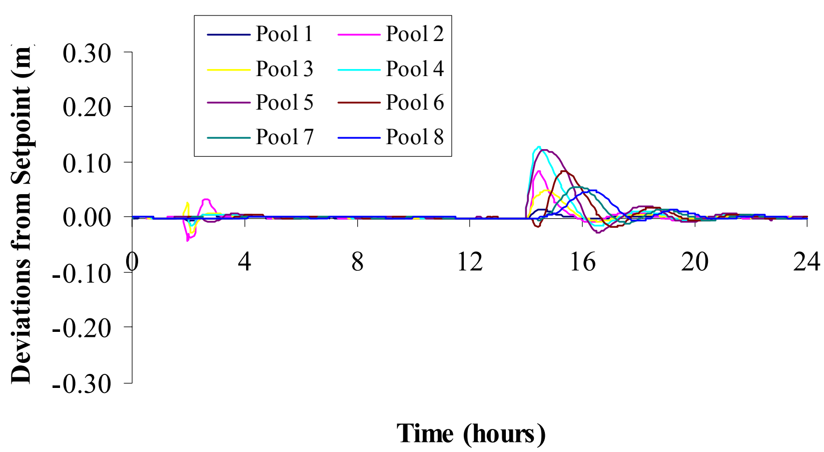

Figure 4. Setpoint deviations for the fully centralized PI controller on ASCE test canal 1-1 (no gate constraints and untuned conditions).

One of the drawbacks to the USWCL controller is that it is applicable only to a single inline canal system. In other words, it cannot be applied to branching canal networks. In reality, canal operators would desire to automate an entire canal network and not just a single branch of that network. Work was done on the USWCL controller to modify it to be able to handle branching canal networks. The method has been developed and it appears to give reasonable controller constants; however, no simulation test has been performed because CanalCAD cannot handle branching canal networks. To overcome this obstacle, the hydraulic simulation package SOBEK was obtained from Delft Hydraulics in the Netherlands. This Windows-based program is capable of handling branching canal networks and the USWCL controller can be programed into it.

MSIDD Field Hardware Modifications and Software Upgrades: As part of the CRADA with Automata, the control sites on the WM lateral were equipped with Automata's "Field Controller" (FC) Remote Terminal Unit (RTU). This unit uses Automata's proprietary communications protocol. To reduce the RTU firmware programming effort, a translator was used at the base station to translate standard MODBUS communications to Automata's protocol. The FC units have been replaced with a new 10-bit version of Automata's Mini RTU. This unit provides functionality similar to that of the FC unit and uses MODBUS as its native communications protocol. This eliminates the need for the intermediate translator. Originally, communication was over narrow-band FM radios. Interference from repeaters in the Phoenix and Casa Grande areas of Arizona have hampered the performance of the control system. To eliminate the interference problem, the FM system has been replaced with a 900 MHz spread-spectrum radio system.

The control software has been upgraded to improve user access to control actions proposed by the system. There are two modes of operation. In "Automatic" mode, control actions are sent automatically to the RTUs. In "Review" mode, the operator is given an opportunity to modify or delete the proposed control actions.

INTERPRETATION: The feasibility of a plug-and-play type canal automation system looks promising. Ensuring proper functioning of the system for a given canal will still require some engineering analysis to determine hydraulic properties and controller constants so that the automation performs adequately.

FUTURE PLANS: Additional simulation studies need to be performed using the controllers developed from Schuurmans and van Overloop's new tuning program. These simulations will include tests to determine the appropriate weighting on the control actions in the tuning program as well as test to determine if the high frequency filter works properly on pools that are completely under backwater. Also, the USWCL controller will be coded into SOBEK and simulation tests will be performed on branching canal networks.

COOPERATORS: Lenny Feuer, Automata, Inc., Nevada City CA; Gary Sloan, MSIDD, Stanfield AZ; Jan Schuurmans, University of Twente, The Netherlands; Peter-Jules van Overloop, van Overloop Consultancy, The Netherlands; Cliff Pugh, USBR, Denver; Charles Burt, California Polytechnic State University, San Luis Obispo CA; Bob Gooch, Salt River Project, Phoenix AZ; Victor Ruiz, IMTA, Cuernavaca, Mexico; Pierre-Olivier Malaterre, CEMAGREF, Montpellier, France.

CANAL AUTOMATION PILOT PROJECT FOR SALT RIVER PROJECT'S ARIZONA CANAL

E. Bautista, Research Hydraulic Engineer; A.J. Clemmens, Supervisory Research Hydraulic Engineer; R.J. Strand, Electrical Engineer; and B.T. Wahlin, Civil Engineer

PROBLEM: The Salt River Project (SRP) is the largest municipal and agricultural water supplier in the Phoenix valley. The district also has a long history of being progressive in the management of its water distribution system. In 1995 SRP initiated an in-house research and development project in cooperation with the U.S. Water Conservation Laboratory (USWCL) to determine the feasibility of implementing canal automation within its distribution network. Canal automation is expected to improve service, reduce operating costs, and improve SRP's stewardship of resources. The objective of this project is to develop an automated canal control system that is compatible with SRP's current canal operational strategies and systems.

APPROACH: The proposed canal control scheme has three main components: (1) downstream water-level feedback control to handle disturbances and errors in flow rate, (2) open-loop feedforward routing of scheduled or measured offtake flow changes, and (3) check structure flow-rate control. Phase I of this pilot project consisted of the development of an automatic control system and simulation studies to test its ability to control water levels on an SRP canal system reach. The upper portion of the Arizona Canal was chosen as the study site. This section includes 5 pools, separated by check structures, and a major branch point at the heading of the Grand Canal. Findings of this initial phase were reported by Clemmens et al (1997).

In view of the promising results, SRP decided to continue with the next phase. In Phase II of the pilot project, which is currently underway, we are investigating various control system issues identified during Phase I and programming the canal automation system into SRP's computing environment.

As indicated in the 1999 Annual Report (Bautista et al., 2000), SRP has been upgrading their Supervisory Control and Data Acquisition System (SCADA) and their computer systems. Consequently, many aspects of the automation project have been delayed until the upgrade is complete. There are other items on which we have been able to continue our research and development efforts.

(1) A computer program has been under development to carry out the feedforward control calculations. Testing of the program is currently underway.

(2) A study was initiated in 1999 by Jan Tel of Delft University of Technology in cooperation with the USWCL and SRP. The objective of the study was to obtain a more accurate head-discharge relationship for SRP's radial gates. Simulation tests have previously demonstrated that performance of the control system will improve with improved gate flow predictions. These predictions are currently very uncertain, with likely errors of 10% under free-flow conditions and 30% under submerged flow conditions. Even if SRP ultimately does not adopt the proposed automation system, improving gate discharge predictions will improve their canal flow control capabilities.

(3) Prior to field testing, we will need to conduct extensive simulation tests with the automatic control system. The control algorithms were coded into the unsteady flow simulation software Mike 11 during Phase I of this project. That code was developed to handle a specific segment of SRP's delivery system and does not provide the flexibility needed to conduct control tests with the entire Arizona Canal or with other canal systems. Thus, the control algorithms in Mike 11 have been under further development.

FINDINGS: (1) A working version of the canal scheduling program is currently being tested by our cooperators in SRP. The program utilizes water order information compiled through SRP's water accounting database, WTAP. Extensive programming has been required to ensure that WTAP data is properly retrieved and the integrity of all input data is preserved. Also, various elements of the interface have been modified to improve the program's user-friendliness.

Tests are being conducted to compare the program's output with SRP canal operations. These tests will help us assess the potential for implementation. SRP canal operations are complex. Operators receive next day's orders through WTAP and by phone. Based on these demands, they develop a schedule of flow changes. The scheduling process is based on experience. In addition to the known demands, operators take into account possible canal losses or gains (from canal infiltration, gate leaks, return flows, rainfall etc.) and trends in water levels. For example, if water levels are increasing throughout the canal (i.e., supplies exceed demands), they will service some demand increases without scheduling them in the expectation that those unscheduled changes will compensate the excess flow in the system and stabilize the water levels. Operators realize that flow predictions through their check structures is imprecise and, therefore, they do not attempt to develop very detailed schedules. Furthermore, they seek to minimize the number of scheduled changes, which they perform manually through the SCADA system.

In addition to the scheduled changes, operators often try to respond to same-day requests for flow cuts or increases (so-called red changes because they are not scheduled). Operators try to satisfy these red changes by finding an increase or cut of similar magnitude to counteract the requested change. Also, they may observe increasing or decreasing trends in pool levels and try to use the requested change to balance the flow. In other cases, if pump capacity is available, the operators will try to respond by turning pumps on or off. Still, in other cases operators will borrow from pool storage to accommodate these short-notice demands. In addition to red changes, canal flows are subject to other unanticipated conditions, such as partial or total shutdown in water treatment plant operations, flushing of water treatment plant filters, unexpected opening of turnouts, storm runoff, etc., all of which impact flows and levels. Clearly, there is a lot of guesswork involved in the operation of the canal. Because of all of this uncertainty, the schedule developed during the previous day is used only as a guide and may depart substantially from actual operations.

Testing of the scheduling program will be conducted in three stages. During the present initial stage, we are comparing the program's output with the planned schedules and the actual system flows. These tests will be conducted over several weeks to identify conditions that are not being accounted for by the scheduling program. These tests will also help us determine the extent to which operators' schedules depart from actual daily flows. We expect the program output to bear some similarities to both the operator-computed schedules and the patterns of daily flows. If this assumption proves true, then these tests should also help us convince the operators to test the program-generated schedules as their daily operating plan. The second testing phase will consist, therefore, of manual implementation of the program output. After SRP completes its SCADA upgrade, we will request SRP's approval to implement flow control on their check structures and to automate the execution of the computed schedules. Thus, the last testing phase will consist of automatic control in real time.

Figure 1 is an example of scheduled and actual discharges at the head of the Arizona-Grand Canal system based on data collected for October 13, 2000. Because of water travel time, flow rate changes for a given day need to be initiated the day before. The program and operator schedules are quite similar except for the initial flow condition used by the operators and the magnitude of a major flow cut occurring at midnight. The actual flow through the headgate is less than the scheduled values, and it appears that throughout the day operators were trying to catch up with the requested system flow. These discrepancies are thought to be related to the fact that data were collected following a period of intense rainfall and runoff into the canal. According to the operators, there was excess volume of water in the system that they were trying to eliminate. Water level data for the illustrated test period have not been analyzed to verify this statement.

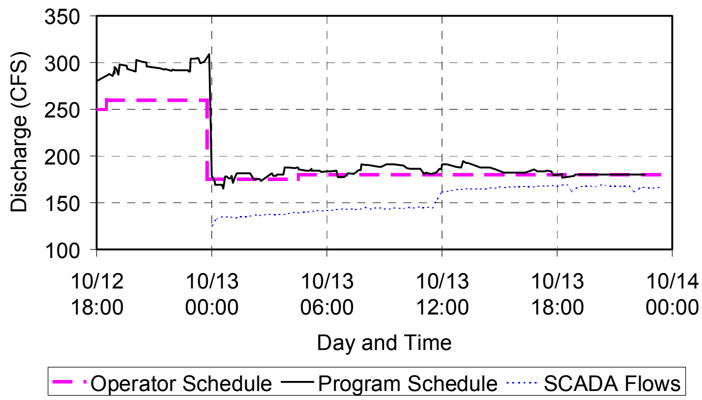

Figure 1. Scheduled and actual flows at the head of the Arizona Canal for schedule date 10/13/2000.

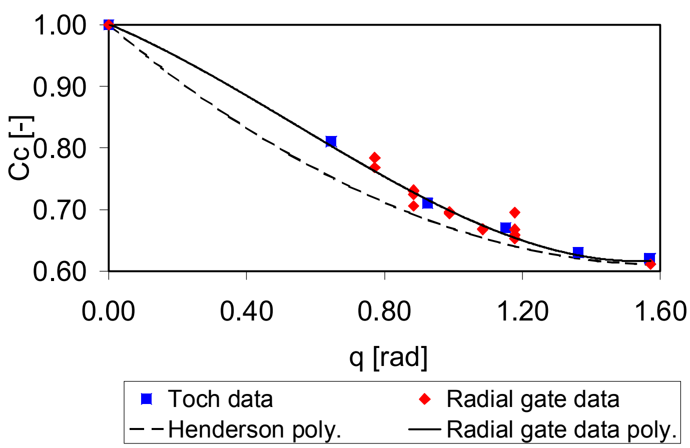

Figure 2. Contraction coefficient for radial gates under free flow conditions; experimental data and best fit polynomials.

(2) Results of the SRP radial gate study were partly inconclusive (Tel, 2000). The analysis under free-flow conditions produced a relationship for the contraction coefficient that fits data from this and previous studies as well or better than a commonly used relationship proposed by Henderson (1966). These results are illustrated in Figure 2. The analysis also concludes that small energy losses occur under free flow. An energy loss coefficient is proposed for discharge calculations but an approach for computing the value of that loss coefficient is not

provided. From the submerged flow analysis it was concluded that important flow parameters could not be measured with sufficient accuracy. Thus, the study did not suggest ways of improving the accuracy of the radial gate head-discharge relationship under submerged flow conditions.

(3) Development of the Mike 11 automatic control code continued intermittently during 2000 and is expected to be completed early in 2001.

INTERPRETATION: Initial testing of the scheduling program suggests that there is some uncertainty in the available data and that operators rely on experience to compensate for this uncertainty. Despite this, results suggest that the computed schedule can assist operators in developing their daily operational plans.

FUTURE PLANS: A report is under preparation summarizing the Phase II activities and accomplishments. At this time and because of the delays with SRP's SCADA system upgrades, the future of Phase III, testing in real time, seems uncertain. SRP operators remain interested in testing the feedforward control program and so we expect to begin manual implementation of schedules in 2001. At the same time, operators have manifested skepticism of the feedback control component and, thus, there is less enthusiasm to test that part of the control system. We plan at least to conclude the control system simulation tests.

COOPERATORS: Robert Brouwer and Jan Tel, Delft University of Technology, The Netherlands; Jan Schuurmans, University of Twente, The Netherlands; Robert Gooch, Joe Rauch and Grant Kavlie, Salt River Project, Phoenix AZ.

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