IRRIGATED FARM MANAGEMENT

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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

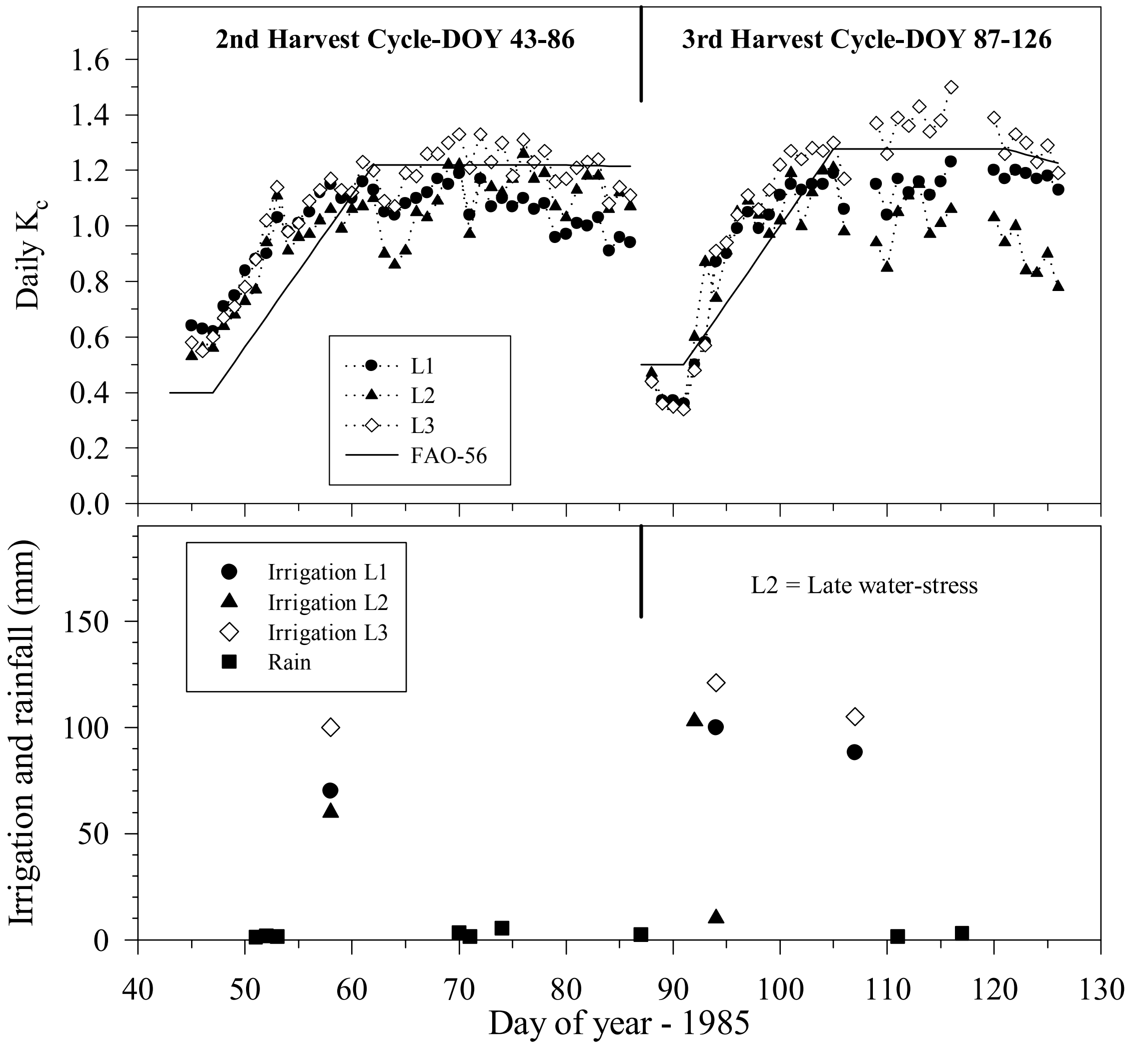

Figure 1. Daily K_c and irrigation and rain during 2nd and 3rd harvest cycles of alfalfa.

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.

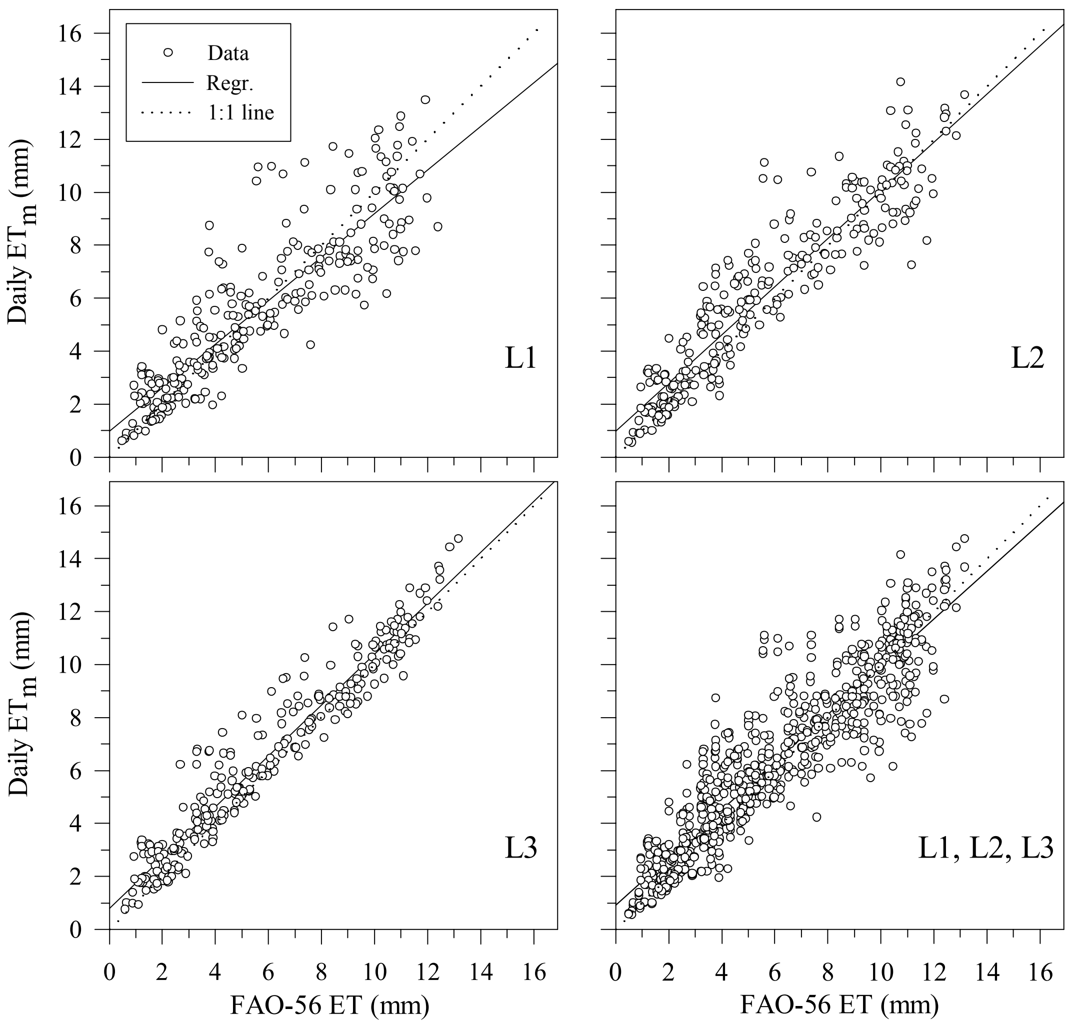

Figure 2. Linear regression of measured and predicted ET using the single K_c model of FAO-56.

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.

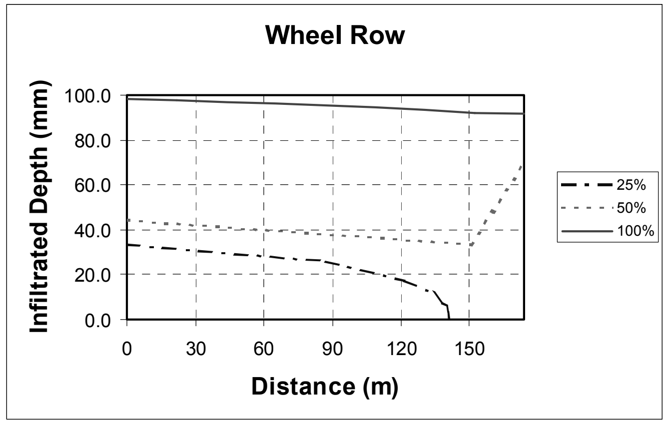

Figure 1. Cumulative one-dimensional infiltrated depth with distance after 25, 50, and 100% completion of irrigation for the wheel furrow of a fertigated furrowed level basin.

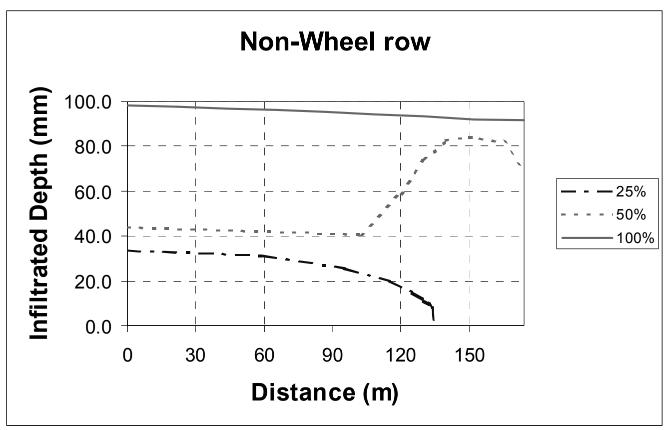

Figure 2. Cumulative one-dimensional infiltrated depth with distance after 25, 50, and 100% completion of irrigation for the non-wheel furrow of a fertigated furrowed level basin.

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.

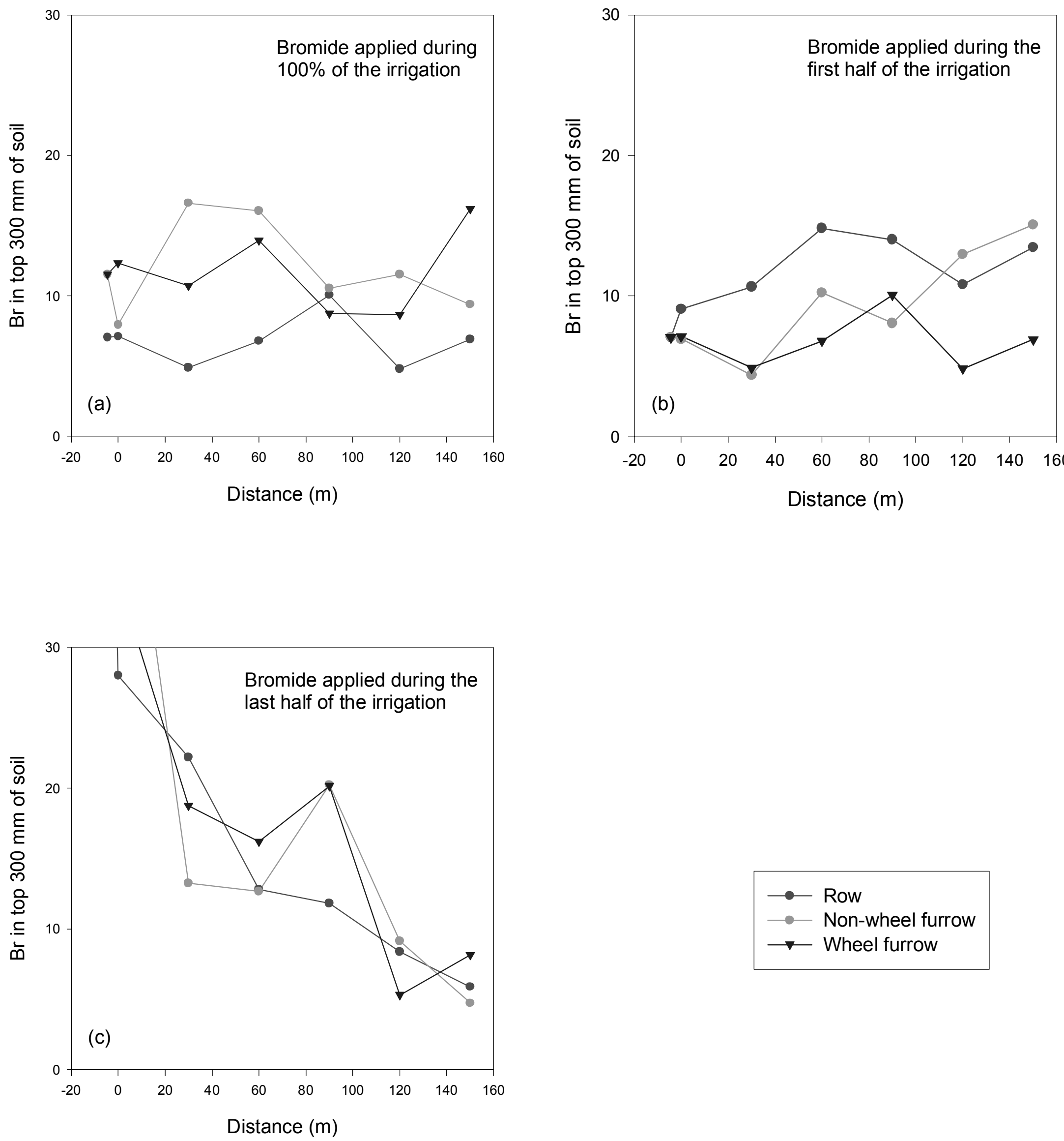

Figure 3. Changes in concentration (mg kg^{-1}) in soil bromide in the top 300 mm of soil from pre-fertigation sampling to post-fertigation sampling for the average of two in row values and for wheel and non-wheel furrow for (a) 100%, (b) first-half and (c) last-half of irrigation injection.

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.

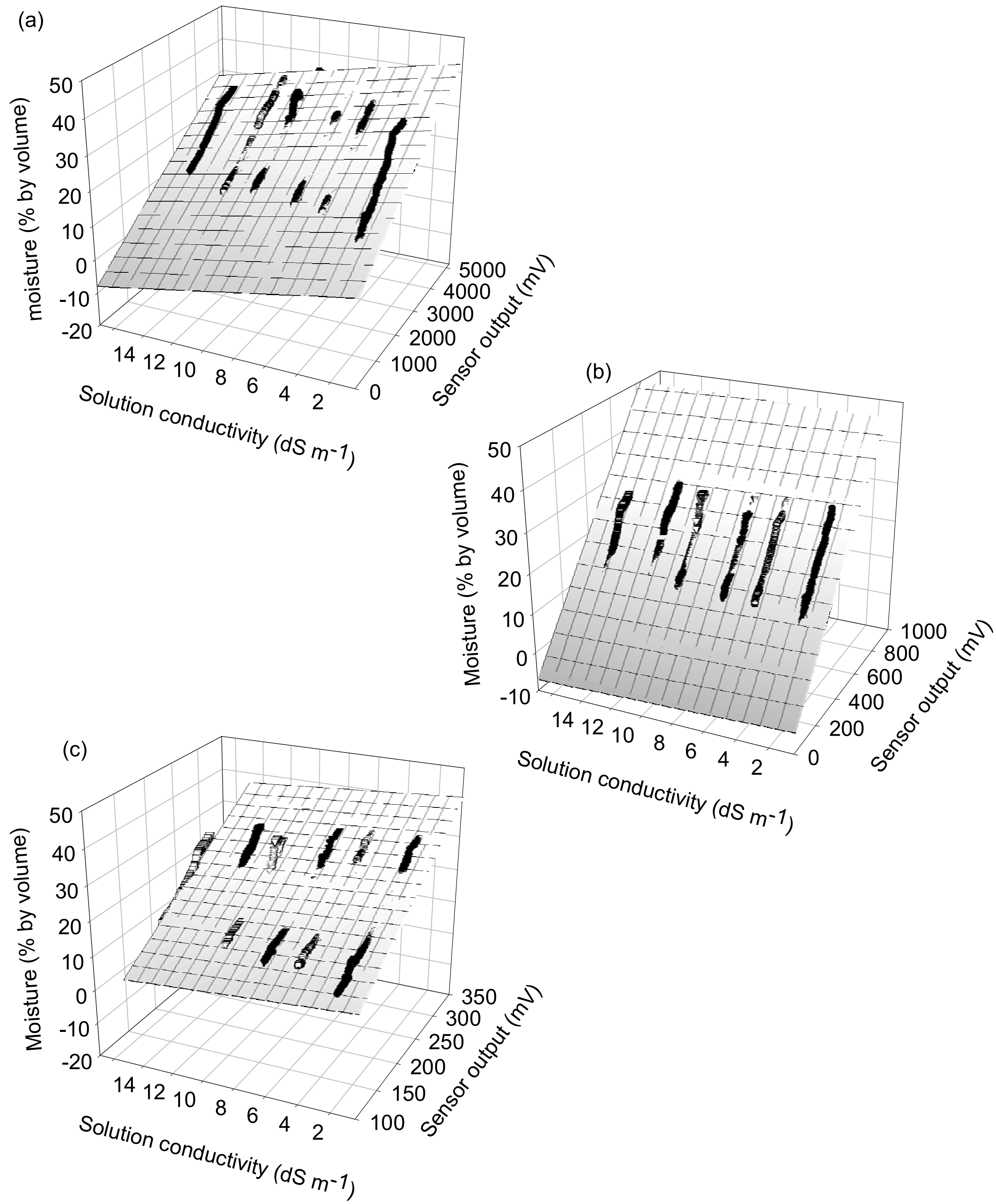

Figure 1. Response surfaces of (a) Aquatel-TDR, (b) Theta, and (c) Trime to moisture content versus solution salinity and sensor output.

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.

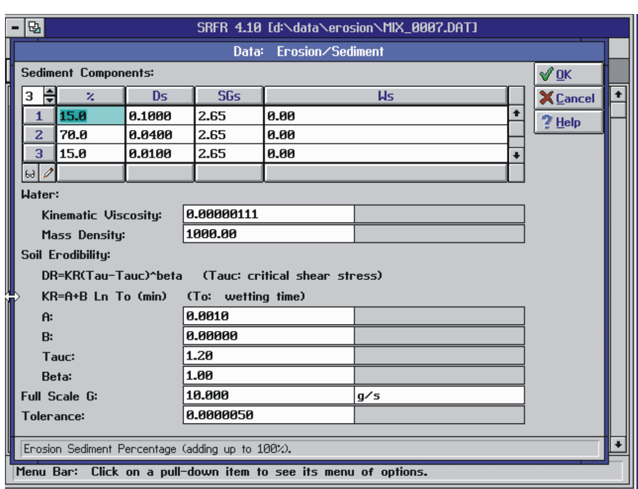

Figure 1 Data-input screen for specifying field data, including particle-size distribution, for erosion computation.

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

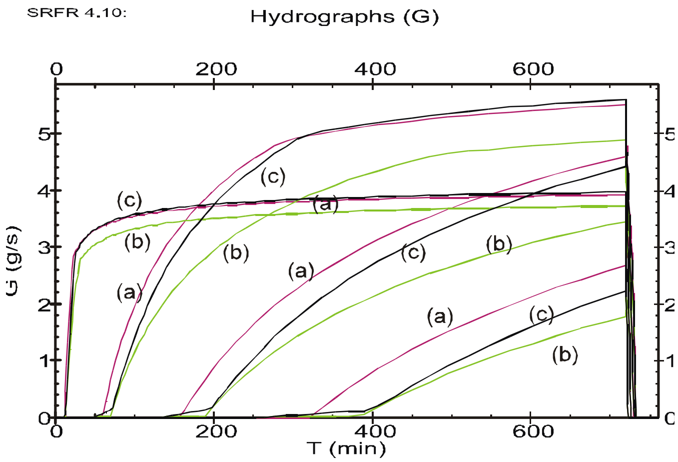

Figure 2 Influence of treatment of particle-size distribution on transport capacity and consequent total sediment load at furrow quarter points; (a) distribution represented by median diameter; (b) as per WEPP (1995); (c) as per Wu and Meyer (1989).

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.

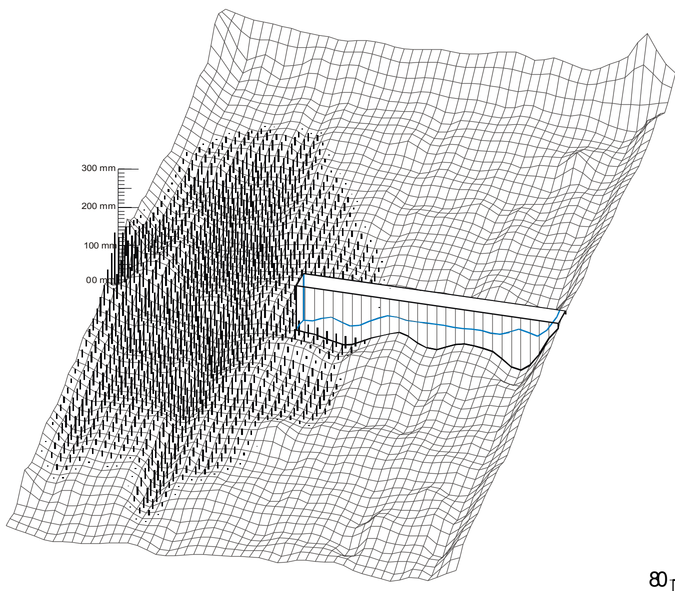

Figure 2 Simulated depths as irrigation stream encounters raised roadway

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.

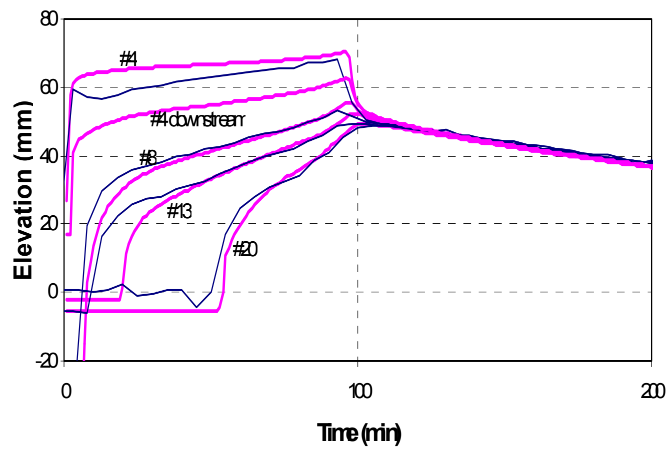

Figure 4 Comparison of simulated (broad grey) and measured (narrow black) depth hydrographs.

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 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.